JERNKONTORET
RESEARCH

SCIENTIFIC REPORT
D 853

The Steel Eco-Cycle

ENVIRONMENTAL RESEARCH PROGRAMME

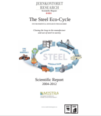
Closing the loop in the manufacture
and use of steel in society

Scientific Report
2004-2012

MISTRA
The Swedish Foundation for
Strategic Environmental Research

www.stalkretsloppet.se

Sc Report



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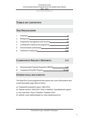

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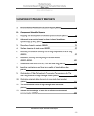

Introduction

The Steel Eco-Cycle is an environmental research programme with the goal of creating sustainable manufacture and use of steel, with the vision of *closing the loop in the manufacture and the use of steel in society*. The eight-year-long programme, entitled The Steel Eco-Cycle, was completed in 2012.

The programme is built around a network of researchers and projects. Organisation of the projects has been marked by substantial participation of industry representatives in combination with researchers from universities and institutes in order to ensure both high industrial and scientific value.

The Steel Eco-Cycle is funded by the Foundation for Strategic Environmental Research, Mistra, and the Swedish steel industry in cooperation with the mining, scrap-recycling and manufacturing industries. The programme was hosted by the Swedish Steel Producers Association, Jernkontoret. Jernkontoret’s own well-established research organisation has been very successful in disseminating results throughout the industry.

Processes and procedures have been developed. Many of these developments have been applied by the industry during the research period.The potential for marked progress by conservation of natural resources and energy, and by the reduction of carbon dioxide emissions, is high. Developed methods for life cycle environmental evaluations can be used to further develop processes and new steel grades in a sustainable direction.

The outcome of the Steel Eco-Cycle programme research is summarised in this document and in the associated scientific reports from the component projects.

Sc Report

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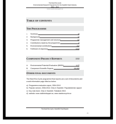

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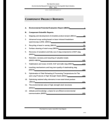

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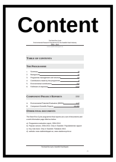
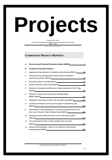
OTHER FINAL DOCUMENTS

The Steel Eco-Cycle programme final reports are a set of documents and a web information page titled as below.

a) Programme evaluation report, 2004-2012.
b) Popular version, 2004-2012. Only in Swedish: Populärteknisk rapport
c) Key note book. Only in Swedish: Faktabok 2013.
d) website: www.stalkretsloppet.se; www.steelecocycle.se





1. Summary

The Steel Eco-Cycle is an integrated research programme, initiated and organised by the Swedish steel industry to meet future demands for steel eco-efficiency from customers, the public, and authorities. The focus is on the conservation of natural resources and energy (eco-efficient manufacturing) and the safe use, recyclability and identification of the environmental value from a life-cycle perspective.

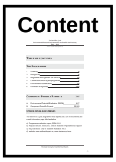
The programme began at the end of 2004 and was completed by the end of 2012. The progress within the different components projects has been substantial, transferring many research questions from the concept stage to the method development and implementation stage.

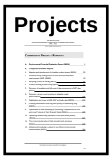
The Steel Eco-Cycle is the first large and coherent research effort directed towards an integrated analysis of environmental aspects in the steel industry in Sweden. In this programme the steel industry collaborated with the mining, the scrap handling and manufacturing industries.

The component projects have been classified into four scientific work areas: *environmental evaluation*, *steel application*, *steel recovery*, and *steel production*. The environmental evaluation projects describe the interactions between the environment and society and develop reliable methods to evaluate the environmental value. The technical projects, however, focus on closing and optimizing the use of energy and resources at the different stages such as usage, recycling, and production of steel.

The main purpose of the programme is to make the Swedish steel industry more aware of environmental trends and better prepared for new demands from society by increasing its knowledge in order to develop measures to meet these demands. The research activities have therefore been developed with extensive participation from the steel industry. The industry has also participated actively in the component projects.

The main results of the programme are as follows: environmental evaluations show that the most effective way for continuously improving the environment is to develop even stronger and more resistant steel grades, as well as carrying on streamlining the materials and energy use in the production processes. Such actions directly correspond to the needs of society to develop in a sustainable direction. The sustainability factors should be considered already at the research and development stage in order to play a more decisive role.





2. Background

Steel is the most commonly used and recycled metallic construction material in the world. It is therefore of great importance to give it an environmental value which can be continuously improved. During the year 2010, production of steel amounted to almost 1 500 million tonnes, of which 32 million tonnes was stainless steel, destined for products, structures and buildings all over the world. All other metals together amounted to less than 80 million tonnes per year.

This huge disparity is shown in Figure 1. The world steel consumption is expected to rise to approximately 2 800 million tonnes by the year 2050.

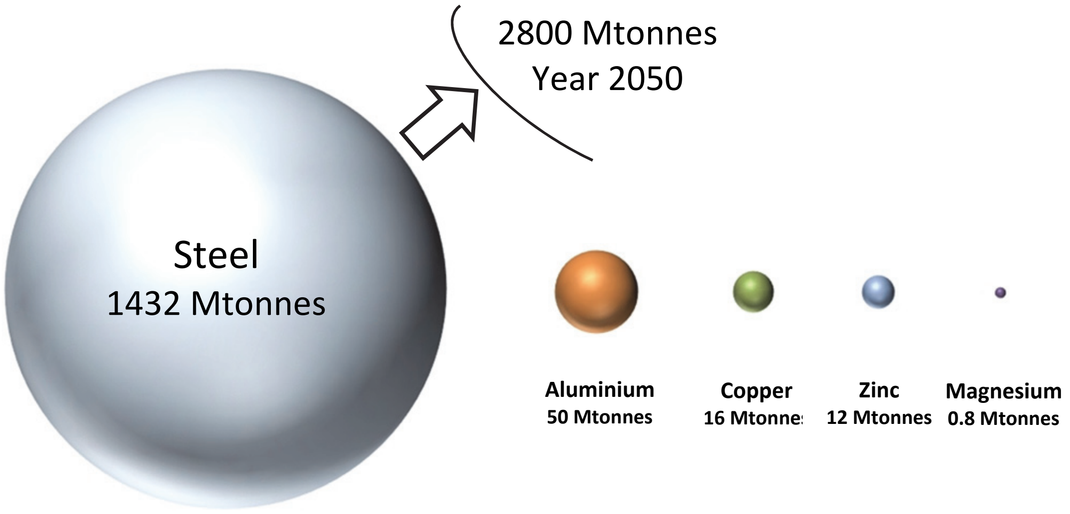


Figure 1. The production of steel globally is more than 15 times larger than all other metals together.

Today, the steel consumption is so large that supply of steel scrap, despite the high rate of recycling, cannot satisfy more than 30 per cent of steel demand globally and 40 per cent within Sweden. By the year 2050, the recycling of scrap will only satisfy some 50 per cent of the global demand. In order not to suffer from a shortage of steel, the remaining part must be produced from iron ore, even if the recycling rate is 100 per cent. This is predicted to result in raw material shortages and rising costs.

This is reflected in the long-term environmental policy, set by the European Union and Sweden. The aim is to reduce the greenhouse gas emissions by 80% until 2050. Environmental demands are continuously rising and today encompass processes (air, water and soil pollution), energy and resource efficiency as well as products.

In addition to steel scrap, slag and other residues including their content of valuable metals must be reused as well. The amount of steel and slag production over time is illustrated in figure 2.

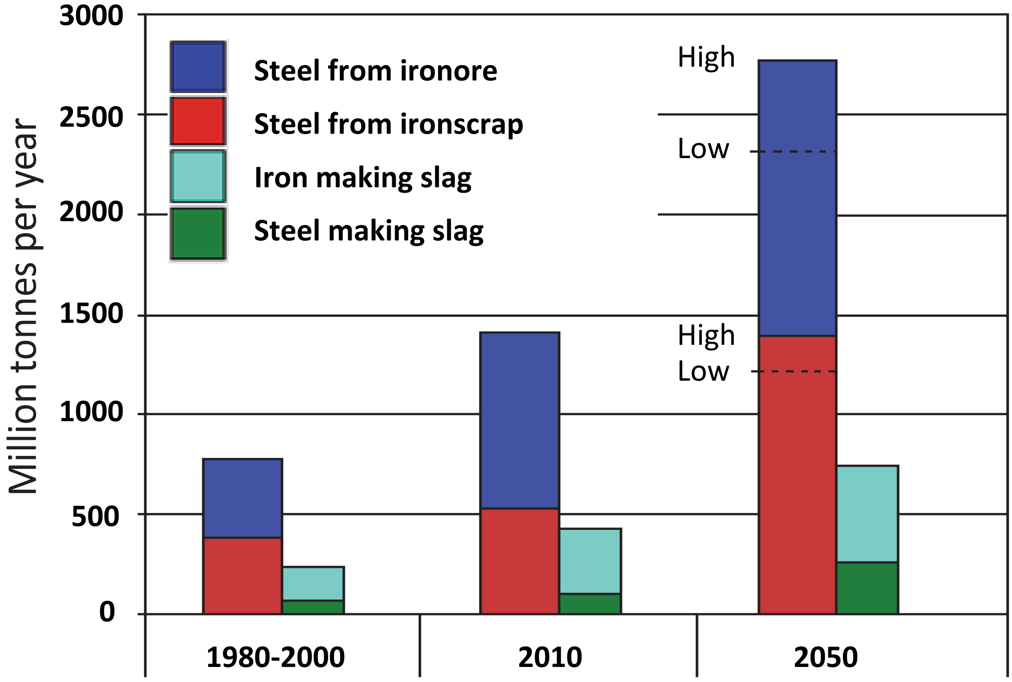


Figure 2. Annual production of steel and slag from 1980 and a forecast for the year 2050.

The global production of material has increased rapidly during the course of the Steel Eco-Cycle programme. Figure 3 illustrates the sustainability problem in the form of the increasing demand for materials and energy, particularly in the rapidly developing economies like China and South Asia. There is obviously an urgent need for solutions that can conserve energy and natural resources.

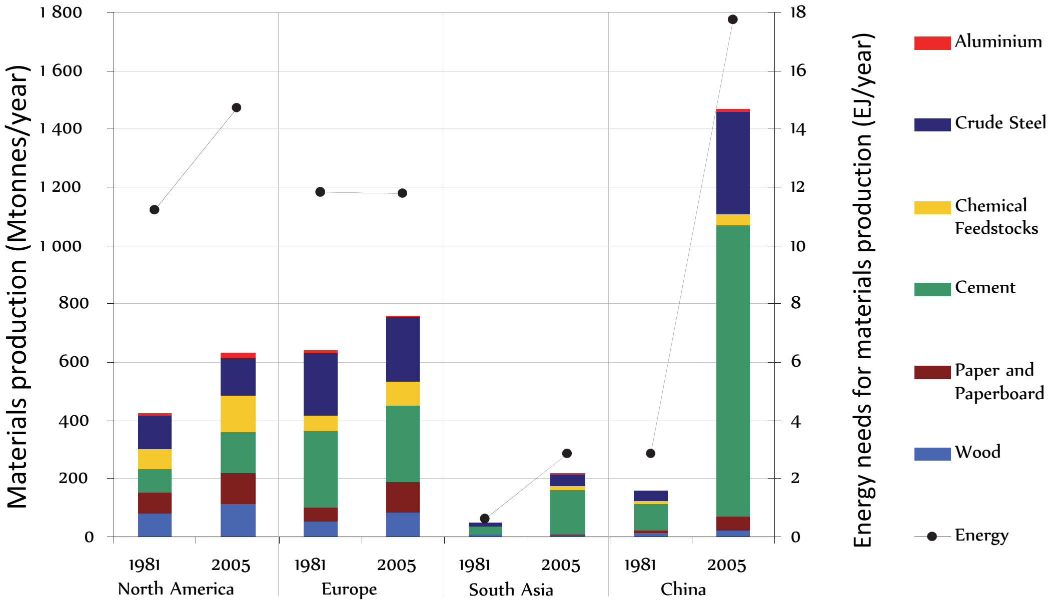


Figure 3. *Production of materials and use of energy 1981-2005 (source: IEA).*

The use of steel in Europe is also increasing, although at a lower rate compared to southern Asia. The consumption of steel in the EU27 countries was 313 kg per capita in 2011, compared to 337 kg in 2001, a decrease of 7 per cent. In Sweden, the development has been different; the consumption was 425 kg in 2011, compared to 348 kg in 2001, with an increase of 22 per cent. This increase in steel consumption illustrates the need for a holistic research approach covering all aspects of the steel eco-cycle. As a consequence of this development, official bodies plan and issue regulations aiming to control goods, products and services in society to achieve a more efficient use of natural resources etc.

The demands will successively be tightened on manufacturers to disclose information on environmental impact and energy consumption from a life-cycle perspective i.e. for raw materials, manufacturing and use of products, recycling, end-of-life treatment and transportation.

Within the environmental research programme, several environmental assessments have been made of process improvements. Also, case studies relating to steel construction have been developed in the course of the research programme. They have shown how a more scientific and quantitative analysis can govern activities which make a contribution to sustainable development.

3. Programme management and structure

The organization of the programme is supported by strong industrial representation. The mining and steel industries, scrap dealers and manufacturing industry have all appointed a number of engineers from production, R&D and environmental disciplines, mainly to be members of the component project groups.

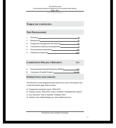
The Swedish Steel Producers' Association, Jernkontoret, is the host of the programme. The programme board includes representatives from some of the largest companies in Sweden. The members are as follows:

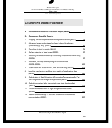
• Jarl Mårtenson, Chairman *	Ovako AB
• Hans Lindh	Volvo Car Corporation
• Peter Samuelsson	Outokumpu Oyj
• Jan Eckerlid	Svensk Kärnbränslehantering AB
• Ulf Arnesson	Stena Recycling AB
• Fredrik Gunnarsson	Mistra
• Göran Andersson, Programme Director	Jernkontoret

* former Chairmen have been Göran Carlsson, SSAB and Martin Pei, SSAB.

Important research groups from universities and institutes have been engaged to carry out research in direct cooperation with industry. This provides the participants with the opportunity to acquire in-depth and up-to-date knowledge on environment aspects and apply this knowledge in the development of new processes and steel products.

The way in which the programme is organized, relying on the expertise of different scientific disciplines and representatives from the industry, has been deemed as unique by Mistra's independent evaluators. The concept of the programme structure is shown in Figure 4.





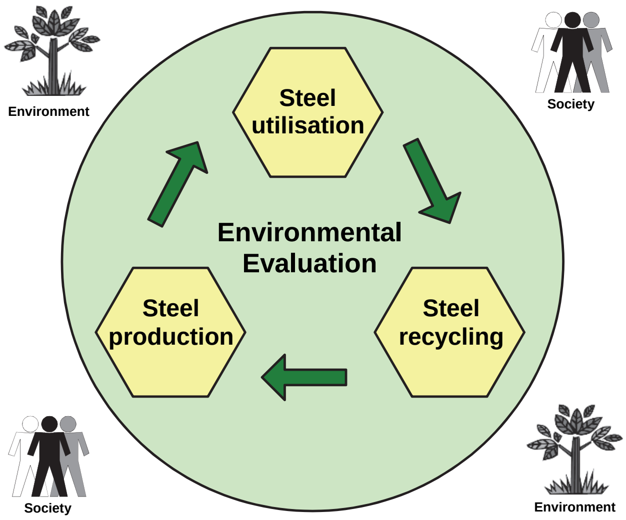


Figure 4. Chart summarising the programme structure

A project group, with members from the industry and the research team, supports each component project. The project leaders are responsible for the daily scientific leadership of the projects, but each project is continuously evaluated and the research activities are decided by the project group.

Research committees ensures that ongoing deliverables were fulfilled according to time schedule, economy, and the goal of the entire Steel Eco-Cycle programme.

In the project groups, the Chairman and Project Leaders are members of the research groups for steel recovery, steel production and steel application.

The principal organisation of the programme and project management is summarised in Figure 5.

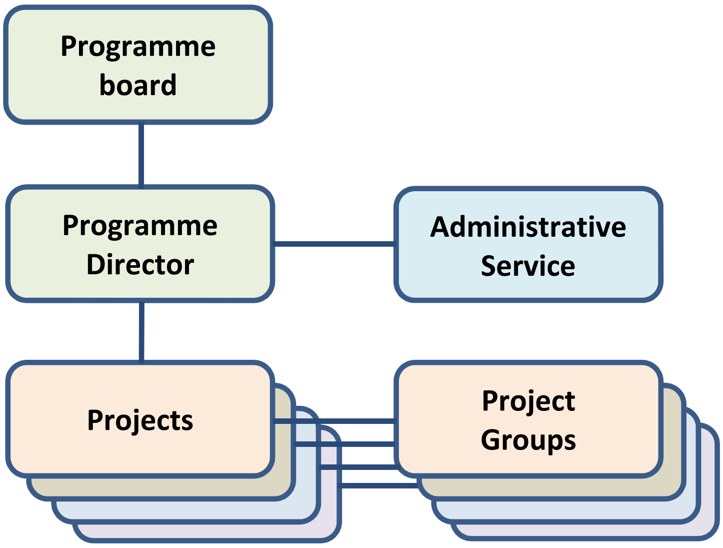


Figure 5. *Organisation of the Steel Eco-Cycle programme*

The primary user group has been directly involved in the research programme, through research committees and project groups. The following companies and research institutes together represent a large national and international network serving the progress of the programme. The programme participants are listed in Table 1.

Industries

AB Järnbruksförnödenheter
AB Sandvik Materials Technology
Bombardier Transportation
Cargotech HIAB
Green Cargo
Harsco Metals Sweden AB
Höganäs AB
IKEA of Sweden AB
LKAB
Merox AB
MultiServ AB
Metso-Minerals
Outokumpu Oyj
Outokumpu Stainless AB
Outokumpu Oy
Ovako Bar AB
Ovako Steel
Rautaruukki Oyj
RHI Refractories Nord AB
Saab
Scania
SSAB AB
SSAB EMEA
SSAB Merox
Stena Recycling AB
Uddeholm Tooling AB
Volvo Car Corporation
Volvo Truck
Volvo VCE

Universities, institutes, consultants and associations

Linnaeus University
Royal Institute of Technology (KTH)
Luleå Technical University

Swedish Environmental Research Institute
Swerea MEFOS
Swerea KIMAB
Stålbyggnadsinstitutet (Swedish Institute of Steel Construction)

Ekerot Resources AB
Minpro AB
Kobolde & Partners AB
PM Technology AB
Sperle Consulting AB

World Steel Association
Jernkontoret

Table 1. Participating companies and organisations

4. Contributions made by the programme

The Steel Eco-Cycle programme is the first large and coherent research effort in Sweden and probably worldwide, which is directed towards an integrated analysis of the environmental aspects in the steel industry, the mining industry, scrap handling and the manufacturing industry. The programme is composed of component projects, carried out by three universities and four research institutes, covering the entire steel eco-cycle. The technical projects focus on closing and optimising the use of energy and materials and reducing the environmental impact in different parts of the life-cycle chain of use, recycling, and production of steel.

In addition, two evaluation projects describe the interactions with the environment and society in order to develop reliable methods to evaluate the environmental value of process and product changes.

The component projects have been classified into four scientific work areas: *environmental evaluation*, *steel utilisation*, *steel recycling* and *steel production*.

The results obtained create a substantial and significant base for environmental life-cycle evaluations. The programme deliverables are briefly summarised in Table 2.

Structure	Concepts	Methods	Know-how
Environmental evaluation		LCA tool for environmental profiling of steel production and use. Preference based (con-joint) evaluation of environmental performance.	Experience, data and network for efficient practical application of LCA and preference based evaluations. Environmental stakeholder analysis, improved communication and decision-making processes.
Steel application		Processing for improved properties and low consumption. Design and evaluation methods to minimise weight and reduce environmental impact.	Implementation of optimal heating and hot rolling parameters. Guidelines and advice: how to minimise weight, reduce environmental impact, and improve recyclability.
Steel recovery	New concept ideas for recycling	Classification and sorting of scrap online. Combined preheating and surface cleaning.	Scientific knowledge base on recovery of steel and material flows in society. User experiences, e.g. from large-scale experiments.
Steel production	Refined concepts for slag treatment and metallurgical refining.	Methods for slag treatment, alloy utilisation and metallurgical refining.	Thermodynamics and kinetics of slag-steel interactions. Improved databases. Strengthening mechanisms and combinations of retained elements User experiences, e.g. from large-scale experiments.

Table 2. Steel Eco-Cycle deliverables in summary

In order to achieve its ambition for the Steel Eco-Cycle programme, it is composed of a spectrum of component projects to cover the entire steel eco-cycle. The projects were selected from about 50 proposals by classifying each project by three factors: Industrial value, Environmental value and New technology. The selected projects have been used as cases for the environmental evaluation in a life-cycle perspective, each project individually as well as the Steel Eco-Cycle programme as a whole.

The actual component projects are illustrated in Figure 6. For more details see the attached scientific reports.

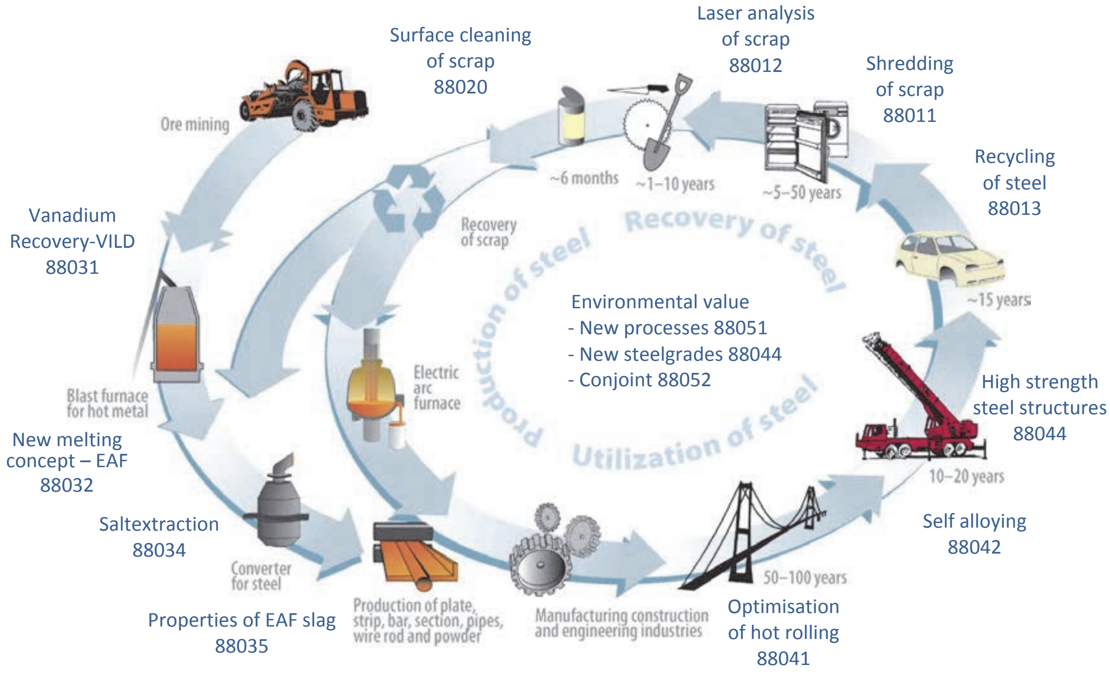


Figure 6. *The "Steel Eco-Cycle" with component projects.*

The individual component projects are summarized below:

- *88011 – Mapping and development of the shredder product stream*

The project has developed and reported methodologies that could be used by shredders to improve practice and products. Ended by 2008 and knowledge transferred to project 88013.

- *88012 – On-line classification of steel scrap using intelligent evaluation from a CCD-spectrometer equipped LIBS*

A laser-based technique and prototype instrument has been developed for fast on-line analysis of steel scrap. The prototype has been evaluated and tested in laboratory as well as in industrial settings. The programme component has also been part of a European research collaboration partly financed by the European Research Fund for Coal and sSteel, RFCS. The work has been awarded the Greentech award by the Swedish Association of Graduate Engineers and the 2011 prize from the King Carl XVI Gustaf Fund for Science, Technology and the Environment.

- *88013 – Recycling of steel in society*

The project, amongst other things, has resulted in two models: one Material Flow analysis (MFA) model and another model to illustrate the iron and steel flows in Sweden from the beginning of iron and steel making until today. In addition, a new method to calculate the recycling quota has been presented. Within the project a method for Random Sampling Analysis, RSA, of different scrap qualities has also been developed to improve the possibility to blend scrap with more accuracy. RSA has also proved its value in assessing the value of alloys in a scrap delivery without costly melting tests. Finally a web based model for scrap optimization, RAWMATMIX®, has been developed, taking scrap properties and other parameters into account when calculating an optimal mix and assessing a carbon footprint for the charge. The system is currently used at steel works in Sweden and Norway.

The increased knowledge about scrap metallurgy generated by the project is now designated as "SKROTGÅRDSMETTALURGI" (scrap yard metallurgy) and has been integrated into education at Sweden’s Royal Institute of Technology (KTH) with an annual seminar in this field where industry and researchers meet. The work in this field is continued in a number of projects and project proposals e.g. collaboration with China on carbon footprint in a VINNOVA financed pre-study, improved carbon footprint tracking and scrap quality monitoring. An annual update of the recycling quota is also discussed.

- *88020 – Surface cleaning of steel scrap*

A method has been developed for surface cleaning of steel scrap by making use of plastic waste. The development of the concept has been through both small-scale experiments and large-scale pilot trials. Pilot scale equipment has been constructed and erected. The concept has been tested and important lessons for the future industrial implementation of the concept have been learned. Test results have indicated successful removal of zinc and organic compounds on the scrap but further process optimisation is needed. The project has also received funding from the Research Programme of the Research Fund for Coal and Steel RFS-PR-09028, SSAB EMEA and the Swedish steel industry through Swerea MEFOS joint research.

- *88031 – Recovery of vanadium in LD-slag – VILD*

The project has developed several cost-effective methods for production of vanadium products based on Swedish and Finnish LD (BOF)-slag. These have been developed and verified in pilot and industrial scale tests. One of the methods is already in process of commercialization and another one under industrial evaluation. The project including detailed LCA analysis and initial CAPEX and

OPEX studies have shown the great economic and environmental potential of the methods developed.

- *88032 – Optimization of unit processes in steelmaking to counter the loss of metal values to slag and dust*

Research related to minimization of metal losses to slag and dust through studies of thermodynamic processes. Computer models have been developed and used as a tool in combination with laboratory and industrial trials. Cr-losses were significantly lowered by replacing the oxygen with CO_2 in the injected gas during decarburization of steel melts both in EAF and AOD process. A new process was invented for Mo addition in EAF furnaces and the Mo yield was increased from 90% to 99.5% in the full-scale 70 ton EAF. This is a significant achievement in the process optimization of Uddeholms AB. Ovako Steel, Outokumpu Stainless and Sandvik Materials Technology have also shown strong interest in applying this process.

- *88034 –Development of a novel process route for recovery of metal values from slag and dust by molten salt extraction*

Research including laboratory and industrial studies on a pilot scale related to the extraction of metal from slag was performed. The project has resulted in reports on extraction, electrolysis, synthesis and condensation in this new scaled-up process. Successful electrode position of ferrochrome from the salt bath after salt extraction of Cr_2O_3-containing slag has been demonstrated. This process has been extended to the recovery of rare-earth metals from electronic wastes. Process developments towards the recovery of Fe and Mn from steel slag by oxidation-electromagnetic separation route were carried out successfully and nano manganese ferrites with optimized magnetic properties could be precipitated out of the slag by this innovative process.

- *88035 – Leaching mechanisms and long-term quality of steelmaking slag and 88033- Stabilization and reuse of AOD, EAF and ladle slags*

The short and long-term quality of original and modified steel slags with a focus on leaching properties was studied. Theoretical investigations on a lab scale as well as industrial full-scale trials were conducted in order to present and develop scientifically based recommendations regarding slag compositions and handling processes in order to make slag a marketable and valuable product. Several of the recommended techniques are today adopted and used by the Swedish steel industry.

- *88041 – Improving high strength steels with energy efficient processing routes for environmental benefits*

The project has studied how mechanical properties of steels can be maintained while decreasing the energy consumption of the production process by lowering the temperature during processing or eliminating process steps. Laboratory and full-scale pilot tests have been performed, resulting in more energy-efficient rolling processes without compromising the quality of the end-product. Recommendations have been given to the strip, heavy plate and long products producers about the most promising processing parameters for obtaining the best mechanical properties of the studied steels. For example an 80°C reduction in slab reheating temperature can reduce energy consumption by up to 8 per cent for the heating of steel before rolling. Knowledge from this project makes it possible to eliminate a hardening process and improve the productivity during hot rolling of heavy plate and strip.

- *88042 – Optimizing retained alloy elements in new steel sheet products*

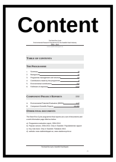
Semi-products from recovered Vanadium can be used for alloying instead of FeV, providing considerable savings. Less expensive alloying with recovered alloys can also decrease the use of other purchased alloys, e.g. Nb. Ended by 2008 and transferred to project 88031.

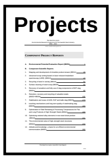
- *88044 – High strength steel structures for reduced environmental impact*

Life-cycle analyses have been performed in order to understand and quantify the environmental benefits associated with an increased use of Swedish advanced high strength steels. The awareness of the significant upsides of using less material without compromising the durability of a structure has been raised in the industry and in the public by efficient communication of the results. A numbers of case studies, software for calculation of the environmental and economic benefits and a handbook on assessing the environmental value of using high strength steel grades are effective tools in the communication process.

- *88051 –Evaluation of environmental impacts*

The project has quantified the environmental impact of the Steel Eco-cycle programme, based on assessments in cooperation with each individual project. The environmental data obtained using a LCA approach is considered a key element in the communication of the programme results. The LCA approach has also introduced comprehensive analyses of the project technologies as part of manufacturing chains including upstream and downstream processes.





- *88052 –Attitude and knowledge – a basis for an efficient environmental communication*

Attitudes towards environmental issues have been studied for the steel industry and its stakeholders. Stakeholder preferences for steel characteristics as well as for industry-specific sustainability issues have been identified. The project has assessed what factors influence environmental decision-making (knowledge, public concern, legislation, economy etc.) The results can be utilised in two different ways; first, key stakeholders' attitudes to environmental issues have been identified and this knowledge comprises a basis for strategic environmental decisions. Second, an easy-to-use manual on the method used in the project has been written; it can be used to conduct similar surveys in the future by the industry itself. .

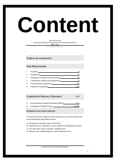
The integrated and the component project results are impressive since the theoretical and technical improvements from the research could be used in the industry after only four years of research. The savings in energy consumption and the reduction of carbon dioxide emissions were, in fact, considerably higher than assumed in the programme proposal.

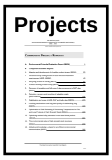
5. Environmental contribution

Environmental evaluation, as the term is used in this report, describes how different steel grades and manufacturing processes can be assessed from a life cycle perspective.

For steel, this means that change needs to be quantified and analysed during the steel's life cycle, from raw material to production of steel and steel products, manufacturing and use of products and structures as well as recycling of steel scrap and waste products.

Figure 7 shows the life cycle of steel including manufacturing and usage as well as recycling of steel scrap which becomes new steel in products; a cycle that can be repeated indefinitely without the properties of steel being affected.





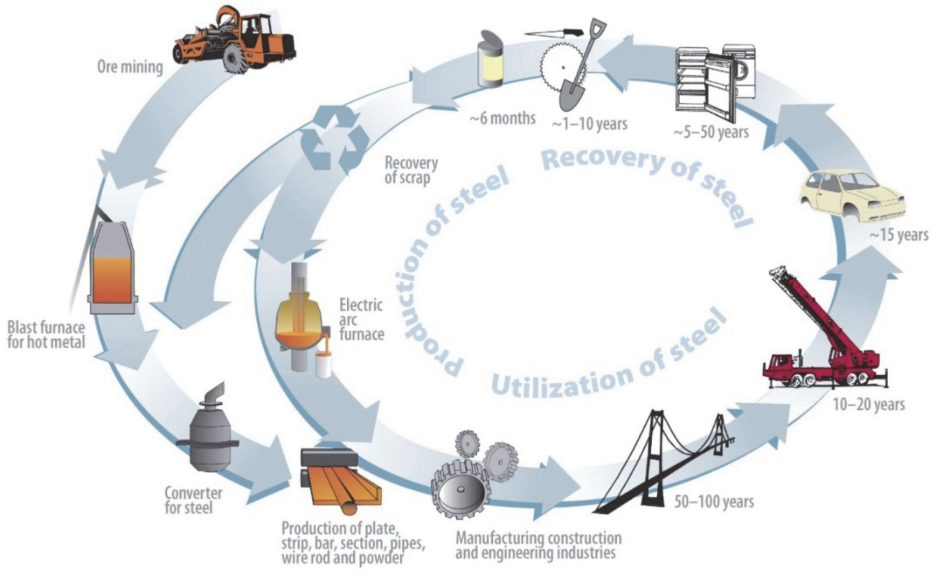


Figure 7. Steel life-cycle as a closed loop

Steel is and will remain the most commonly used and recycled material. The high rate of recycling makes steel unique among other modern materials.

The greater challenge is to put this change into a wider context and analyze the consequences from a life cycle perspective. The most important aspects are shown in Figure 8.

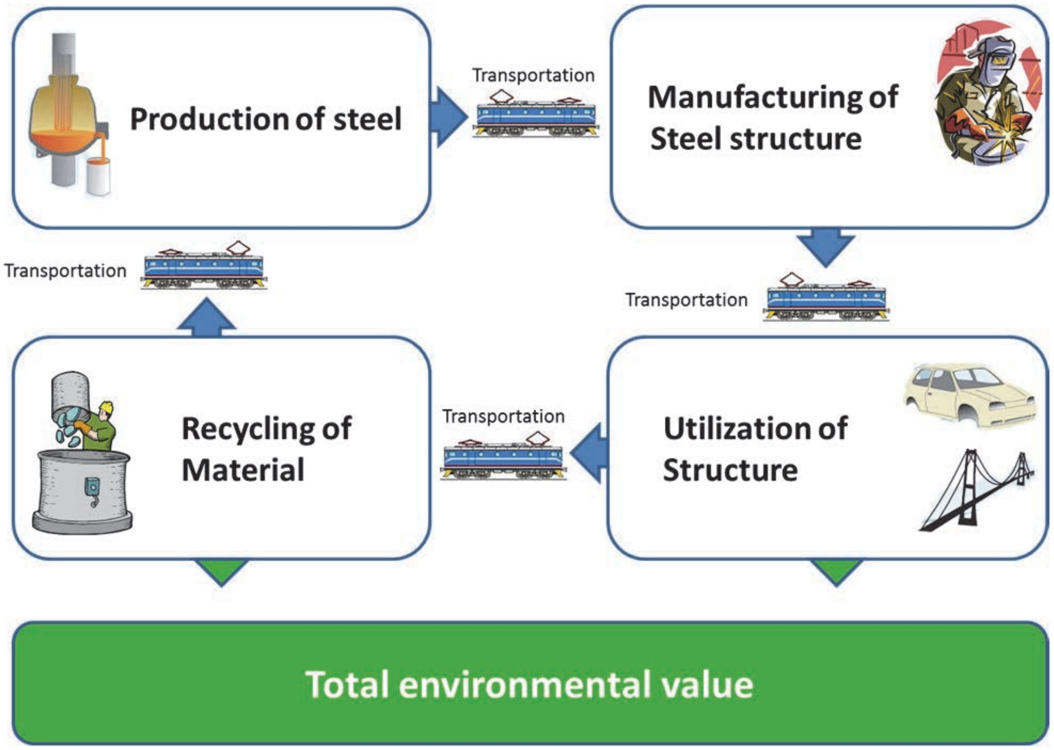


Figure 8. Important elements for environmental assessment of steel

Environmental evaluation of steel production techniques

Within the Steel Eco-Cycle environmental research programme, nine technical process methodologies have been developed. This development has, for example, increased the knowledge of supply and quality of steel scrap, increased the yield of scrap in production and increased the rate of recycling of slag, all for the purpose of strengthening the steel eco-cycle. Developed technologies have been assessed from an environmental perspective showing less emissions of carbon dioxide and less use of material and energy. The potential environmental savings which are a result of the developed methods are shown in Table 3. The table shows that the environmental value of the technical improvements in the steel industry can be multiplied by a factor of 3-6 when the environmental improvement from reduced raw material consumption is included.

Potential	Carbon dioxide	Energy
Raw material production	**-1 100 ktonnes/year**	**-4 100 GWh/year**
Steel production	**-200 ktonnes/year**	**-1 200 GWh/year**
Total	**-1 300 ktonnes/year**	**-5 300 GWh/year**

Table 3. Potential improvement of the environmental value from technical measures in the Steel Eco-Cycle project 88011 to 88042.

The effects on the consumption of raw materials are shown in Table 4.

Specification of outcomes	Unit	Potential for savings and additional values (excluding 88044)
FeV (as pure V)	**tonnes/year**	**5 000**
Cr	**tonnes/year**	**28 000**
Ni	**tonnes/year**	**2 600**
Mo	**tonnes/year**	**310**
Iron ore pellets	**tonnes/year**	**510 000**
CaO	**tonnes/year**	**81 000**

Table 4. Summary of the raw material savings according to the environmental evaluation for projects 88011 to 88042

The potential reduction of landfill and potential savings from the handling of by-products and residual products are shown in Table 5.

Specification of outcomes	Unit	Potential for savings and additional values (excl. 88044)
Crushed aggregates from rock	**tonnes/year**	**200 000**
Landfilling of slag & dust	**tonnes/year**	**300 000**
Waste management of ASR*	**tonnes/year**	**76 000**

*ASR – Automotive Shredded Residue

Table 5. Summary of the savings of natural resources according to the environmental evaluation for projects 88011 to 88042

Environmental evaluation of new steel grades

In the Steel Eco-Cycle programme, ten different case studies have been performed on steel construction, where conventional steel has been steel replaced by high-strength steel. By using stronger and more resilient steel, weight reductions of between 20 to 40 per cent have been obtained. Weight reductions lead to savings of natural resources, which means significant environmental gains throughout the life cycle. If the new steel grades are used to develop new light vehicles, fuel savings throughout the life time will increase with every additional kilometer of driving.

Where, for example, 1 million tonnes of advanced steel replace 1.3 million tonnes of conventional steel in the road vehicle fleet , the environmental gain will be large, Table 6. The environmental gains due to lesser use of steel correspond to ten per cent of the total gain. Ninety per cent of the gain is achieved during use, due to less fuel consumption. In total, the reduced energy use during the vehicle's life time amounts to 30 000 GWh and to 8 000 ktonnes of carbon dioxide. This is more than the annual energy consumption and carbon dioxide emission of all steel production in Sweden.

Process	Carbon dioxide	Energy
Raw material production	**-200 ktonnes**	**-850 GWh**
Steel production	**-500 ktonnes**	**-2 150 GWh**
Use	**-7 300 ktonnes**	**-28 000 GWh**
Total	**-8 000 ktonnes**	**-31 000 GWh**

Table 6. Potential environmental savings when one million tonnes of high-strength steel replace 1.3 million tonnes of conventional steel in the road vehicle fleet.

The environmental gains from fixed structures are not as large since there is normally no use phase that contributes to savings, but the relative gains can be substantial. One example demonstrating this is a life cycle assessment performed on the Friends Arena in Solna, Table 7. By using 32 % high strength steel in the roof structure, the weight reduction amounts to 584 tonnes, from 4 584 tonnes to 4 000 (or 16 %). By manufacturing and transporting a smaller amount of steel, a considerable environmental gain is obtained also.

Weight of the permanent roof [tonne]	Weight reduction [tonne]	Weight reduction [%]	Reduced environmental impact CO_{2e} [tonne]	Reduced environmental impact CO_{2e} [%]
4000	**584**	**13**	**1340**	**16**

Table 7. Weight and environmental savings with high strength steel in Friends Arena, Solna

Case study	**Weight reduction[1] WR [kg]**	**Weight reduction[1] WR [%]**	**CO_{2e} saving[2] [kg]**	**Energy saving[2] [kWh]**	**Specific CO_{2e} saving [kg/kg WR]**	**Specific Energy saving [kWh/kg WR]**
Active structures						
Semitrailer tipper	1 136	25	30 000	120 000	26	106
Articulated truck	39	21	1 600	6 400	41	164
Loader crane	114	17	4 650	18 600	41	163
Trailer	500	37	25 000	100 000	50	200
Car bumper	3.5	33	29.5	118.0	8	34
				Average	33	133
Passive structures						
Storage tank	19 100	33	65 000	227 500	3.4	12
Spiral dewaterer	3 000	31	1 970	7 880	0.7	3
Friends Arena case A	585	21	900	3 600	1.5	6
Friends Arena case B	732	28	1 000	4 000	1.4	5
Chair frame 1.2 million	325	11	719	2 876	2.2	9
				Average	1.8	7

1) Weight reduction of upgraded parts 2) Including recycling

Figure 8. Summary of results from the case studies

Results from the case studies are summarised in Table 8. Active structures are mostly vehicles which gain environmental savings over their whole life and considerable gains are obtained during the use of the vehicle. For passive structures the environmental gains are mostly associated with the fact that less steel has to be produced and transported.

Development of new steel grades

The research has shown that it is important to make an environmental assessment already at the development stage and to take into account the properties of the final product.

It might be the case that a new steel grade has a higher environmental impact in the production phase but delivers environmental gains in a life cycle perspective. When developing new steel grades it is important to “compose” the steel in such a way that the combination of raw material, production method and area of application gives the lowest possible environmental impact during the product life cycle.

Figure 9 gives an indication on the environmental load of different alloying elements. With the aid of this data, the alloying concept can be evaluated from an environmental viewpoint.

Greenhouse gases are expressed as carbon dioxide equivalents (CO_{2e}). This value consists mostly of carbon dioxide but also of emitted methane etc.

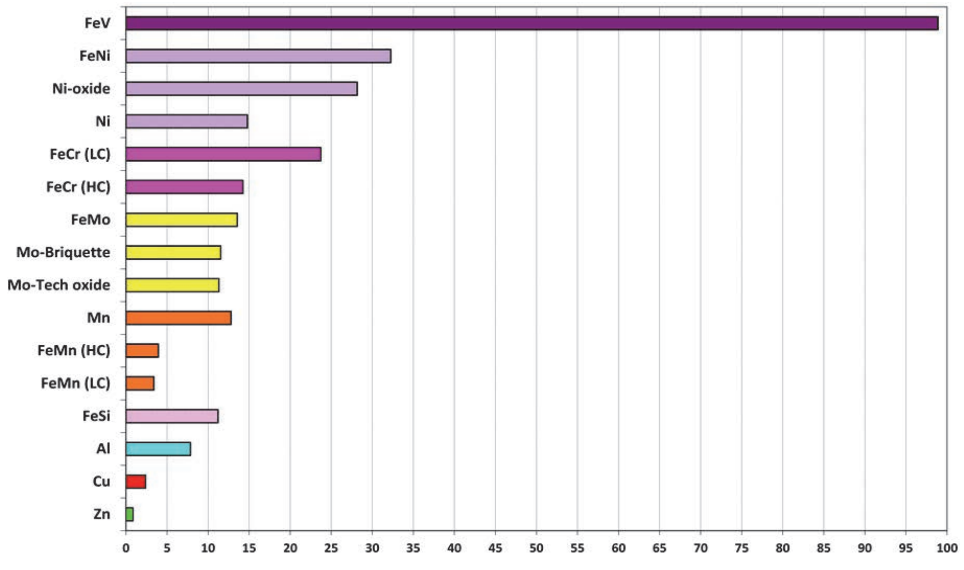


Figure 9. Examples of total greenhouse gas emissions when producing various alloying metals (kg CO_{2e}- per kg of pure alloy metal).

6. Fulfilment of the Steel Eco-Cycle objectives.

The Steel Eco-Cycle was initiated and organised by the Swedish steel industry to meet future demands for eco-efficiency.

The demands for sustainability from customers, the public and authorities were expected to become more based on a holistic view, focusing on *the conservation of natural resources and energy* (eco-efficient manufacturing), *safe usage* and *recyclability*.

The Steel Eco-Cycle has been successful in supporting the industry with new methods for assessment of environmental benefits, by operating a number of component projects with high industrial relevance, covering the entire steel eco-cycle.

The Swedish steel industry is famous worldwide for the development and production of high performance steel products as well as energy efficient production with low environmental impact.

The main purpose of the programme is, however, to extend awareness about the environmental aspects of the Swedish steel industry in an integrated and holistic way. Therefore, research has been carried out with extensive participation by the mining, scrap-handling and manufacturing industry, in cooperation with the steel industry.

The vision of the Steel Eco-Cycle research programme is: **closing the loop of the manufacture and usage of steel in society**. Conservation of natural resources and energy as well as the reduction of emissions were the main objectives.

These ambitions have been accomplished by:
-Effectively economising the use of steel in applications and products.
-Increasing the recycling of scrap metal and optimising the use of alloys in the steel eco-cycle.

The research programme also provides:
-Increased interdisciplinary and multidisciplinary cooperation between the research groups and the users of research results from the programme.
-An increased number of qualified researchers within the environmental field.
-A basis for commercialisation of achieved results.

The environmental effects of the programme have been evaluated by the Swedish Environmental Research Institute (IVL) in cooperation with industry. The study was made from a life-cycle perspective.

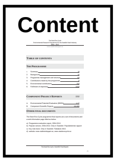
The objective, according to the programme plan, was*:*

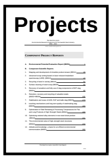
“The projects related to production technology are estimated to provide feasible technical solutions to reduce CO_2 *emissions from the Swedish steel industry by 1000 ktonnes/year and energy consumption by 600 GWh/year at the current production level (2004). The savings potential for several raw materials are also high. The projects related to product design are expected to achieve technical solutions that may reduce weight in steel structures by 20-25 % (based on previous experience from the car and heavy vehicle industry, and other equipment for transport and cargo handling). Much of the research within the programme is expected to have a considerable impact in reducing the amount of contaminants released into the biosphere.”*

The attached Environmental Evaluation Report (attachment A) and the Scientific Report (attachment B) of each component project prove that all planned objectives in the Steel Eco-Cycle programme have fully been met.

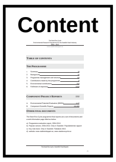
COMPONENT PROJECT REPORTS

B . Component Scientific Reports





Sc Report



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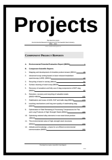

Projects

REPORT

The Steel Eco-Cycle

Phase 1+2, 2004 - 2012

Environmental Potential Evaluation

The Steel Eco-Cycle Programme Phase 1+2

December 2012

A report from project 88051

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14 December 2012

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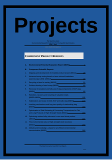


SUMMARY

The Steel Eco-Cycle programme comprised 11 technical development projects. Their potential environmental significance has been evaluated with life cycle assessment (LCA) methodology. The evaluation shows that the programme provides a significant potential contribution to the conservation of natural resources and energy in the manufacturing and use of steel. The projects of the programme have the potential to provide technical solutions for reductions in CO_2 emissions and energy consumption exceeding the programme objectives of 1000 ktonne/year and 600 GWh/year, respectively, for the Swedish steel industry. There is also a potential to save material resources and mitigate other aspects that have a negative influence on the environment in addition to resource consumption and carbon dioxide emission.

The focus of this report is on quantitative calculations of energy savings, carbon dioxide abatement and efficient use of steel products and by-products from steelmaking. The objective is to identify and quantify the strength of the programme.

The evaluation arrives at a quantitative assessment of each individual project by comparing it to a presently established technology providing the same function, and compiles the individual project assessments to produce one assessment of the entire Steel Eco-Cycle programme, presuming that the results are fully explored without any practical limits. The detailed technical background of each individual project evaluation is not described for confidentiality reasons.

Current steelmaking technology is described by two LCA models, one for ore-based and one for scrap-based steel manufacturing. For new technologies, specific data is collected from inventories of the processes being developed. Peripheral processes, i.e. processes which supply commodities like alloying metals, slag formers, transport, and electric power and other energy wares, are described by data from databases and from the literature (generic data). The inventories have been compiled in co-operation with the technical projects. Inventory data and evaluation results have been communicated between the project teams and the evaluation team.

In addition to the quantitative evaluation results, a profile of the environmental effects of each new technology has also been obtained. These profiles can be used to identify improvement opportunities for process chains extending over three industrial sectors: steel making, steel recovery and the use of steel in products. These new technology profiles are of great significance, and though not reported in detail here, they have been reported to each project group.

CONTENTS

1 INTRODUCTION

The objectives of the Steel Eco-Cycle programme include developing feasible technical solutions to reduce the CO_2 emissions from the Swedish steel industry by 1000 ktonnes/year and reduce energy consumption by 600 GWh/year at the 2004 production level. These objectives represent a significant contribution to the conservation of natural resources and energy in the manufacturing and use of steel.

The Steel Eco-Cycle programme has operated 11 technical projects and 2 environmental evaluation projects during its two phases. The technical projects are evaluated in this report as a prospective evaluation of the R & D results. The detailed technical background of each individual project evaluation is not described for confidentiality reasons. Figure 1 gives an overview of the Steel Eco-Cycle and the projects of the research programme.

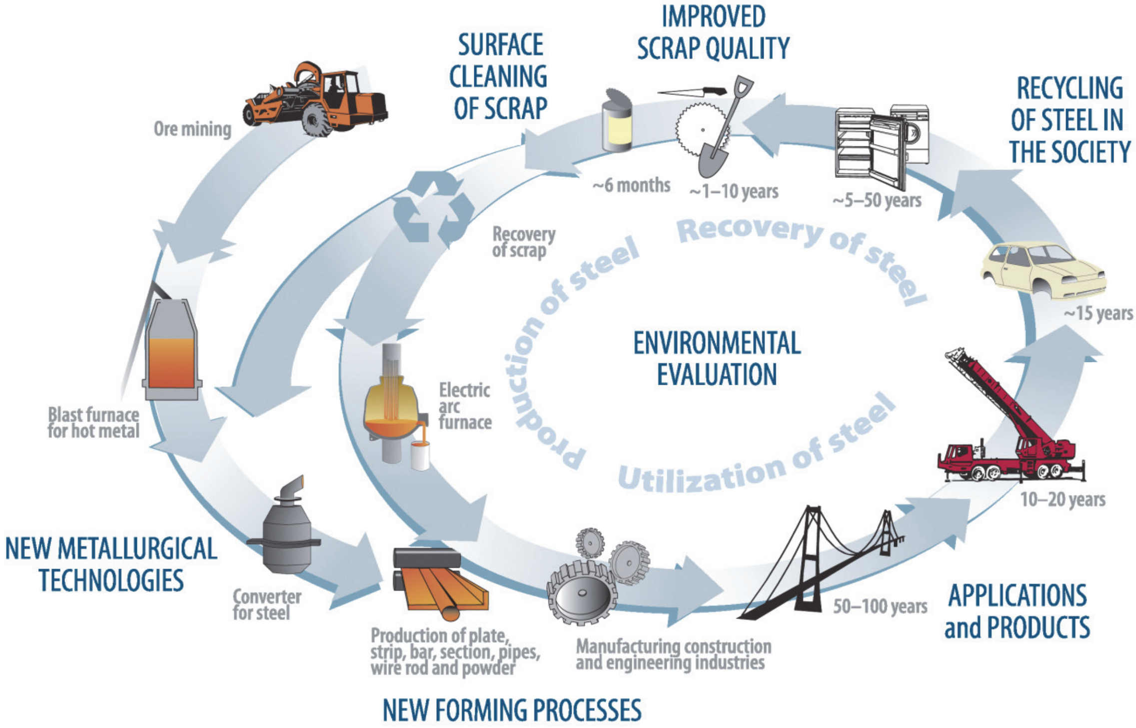


Figure 1. *The research programme theSteel Eco-Cycle.*

This report is focused on quantitative calculations of energy savings, carbon dioxide abatement and efficient use of steel products and by-products from steel making. The objective is to identify and quantify the strength of the programme. The life cycle assessment (LCA) technology used is standardised by ISO since 1997 [1] and since the early nineties there has been a consensus, a code of practice, how to carry out a LCA [2].

The projects in the Steel Eco-Cycle research programme cover the whole steel eco-cycle. The names given in table 1 are used throughout this evaluation report. The two assessment and analysis projects, 88051 and 88052, are not technical projects.

Table 1. *Projects of the "Steel Eco-Cycle" programme.*

No.	**Title**	**Short name**
88011	Mapping and development of the shredder product stream.	Shredding
88012	Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS)	Laser analysis of scrap
88013	Recycling of steel in the society	Recycling of steel
88020	Surface cleaning of steel scrap	Surface cleaning of scrap
88031	Recovery of vanadium and full use of the slag components in BOF slag	Vanadium recovery
88032	Retention, recovery and recycling of valuable metals	New melting processes EAF
88034	Retention, recovery and recycling of valuable metals from slag by salt extraction and electrolysis	Metal recovery from slag by salt extraction
88035 [1]	Stabilisation and reuse of AOD slag as a substitute for gravel in constructions.	Properties of slag
88041	Improving high strength steels with energy efficient process routes	Optimisation of hot rolling
88042	Optimising retained alloy elements in new steel sheet products	Tolerance of recycled elements
88044	The environmental value of high-strength steel structures	High-strength steel structures
88051	Evaluation of environmental impacts	Environmental impact
88052	Conjoint analysis as a decision tool for evaluation of environmental performance	Conjoint

[1] During phase 2 (2009 – 2012) this project replaced the phase-1 project 88033 Stabilisation and reuse of AOD, EAF and ladle slag.

2 OBJECTIVE OF THE ASSESSMENT OF THE STEEL ECO-CYCLE PROGRAMME

The objective of the work described in this report is to make a quantitative assessment of each individual project by comparing it to a presently established technology delivering the same function. The individual assessments are then aggregated to an assessment of the entire Steel Eco-Cycle programme, presuming that the results are fully explored without any practical limits.

3 METHODS

3.1 Methodological choices for the environmental evaluation

For the Steel Eco-Cycle programme the general LCA procedure (described in the Appendix) is more precisely specified and defined by several methodological choices.

3.1.1 Data selection

The present steel-making technology is basically described by two LCA models, one for ore-based steel manufacture and one for scrap-based steel manufacture. The core process models are built from specific data collected from Swedish steel plants (SSAB for ore-based and Outokumpu Avesta for scrap-based steel production, the latter plant being representative for scrap-based steel manufacture in Sweden). For the new technologies specific data is collected from inventories of the processes being developed.

Peripheral processes, i.e. processes which supply commodities like alloying metals, slag formers, transports, and electric power and other energy wares, are described by data from databases and from the literature (generic data). The following databases have been used:

- Steel data from WSA *(World Steel Association, formerly IISI International Iron and Steel Institute, Brussels).*

- The professional database from PE Europe *(PE International GmbH, Life Cycle Engineering, Stuttgart).*
- Ecoinvent 2.0 *(The Swiss Centre for Life Cycle Inventories).*
- Data from IMOA *(International Molybdenum Association, Brussels).*

The peripheral processes are assumed to be unaffected by the development of new processes in the Steel Eco-Cycle programme.

3.1.2 System boundaries

For the specific processes, the upstream boundaries are the origins of the starting materials in nature. For the use of nuclear power this means that the starting material uranium is reported as a non-renewable energy resource with its potential energy content, which is about 3 times the electricity delivered. The same principle applies for fossil fuels but with factors dependent on the efficiency of conversion to electricity for each specific fuel.

The downstream boundaries are the final disposal of the products and the waste materials. No environmental burden is allocated to steel scrap at the site of its origin. The only environmental burden allocated to steel scrap is that caused by the necessary handling and transport. In those cases where valuable materials are generated by the new technologies, the systems describing the present technologies are expanded to include the supply of these materials from virgin resources.

3.1.3 Categories of environmental impact

For both phases of the Steel Eco-Cycle programme impact assessment is limited to the following categories:

- Use of non-renewable energy resources.
- Use of renewable energy resources
- Emission of carbon dioxide.
- Other relevant impacts, such as avoided landfilling or saved natural resources, in cases where the above-mentioned impact categories do not address the relevant issues.

3.1.4 Geographical boundaries

All core processes (existing and new ones) are assumed to be located in Sweden. This is assumed to be the case also for processes involved in scrap recycling, regardless whether the scrap is actually used in Sweden or exported. Electricity is assumed to be supplied by the Swedish grid (see discussion below). Concerning the peripheral processes a reasonable assumption is made as to their geographical location, and they are assumed to be supplied with average electricity from the region in question. In several cases only aggregated database data including the supply of energy is available.

3.1.5 Allocations

For processes turning out more than one product the total environmental impact is calculated. No allocation of environmental burdens on individual products is performed.

3.1.6 LCA calculation software

All LCA modelling and calculation is carried out with the LCA software GaBi 4.2 [3].

3.1.7 Electricity supply systems

When benchmarking two technologies in Sweden against each other, it seems most realistic to assume that both of them are supplied with average electricity. Once the new technology has been established, it is not obvious why precisely that technology should use marginal electricity for ever, while the reference technology would have continued on average electricity for ever. However, in cases where the new technology uses significantly more electricity than the existing one, a sensitivity analysis with marginal electricity is clearly warranted. See section 6.1.2 for a discussion about sensitivity to electricity supply assumptions.

Marginal electricity is assumed to be electricity supplied by a natural-gas fired power plant, since this reflects the current technological situation.

Data used for Swedish average electricity is presented in Table 2 below.

Table 2. *Composition of Swedish average electricity 2011.*

Supply mix [1]	**%**
Nuclear power	37,16
Hydropower	43,08
Wind power	3,96
Hard coal and peat	0,62
Natural gas	0,60
Oil	0,28
Biofuels	4,5
Waste	0,69
Gas turbines & diesel power	0,09
Unspecified sources	0,01
Import from Denmark	1,80
Import from Finland	2,56
Import from Norway	4,53
Import from Poland	0,18
Import from Germany	0,39
Transmission losses	5,72

[1] Annual average values according to statistics from Svenska Kraftnät 2011, supplemented with IEA statistics from 2009. The supply mix is the production mix plus the gross import.

The data used for each specific energy source has been collected from the database Ecoinvent [8] and from IEA statistics for the import countries. The resulting CO_2 emission used in the evaluation is 45 g/kWh electricity delivered to the user.

3.2 Assessment procedure for the individual projects

The assessment is carried out in the following steps:

1. Collection of general information about the objectives and the technical solutions proposed by the Project. This information is collected from reports and discussion with the research team.
2. Construction of a conceptual model comprising the technical system proposed by the Project and also the existing process, which is to be replaced or improved by the proposed new technology.
3. Construction of an inventory questionnaire based on the conceptual model. The purpose of the questionnaire is to collect quantitative data. The questionnaire is communicated to the research team.
4. The research team corrects and modifies the conceptual model as necessary, and fills in the required data.
5. The completed questionnaire is returned. It is then checked for plausibility, consistency and completeness.
6. The conceptual model is translated to a LCA calculation model in the software GaBi 4.2. The collected data is transferred to the model.
7. Numerical values of the impact categories listed in the preceding section are calculated for the new technology and for the reference technology per functional unit.
8. The final assessment result, the saving, is calculated for each impact category as the difference between its value for the reference technology and its value for the new technology. A positive value thus means a decreased impact, a “saving”, a negative value instead an increased impact.

The functional (or reference) unit is chosen as 1 tonne of steel of the relevant type wherever practically possible. In two cases 1 tonne of slag, and in one case the vehicle fleet in Sweden, are more appropriate functional units.

As an example Figure 2 shows the conceptual model and questionnaire constructed for the Project 88013 Recycling of Steel.

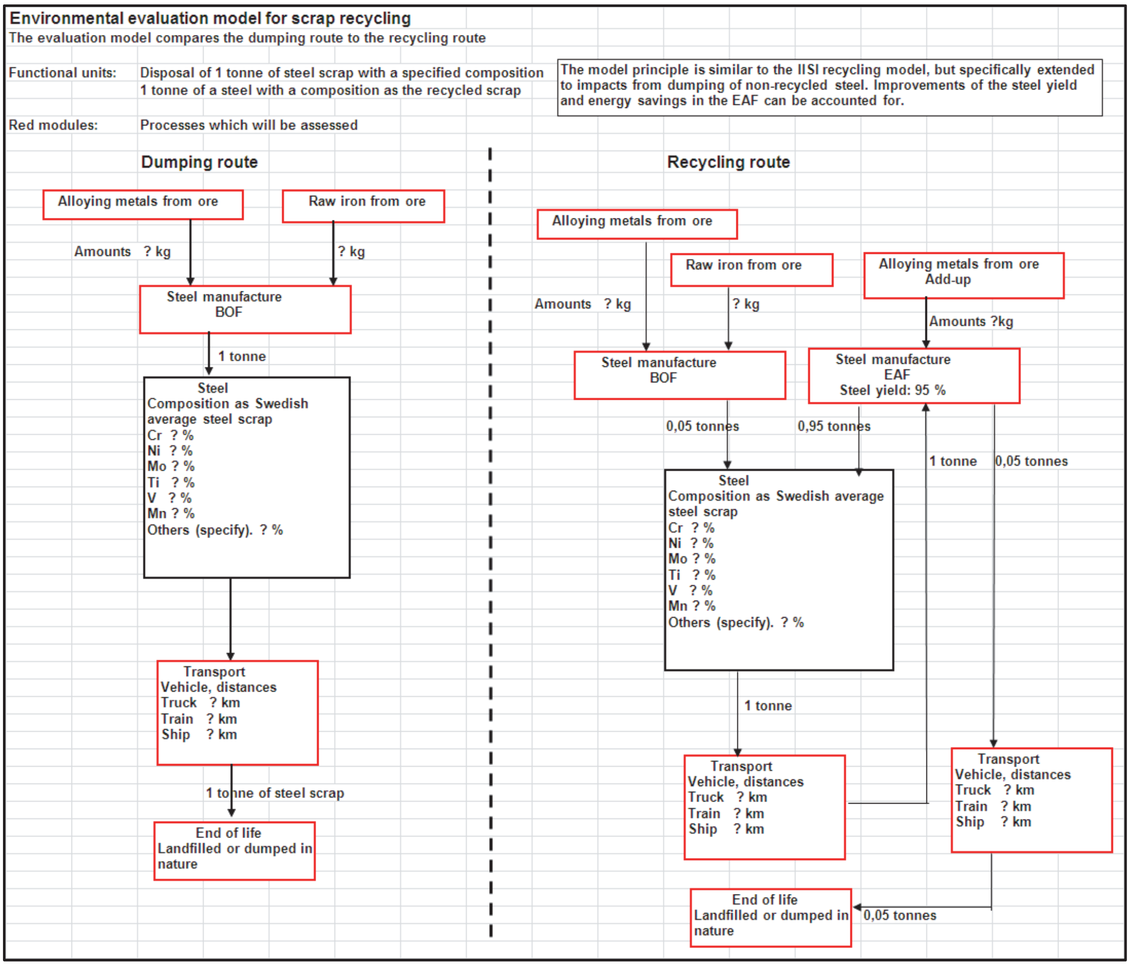


Figure 2. *Conceptual model and questionnaire for the LCA assessment of the Project Recycling of Steel. The dumping route is used to represent losses of various types and does not make any assumptions about their origin. The 0,05 tonnes of virgin steel in the recycling route make up for losses in steel recycling as noted in Table 3 below.*

One of the aims of project 88013 Recycling of Steel is to develop tools to optimise the recycling of steel. The goal of the environmental assessment is thus to calculate the potential environmental benefit of making more steel scrap available for recycling. The present situation is represented by a linear once-through system, the dumping route, where ore-based steel is used once and then discarded and dumped on a landfill or in nature, thus being withdrawn from recycling in the worst possible way.

The results of the new and improved organisation of steel recycling means that the originally discarded steel is instead recycled to produce new steel. This situation is represented by a model of scrap-based steel production, the recycling route.

Both systems have in theory the same two functions. They produce one tonne of steel and they dispose of one tonne of steel scrap. Since the impact assessment boundaries in our case are limited to resource use and carbon dioxide emissions, the production of one tonne of steel is in the actual practice the only function considered. The environmental impacts of dumping steel scrap are not considered.

The process steps following the BOF and the EAF furnaces respectively (rolling, coating and finishing) are assumed to be the same in both systems, and are consequently not considered in the assessment. The same applies to the use phase.

Figure 2 shows a copy of the original Excel sheet used for the assessment. The data acquisition questions are entered directly into the flowchart at the appropriate points. Figure 3 shows the flow sheet of the recycling route for stainless steel as it appears in the GaBi model.

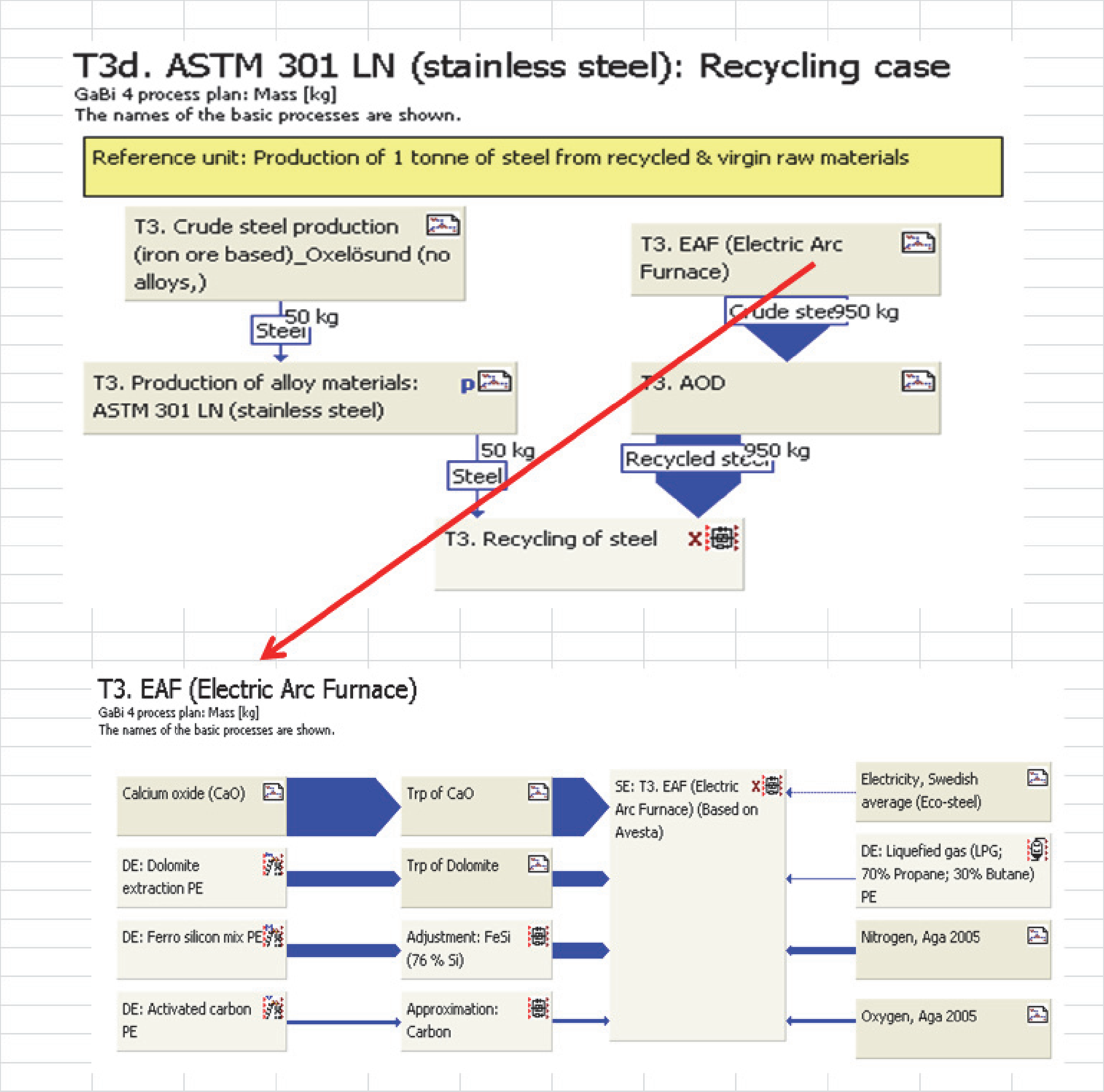


Figure 3. *GaBi flowchart of scrap-based manufacture of stainless steel. The four uppermost modules are themselves aggregated flowcharts. The lower part of the figure shows the flowchart behind the module T3. EAF (Electric Arc Furnace). Several modules of the lower chart are in their turn aggregated flowcharts of inventories. The module SE:T3.EAF (Electric Arc Furnace) (based on Avesta) is an example of a core process. The other modules of the lower chart describe peripheral processes.*

3.3 Method to assess the total environmental potential of the programme

For the purpose the programme Steel Eco-Cycle a simple scale-up calculation is used to assess the potential of the entire programme. For each project the environmental savings per functional unit are multiplied by the annual output or the annual use (as appropriate) of that functional unit in Sweden during the year 2005. Statistical data from Jernkontoret (the Swedish Steel Producers' Association) and data obtained directly from the participating organisations and companies is used.

The projects are then checked for overlapping results to avoid any double-count. Finally the annual savings for each impact category are added to give an assessment of the projected total annual result of the programme. This assessment method obviously presumes that the new technologies can actually be introduced at the relevant potential all over the Swedish steel industry. No profitability or feasibility analysis is done at this stage, since the aim is to show the technical potential.

A more accurate synthesis of the assessment results of the projects, using a LCA model of the Swedish steel cycle, could not be carried out within the framework of the programme. A general methodology for such an assessment is described in Appendix 1.

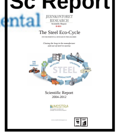
4 SYSTEM DESCRIPTIONS

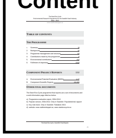
4.1 Technology under evaluation and reference technology

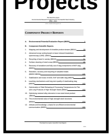
The system models used to assess the technical projects are briefly described in Table 3. Detailed descriptions of the systems are reported elsewhere [4]. For each project two systems are assessed and compared. The column ”New technology” describes the processes included in the assessment of the technical system being developed by the research team of the project. The column ”Reference technology” describes the processes included in the assessment of a reference technology, which can be used to produce the same products and/or services as the proposed new technology. The reported result of the environmental assessment of each project is the difference between the reference technology and the new technology, calculated for each impact category listed in the methodology section.

Table 3. *Survey of the assessment models of the projects (continued on the following page).*

Project	**Compared systems**	
	Reference technology	**New technology**
88011 Mapping and development of the shredder product stream (Shredding) Increased yield of steel from shredded scrap.	A quantity of low-alloyed steel corresponding to the quantity produced from the additionally recovered amount of scrap is produced from iron ore (low-alloyed steel).	The yield of steel from shredding is increased from 70% to 80% [4]. The additionally recovered steel is recycled in a closed-loop, replacing steel from iron ore. The steel is remelted and steel of the same grade (low-alloyed) and for the same applications is produced in an EAF process. The yield is assumed to be 95 % and the remaining 5 % is assumed to be produced from iron ore (virgin raw materials).
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS) (Laser analysis of scrap)	Production of the saved quantities of metals from virgin resources.	The following quantities of metals can be saved if LIBS is introduced by improved use of scrap: Stainless steel[3] • 86,6 kg Cr/tonne of steel • 6,2 kg Ni/tonne of steel Ore-based steel • 60 000 tonnes/a of hot metal (raw iron) • 493 tonnes/a of FeCr • 23 tonnes/a of charge chrome • 190 tonnes/a of Ni • 400 tonnes/a of FeMo
88013 Recycling of steel in the society (Recycling of steel)	Linear material flow. The steel is produced from iron ore (virgin raw materials) and is used once. The scrap is discarded (landfilled or just left in nature)[1]	Recycling in a closed-loop (100 % of the steel is assumed to be collected for recycling). The steel is remelted and steel of the same grade and for the same applications is produced in an EAF process. The yield is assumed to be 95 % and the remaining 5 % is assumed to be produced from iron ore (virgin raw materials).
88020 Surface Cleaning of Steel Scrap Ore-based steel	Production of the saved quantity of hot metal from ore. Disposal of ASR by landfilling (75 %) and incineration (25 %)[2]	Cleaning and preheating of scrap in a furnace fired with ASR (auto shredder residue, combustible waste from vehicle scrapping). Hot metal is saved.
88020 Surface Cleaning of Steel Scrap Scrap-based steel	Generation of the saved quantity of electricity. Disposal of ASR by landfilling (75 %) and incineration (25 %). [2]	Cleaning and preheating of scrap in a furnace fired with ASR (auto shredder residue, combustible waste from vehicle scrapping). Electricity is saved.[4]
88031 Recovery of vanadium and full use of the slag components in BOF slag	No recovery of V This system contains the production of the components which are saved in the new	Recovery of V from BOF (LUVA) slag The main processes for recovery of







Project	**Compared systems**	
	Reference technology	**New technology**
(Vanadium recovery) VILD process	technology. • Production of FeV from virgin raw materials. • Production of iron (coke plant + blast furnace). • Production of calcium oxide (CaO).	vanadium are: • Reduction of LUVA slag. • Selective oxidation of V. • FeV production.
88032 Retention, recovery and recycling of valuable metals (New melting processes EAF) Modified addition of Mo	Production of steel - MoO_3 as alloying raw material The molybdenum-containing scrap based steel is produced by using molybdenum trioxide (MoO_3) as alloying raw material. In this case, molybdenum-containing dust is produced. This dust is sent to a special treatment to avoid leaching of Mo to the environment.	Production of steel by synthesising Fe_2MoO_4 from oxide scale and MoO_3. The molybdenum-containing scrap-based steel is produced by using ferromolybdate as alloying material. The ferromolybdate is synthesised from oxide scale from iron, molybdenum trioxide and coal in situ in the EAF. In this case no molybdenum-containing dust is produced.
88034 Retention, recovery and recycling of valuable metals from slag by salt extraction and electrolysis	No recovery of metals No recovery of chromium, manganese and iron from EAF slag. The EAF slag is landfilled and the metals are produced from virgin raw materials.	Recovery of metals. Recovery of Cr, Mn and Fe from EAF slag by molten-salt extraction followed by electrolysis and recovery of the salt mixture.
88035 Properties of slags	No use of slag AOD slag is landfilled instead of being used as a construction material. Gravel from rock is used for construction.	Use of slag as a construction material. The AOD process is modified to yield a more stable slag, which can replace gravel as a construction material.
88041 Improving high strength steels with energy efficient process routes (Optimisation of hot rolling)	Heating mode S. This is the standard heating procedure at SSAB for high strength steels. S stands for Special Heating Curve, which means a high charging temperature 1255 °C and the criterion that the temperature should be above 1220 °C for at least 35 minutes.	Heating mode M. In heating mode M, a moderate charging temperature is used, approx. 1220 °C. No demands exist for time above a certain temperature. M-mode means that the slab furnace can be operated with 7 % less use of the fossil fuels heavy and light fuel oil and liquefied petroleum gas (LPG) compared to S mode. The result of the rolling project so far is that M-mode rolling can be applied without impairment of the quality of the steel.
88042 Optimising retained alloy elements in new steel sheet products (Tolerance of recycled elements)	Production of Steel (0,1% V) from FeV The vanadium containing steel is produced by using ferrovanadium extracted from slag by the VILD process.	Production of Steel (0,1% V) by using V from BOF slag The vanadium containing steel is produced by making use of the metal product from the first reduction step of the VILD process.
88044 The environmental value of advanced high-strength steel structures Advanced High-Strength Steel (AHSS).	Contemporary use of AHSS Motor vehicles are produced with the same material mix as today even ten years from now	AHSS is used to reduce weight of vehicle structures. Motor vehicles are produced with increasing amount of AHSS to reduce weight and the situation ten years from now is considered.

[1] This does not mean that 0% recycling today is used as reference. This reference is used to represent losses of various types. Current recycling rates are accounted for; see corresponding entry of Table 4.

[2] This reflects the situation at the time of information collection, although using organic material for landfilling is against regulations since 2005. However, a scenario where 100% of the ASR is used for energy production would not give significantly different results with regard to carbon dioxide emissions in the evaluation of the project 88020, since the energy produced from the ASR would have to be replaced by other fuels.

[3] Based on Outokumpu Avesta average data 2005 and an estimate that it will be possible to use LIBS to reach a situation where only 5% of the alloying elements in manufactured 18/8 steel need to be virgin while 95% will be supplied by alloyed scrap.

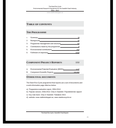
[4] Possible influences on Zn recovery are not modelled at this stage.

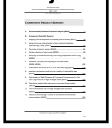
4.2 Reference material, reference unit and scaling factors used for each project

Each project is initially evaluated based on its functional (reference) unit e.g. 1 tonne of steel of a relevant grade or 1 tonne of utilised slag. For the assessment of the entire Steel Eco-Cycle programme the project results are then recalculated to per year values by using the appropriate annual tonnage of the reference unit as a scaling factor. Due to the different nature of the different projects and the way the potential advantages of the technologies is presented it is not possible to use reference units in a fully uniform manner. The reference materials and scaling factors for each project, presented in Table 4, are used to scale up the evaluation results to the national scale.

Table 4. *Reference material, reference unit and scaling factors used for each project (continued on the following page).*

Project	**Reference material & reference unit**	**Scaling factor [tonne/year]**	**Source of the scaling factor**
88011 Mapping and development of the shredder product stream (Shredding) Increased yield of steel from shredded scrap.	1 tonne of steel produced from steel scrap	34500	3 % of the total annual amount of shredded scrap in Sweden in 2005, 1100000–1200000 tonnes/a. (30 % of the theoretical potential of the experimental result).
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS) (Laser analysis of scrap): Stainless steel	1 tonne of stainless steel	300000	Half of the annual production of stainless steel in Sweden. [5]
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS) (Laser analysis of scrap): Low-alloyed ore-based steel	Annual quantities of saved metals.	N. R.	Ore-based steel • 60 000 tonnes/a of hot metal (raw iron) • 493 tonnes/a of FeCr • 23 tonnes/a of charge Cr • 190 tonnes/a of Ni • 400 tonnes/a of FeMo
88013 Recycling of steel in the society (Recycling of steel): Mild steel	1 tonne of steel produced from steel scrap	40000	Potential estimated as 3% increase in recovery rate
88013 Recycling of steel in the society (Recycling of steel): Stainless steel	1 tonne of steel produced from steel scrap	9400	Potential estimated as 3% increase in recovery rate
88020 Surface Cleaning of Steel Scrap: Ore-based steel	1 tonne of ore based steel	3924000	Annual ore based production of raw steel. [5]
88020 Surface Cleaning of Steel Scrap: Scrap-based steel	1 tonne of scrap based steel	1932000	Annual scrap based production of steel. [5]
88031 Recovery of vanadium and full use of the slag components in BOF slag (Vanadium recovery)	1 tonne of ore based steel, which generates 50 kg of LUVA slag, of which 25 kg is treated in the FeV45 (VILD) process	3824000	Annual ore based production of raw steel, less the quantity of steel used by project 88042. [5]
88032 Retention, recovery and recycling of valuable metals (New melting processes EAF): Modified addition of Mo	1 tonne of steel produced at Uddeholm Tooling (Hagfors)	30835	Annual production at Uddeholm Tooling [1].
88034 Retention, recovery and recycling of valuable metals from slag by salt extraction and electrolysis	1 tonne of Cr-containing EAF slag	Not determined	Not determined
88035 Properties of slags	1 tonne of AOD slag, which if modified is equivalent to 1 tonne of gravel	200000	Annual quantity of available suitable slag [7]
88041 Improving high strength steels with energy efficient	1 tonne of hot rolled steel (of relevant type)	400000	Annual estimated production.





Project	**Reference material & reference unit**	**Scaling factor [tonne/year]**	**Source of the scaling factor**
process routes (Optimisation of hot rolling)			
88042 Optimising retained alloy elements in new steel sheet products (Tolerance of recycled elements)	1 tonne of relevant steel alloy, which corresponds to about 40 kg of BOF-slag as vanadium source	100000	Annual estimated production where the technology may be used, dependent on P content.
88044 The environmental value of advanced high strength steel structures. Production of high strength steel for vehicles.	1 tonne of saved steel of a specified type. The increased yield strength is attained by minor adjustments of the chemical composition of the steel.	333333	Annual amount of saved steel from using high-strength steel in road vehicles [6].

N.R. = Not relevant.

[1] Only production at Uddeholm is relevant since other procedures for Mo alloying are used by other companies.

5 RESULTS OF THE ASSESSMENTS OF THE PROJECTS AND THE PROGRAMME

In this chapter, the results from the environmental assessment of the projects and the programme are presented. For each project the savings (which may be positive or negative for a specific impact) are given per reference unit as well as per annual tonnage of the reference unit. The impact categories reported are energy resources, emission of carbon dioxide and, if relevant, other significant impacts.

In section 5.1 below, the total result, aggregated for the programme as a whole, is presented. The results from the environmental assessment of each project are presented in section 5.2. Here the presentation has been divided into the following sub-sections:

- Total results per **reference unit** in each project: **CO_2 and energy resources**.
- Total results **per year** in each project: **CO_2 and energy resources**.
- Total results **per year** in each project: **Additional values.**

Some of the projects have potentially further benefits than those which can be quantified at present. Some such benefits are listed in the discussion in section 6.2.

5.1 Summary of the results for the Steel Eco-Cycle programme

The total potential process savings for the Steel Eco-Cycle programme are presented in Table 5. CO_2 emissions and energy consumption are shown together with examples of other environmental benefits, e.g. savings of raw materials such as alloying metals and avoided landfilling of metal containing slag and dust.

Table 5. *The total potential process savings and other savings (additional values) for the Steel Eco-Cycle programme, including upstream and downstream processes. The potential of high-strength steel (88044) is not included.*

Process savings		**Goal**	**Total (including upstream processes)**[1]
CO_2	ktonne/year	1000	1300
Energy	GWh/year	600	5300
Other savings (additional values)		**Goal**	**Total (including upstream processes)**
FeV (as pure V)	tonne/year		5000
Cr	tonne/year		28000
Ni	tonne/year		2600
Mo	tonne/year		310
Mn	tonne/year		0
Iron pellets	tonne/year		510000
CaO	tonne/year		81000
Crushed aggregates from rock	tonne/year		200000
Landfilling of slag & dust	tonne/year		300000
Waste management of ASR	tonne/year		76000

[1] Total emissions of CO_2 and inputs of energy resources for the whole steel industry system including upstream processes (production of raw materials and energy). The energy resources are accounted for as inputs of non-renewable and renewable natural resources (e.g. crude oil, coal, uranium etc.). Note that the efficiency of electricity generation from the non-renewable energy resource uranium is only about 33 %.

Due to the different origin of the savings for project 88044 (The environmental value of advanced high-strength steel structures) these are shown separately. An estimate shows that every million tonnes of advanced high-strength steel (the amount that SSAB produces every year) which replaces conventional steel in a road vehicle fleet results in the savings shown in Table 6. The production benefits are given per year as for the other projects, but the benefits from the use phase are calculated for 10 years, which approximates the service life of a typical vehicle.

Table 6. *Potential savings of using one million tonnes of advanced high-strength steel in a road vehicle fleet.*

Product savings (High strength steel in a road vehicle fleet)		**Steel production [unit per year]**	**Total (including use phase, 10 years) [unit per 10 years]**
CO_2	ktonne	600	8000
Energy	GWh	3300	31000

The above results emphasise the importance of including the use phase in the life cycle assessment of structures in order to recognise the environmental potential of advanced high strength steel.

5.2 Evaluation results for individual projects

5.2.1 *Evaluation results per reference unit in each project*

The results for each project per reference unit are presented in Table 7 for three impact categories: emissions of carbon dioxide, use of non-renewable energy resources and use of renewable energy resources. Negative values denote increased impact instead of savings. Additional values (other savings) in terms of saved raw materials and avoided landfilling of metal containing slag and dust etc. are not presented per reference unit (only per year, see *Table 9*).

Table 7. *Evaluation results per reference unit in each project: CO_2 and energy resources (continued on the following page).*

Project	**Reference unit**	**Savings**			**Comments**
		CO_2	**Non-renewable energy resources**	**Renewable energy resources**	
	Unit	kg/reference unit	MJ/reference unit		
88011 Mapping and development of the shredder product stream (Shredding) Increased yield of steel from shredded scrap.	1 tonne of steel from steel scrap	1256	13176	-2221	The same reference unit as 88013
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS) (Laser analysis of scrap): Ore-based (low alloyed) steel	N.R.	N.A.	N.A.	N.A.	Based on data from SSAB Luleå & Oxelösund, i.e. savings per tonne of steel were not quantified. Total savings in Table 8.
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS) (Laser analysis of scrap): Scrap-based (stainless) steel	1 tonne of steel produced from steel scrap	1307	12453	934	It is assumed that LIBS will make it possible to reduce the present additions of Cr and Ni to make 18/8 steel to a level that replaces losses of 5 %.
88013 Recycling of steel in the society (Recycling of steel): Mild steel.	1 tonne of steel produced from steel scrap	1256	13176	-2221	
88013 Recycling of steel in the society (Recycling of steel): Mild steel. Electricity from natural gas	1 tonne of steel produced from steel scrap	1136	13392	-1472	
88013 Recycling of steel in the society (Recycling of steel): Stainless steel	1 tonne of steel produced from steel scrap	4279	41688	-986	
88013 Recycling of steel in the society (Recycling of steel): Stainless steel Electricity from natural gas	1 tonne of steel produced from steel scrap	4123	42200	-10	
88020 Surface Cleaning of Steel Scrap: Ore-based steel	1 tonne of ore based steel	70	1660	0,342	In the reference case (i.e. when the ASR is not used for the pre-heating of scrap), 75 % of the ASR is assumed to be landfilled and 25 % incinerated.

Project	**Reference unit**	**Savings**			**Comments**
		CO$_2$	**Non-renewable energy resources**	**Renewable energy resources**	
	Unit	kg/reference unit	MJ/reference unit		
88020 Surface Cleaning of Steel Scrap: Scrap-based steel	1 tonne of scrap based steel	-35	684	349	In the reference case (i.e. when the ASR is not used for the pre-heating of scrap), 75 % of the ASR is assumed to be landfilled and 25 % incinerated.
88031 Recovery of vanadium and full use of the slag components in BOF slag (Vanadium recovery)	1 tonne of ore based steel.	130	1188	-155	
88032 Retention, recovery and recycling of valuable metals (New melting processes EAF) Modified addition of Mo. Temp. below 1000 °C.	1 tonne of steel	7	-9	-17	Based on data for CO$_2$ and energy for production of MoO$_3$ (from IMOA - updated in march 2008).
88034 Retention, recovery and recycling of valuable metals from slag by salt extraction and electrolysis	1 tonne of Cr-containing EAF slag	No data	No data	No data	Relevant process data is not yet available
88035 Properties of slag. Stabilisation and reuse of AOD slag as substitute for gravel in constructions.	1 tonne of AOD slag either landfilled or used as construction material	Not calculated	Not calculated	Not calculated	Annual savings are calculated directly in table 8.
88041 Improving high strength steels with energy efficient process routes (Optimisation of hot rolling)	1 tonne of hot rolled steel (of relevant type)	9	122	0,14	The impact of increased yield strength could not be considered.
88042 Optimising retained alloy elements in new steel sheet products (Tolerance of recycled elements)	1 tonne of relevant steel alloy.	6,4	101	62	

Remarks: N.A. = Not available. N.R. = Not relevant.

5.2.2 Evaluation results per year in each project

Table 8. *Evaluation results per year in each project: CO_2 and energy resources.*

Project			**Savings**		
	Scaling factor	**Reference material**	**CO_2**	**Non-renewable energy resources**	**Renewable energy resources**
	tonne/year		ktonne/year	GWh/year	
88011 Mapping and development of the shredder product stream (Shredding) Increased yield of steel from shredded scrap.	34500	Steel	43	126	-21
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS) (Laser analysis of scrap): Ore based (low alloyed) steel	N.R. [1]	N.R.	90	331	4,5
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS) (Laser analysis of scrap): Scrap based (stainless) steel	300000	Steel	392	1038	78
88013 Recycling of steel in the society (Recycling of steel): Mild steel.	40000	Steel	50	146	-25
88013 Recycling of steel in the society (Recycling of steel): Stainless steel	9400	Steel	40	109	-2,6
88020 Surface Cleaning of Steel Scrap: Ore-based steel	3924000	Steel	275	1809	0,373
88020 Surface Cleaning of Steel Scrap: Scrap-based steel	1932000	Steel	-68	367	187
88031 Recovery of vanadium and full use of the slag components in BOF slag (Vanadium recovery)	3824000	Steel	497	1262	-165
88032 Retention, recovery and recycling of valuable metals (New melting processes EAF) Modified addition of Mo	30835	Steel	0.21	-0,080	-0,14
88034 Retention, recovery and recycling of valuable metals from slag by salt extraction and electrolysis	No data	EAF slag	No data	No data	No data
88035 Properties of slag. AOD slag as construction material	200000	AOD slag	0,77	4,1	0,61
88041 Improving high strength steels with energy efficient process routes (Optimisation of hot rolling)	400000	Steel	3,6	14	0,02
88042 Optimising retained alloy elements in new steel sheet products (Tolerance of recycled elements)	100000	Steel	0,64	2,8	1,7
Total max potential for the technical projects (excluding 88044)			1325	5209	59

N.A. = Not available. N.R. = Not relevant.

[1] *A scaling factor is not relevant. Savings per tonne of steel were not quantified, since data on savings were given per year (for SSAB Luleå & Oxelösund).*

Table 9. Evaluation results per year in each project for additional values.

Project			**Additional values = other savings (raw material inputs, avoided landfilling of slag etc.)**										
	Scaling factor	**Reference material**	**FeV (as pure V)**	**Cr**	**Ni**	**Mo**	**Mn**	**Iron pellets**	**CaO**	**Nitrogen**	**Crushed aggregate from rock**	**Landfilling of slag/ dust**	**Landfilling of ASR**
	tonne/year		**tonne/year**										
88011 Mapping and development of the shredder product stream (Shredding) Increased yield of steel from shredded scrap.	34500	Steel						44376	-276	-271			
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS) (Laser analysis of scrap): Ore-based (low alloyed) steel	N.R.	N.R.		334	188	280		80400					
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS) (Laser analysis of scrap): Scrap-based (stainless) steel	300000	Steel		25980	1860								
88013 Recycling of steel in the society (Recycling of steel): Domex 240 YP (low alloyed steel)	40000	Steel						51440	-320	-314			
88013 Recycling of steel in the society (Recycling of steel): ASTM 301 LN (stainless steel)	9400	Steel		1579	583			9165	-526	-329			
88020 Surface Cleaning of Steel Scrap: Ore-based steel	3924000	Steel						304895					26958
88020 Surface Cleaning of Steel Scrap: Scrap-based steel	1932000	Steel											49266
88031 Recovery of vanadium and full use of the slag components in BOF slag (Vanadium recovery)	3824000	Steel	4971					24474	81834			95600	
88032 Retention, recovery and recycling of valuable metals Modified addition of Mo	30835	Steel				34						648	
88034 Retention, recovery and recycling of valuable metals from slag by salt extraction and electrolysis	No data	EAF slag		No data		No d.	No d.	No data				No data	
88035 Properties of slag. AOD slag as construction material	200000	AOD slag									200000	200000	
88041 Improving high strength steels with energy efficient process routes (Optimisation of hot rolling)	400000	Steel										200 [1]	
88042 Optimising retained alloy elements in new steel sheet products (Tolerance of recycled elements)	100000	Steel											
Total max potential for the technical projects (excl. 88044)			4971	27893	2631	314	0	514740	80711	-914	200000	296488	76224

[1] Avoided scales

6 DISCUSSION

6.1 Uncertainty and significance of the results

The results reported in Table 7, Table 8 and *Table 9* are differences between scenarios. In order to assess the uncertainty and significance of the results, it is helpful to consider the absolute values of the environmental impact for the compared technologies. Small, uncertain and potentially insignificant, absolute differences for a project may theoretically be scaled up by a large annual tonnage.

Absolute values of CO_2 emissions as well as non-renewable and renewable energy resources for the technologies have been evaluated (results not shown). The projects contributing most to the total impact of the programme are the scrap-sorting, -recycling and -cleaning projects, the vanadium recovery project and the high-strength steel project. In all these cases high annual tonnages are involved.

For the LIBS project, the scrap-recycling project, the vanadium-recovery project and the application of scrap cleaning to ore-based manufacturing of steel the differences between the reference technology and the new technology are of the order of magnitude of 3 – 10 times. Such differences are considered significant for impact categories like carbon dioxide emissions and use of energy resources.

The evaluation of project 88044 is based on a difference analysis not involving absolute values and is hence considered significant despite the probably relatively smaller difference in absolute values. Likewise, for project 88041 ”Optimisation of hot rolling", the difference between the existing and the new technology is small but accurately known. For all other projects, the difference between the new and reference technology is significant for at least one impact category.

6.1.1 Classification based on project development status

The individual projects in the programme have progressed very differently on the scale from fundamental research to industrial application. It is likely that projects that are far from industrial application have a greater probability for technological changes during the remainder of the development process toward application. Since the environmental assessment is based on the current technology in the project projected towards full scale implementation, this leads inevitably to greater uncertainty in estimated savings for the projects that are at an earlier stage in the development. To assess this uncertainty, we have classified the projects in the following classes:

1. Technology developed and tested under conditions close to application, low uncertainty
2. Experiments in lab scale or other conditions not fully representative for industrial application, medium uncertainty
3. Based only on theory or experiments that are not representative for industrial application, high uncertainty

It should be noted that in this classification no direct account is taken of the applicability of the technology from an economic viewpoint or similar. Such considerations are included in the scaling factor (see Table 4), which is based on expert opinions from project participants and industrial representatives in each project.

The classification of individual projects is shown in Appendix 2. Based on this classification, the aggregated results from the environmental evaluation have been classified accordingly. The result is shown in Table 10. It shows that the majority of the savings estimated in the environmental evaluation has low uncertainty and that the environmental value of the programme is highly significant. Almost all of the savings considered to have a relatively high uncertainty originates in project 88012 (Advanced scrap sorting based on LIBS). These results reflect the high potential of this project and the fact that it is still in a relatively early development stage. Further research is highly relevant and will lead to more accurate estimates of environmental savings for this project.

Table 10. *Classification of the certainty of the calculated aggregated environmental savings.*

		Savings		**Part of total**[1]	
Project class	**Uncertainty**	**CO2**	**Energy**	**CO2**	**Energy**
		ktonne/year	**GWh/year**	**%**	**%**
1 Technology developed and tested under conditions close to application	Low	709	3479	53%	66 %
2 Experiments in lab scale or other conditions not fully representative for industrial application,	Medium	44	110	3%	2%
3 Based only on theory or experiments that are not representative for industrial application	High	572	1679	43%	32%

[01] Compared to results in 8.

6.1.2 *Sensitivity to assumption about electricity production*

As noted above, the evaluation described in this report assumes average electricity supply in Sweden or in the appropriate location for upstream resources. A sensitivity analysis with marginal electricity is interesting to assess the sensitivity of the results to this assumption. Table 11 below shows the results from such a calculation for projects 88013 and 88020 that represent cases with different changes in electricity consumption. Marginal electricity is assumed to be based on natural-gas combustion as noted above.

The results show clearly that the evaluation for electricity intensive projects, such as 88020, is very sensitive to assumptions about electricity. Project 88020 saves a lot of electricity and the savings are much greater if this electricity is assumed to be produced with fossil fuel. The result for 88013 shows that this project is not very sensitive to assumptions about production of electricity.

As noted above, it seems most realistic to assume electricity supplied with average electricity when benchmarking two technologies in Sweden against each other and the results described in this section should only be considered a sensitivity analysis.

Table 11. *Results from evaluation of selected projects with marginal electricity. Marginal electricity is power from natural gas.*

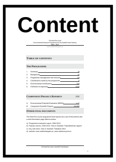
		Savings based on marginal electricity		**Difference compared to average electricity**[1]	
Project	**Reference unit**	**CO2**	**Non-renewable energy resources**	**CO2**	**Non-renewable energy resources**
		kg/ref unit	**MJ/ref unit**	**%**	**%**
88013 Recycling of steel in the society (Recycling of steel): Mild steel.	1 tonne of steel prod from steel scrap	1100	13400	-10%	+2%
88013 Recycling of steel in the society (Recycling of steel): Stainless steel	1 tonne of steel prod from steel scrap	4123	42200	-4%	+1%
88020 Surface Cleaning of Steel Scrap: Scrap-based steel	1 tonne of scrap based steel	2,4	923	+105%	+35%

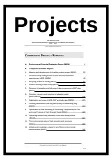
[1] Compared to results in Table 7.

6.2 Energy reporting and conflicting goals

In the reporting of the results fossil energy and nuclear energy are added and reported as non-renewable energy. This has two implications:

1. The value of saved electricity from nuclear power is multiplied by 3 when the savings at the system boundaries (the total savings) are calculated. The same principle but with lower factors apply for fossil fuels as discussed above.
2. There is not necessarily a connection between saved non-renewable energy and decreased carbon dioxide emissions (and vice versa).





The latter point is illustrated by project 88020(scrap based steel) in Table 8. Here a fossil energy carrier (ASR) is used to achieve a saving of energy in an electric arc furnace. If the electric arc furnace is powered by electricity from the Swedish grid, the effect is that a net saving of non-renewable energy is paid for by increased emissions of carbon dioxide. The reason is that nuclear power, which uses non-renewable resources but does not give large carbon dioxide emissions is an important part of the Swedish electricity mix.

An extension of the assessment to include other impact categories would have further highlighted this type of conflicting goals.

6.3 Potential benefits, not yet quantified

In the results we have only included effects that we could quantify with a reasonable certainty. Some of the projects have the potential of bringing further benefits. Some such projects and their potential further benefits are listed in Table 12.

Table 12. *Potential benefits, which have not yet been quantified.*

Project	Not quantified potential benefits
88035 Properties of slag. Stabilisation and reuse of AOD slag as substitute for gravel in constructions.	Use of slag as replacement for burnt lime in cement kilns.
88041 Improving high strength steels with energy efficient process routes (Optimisation of hot rolling)	Increased yield strength which means that less steel is needed for a given application. The project is a part of the development of high-strength steels and is thus connected to project 88044.

7 CONCLUSION

The Steel Eco-Cycle programme, which covers three industrial sectors, namely steel making, steel recovery and the use of steel in products, effectively addresses the issues of environment and energy conservation. The combined potential of the new technologies developed in the Steel Eco-Cycle programme exceeds the quantitative objectives of the programme.

In this evaluation we assume that the objective of the programme applies to the total impacts from a life-cycle perspective and includes upstream savings from reduced raw material consumption. It is also assumed that the relevant potential of each project may actually be realised.

8 REFERENCES

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[6] Jan-Olof Sperle (Sperle Consulting), personal communication 2010.

[7] Bo Björkman, Technical University of Luleå (2012), personal communication.

[8] Ecoinvent 1.2., Database from the Swiss Centre for Life Cycle Inventories, Swiss Federal Laboratories for Materials Testing and Research (EMPA), Dübendorf, Switzerland, www.ecoinvent.ch.

APPENDIX 1: General methodology to be applied in phase 2

Assessment of projects

The method we must apply to correctly assess environmental benefits of new technologies is the holistic and standardised methodology of life cycle assessment, as was noted already in the section on objectives. The word “holistic” means that we include all conceivable and relevant consequences of the processes, that is the supply of all necessary materials and energy carriers (upstream consequences) as well as all relevant consequences for the use of the product, such as change of quality, change of applicability of the product and change of disposal method (downstream consequences).

Obviously our methodology has to be standardised, since our goal is to be able to make claims, that is to be able to assess if a new technology actually achieves environmental benefits compared to the present technology, and if so, to which quantitative extent and in what respects. The life cycle assessment (LCA) technology is standardised by ISO since 1997[1] and since the early nineties there has been a consensus, a code of practice, how to carry out a LCA[2]. According to the standard a LCA has to include the following elements:

- Goal and scope definition
- Inventory
- Impact assessment
- Interpretation

The goal and scope definition defines the object, the purpose and the extent of the study. The purpose must be very explicitly stated. An important decision to make is then to determine the functional (or reference) unit that is the quantitative measure of the function of the products to be assessed. The functional unit is the basis of reference of the inventory and the impact assessment. If two technologies are to be compared in a meaningful way it is obviously very important that the two technologies fulfil the same functions. (For instance, a steel scrap recycling system fulfils two functions, namely production of steel and disposal of steel scrap). The scoping determines what to include in and what to exclude from the studied systems, in other words the boundaries of the technical system to be studied and which environmental impacts to include in the impact assessment.

The inventory compiles all the data necessary to describe the system. The inventory starts with the construction of a conceptual model of the system with the aid of suitable computer software, which can quite simply and conveniently be Excel. When a system overview comprising all relevant processes has been obtained, data is collected for the processes. This is performed either from specific factories and production sites through interviews and questionnaires (specific data), from available databases or from literature sources, such as published LCA reports (generic data). Which sources of data to be used depends on the goal and scope of the assessment, on the availability of data and the practical possibilities to collect data. From the conceptual model a LCA calculation model is constructed, also with the aid of suitable software. Excel can be used for the LCA model as well, but it is preferable to use one of the several software packages designed specifically for LCA. Several such packages are commercially available.

The result of the life-cycle inventory, LCI, is a (usually long) quantitative input-output table with consumption of material and energy resources and generation of products, wastes and emissions. The first step of the impact assessment is the classification. The classification sorts the inventory parameters into the impact categories to which they contribute. The most frequently used impact categories are:

- Resource use (energy and material resources)
- Global warming potential (GWP)
- Ozone depletion potential
- Photochemical ozone creation potential
- Acidification potential

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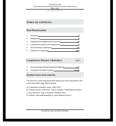
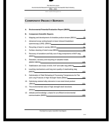
[1] SS-EN ISO 14044, European Committee for Standardization, Brussels, 2006.

[2] SETAC, Guidelines for life-cycle assessment: A Code of Practice, editors F. Consoli et al., Society of Environmental Toxicology and Chemistry, Brussels, Belgium & Pensacola, Florida, USA, 1993





- Eutrophication potential

The next step of the impact assessment, the characterisation, quantifies the contribution of each inventory parameter to the impact category, to which it belongs. For each impact category a maximum potential impact is calculated as a sum of weighted contributions from the inventory parameters. For instance, all greenhouse gases contribute more or less to the impact category global warming potential.

After the characterisation the LCI table has been aggregated to a short table of maximum impact potentials. From this table one can proceed to the interpretation, which is to draw conclusions that address the purpose of the LCA as formulated in the goal and scope definition.

Method to assess the entire Swedish Steel Cycle

The basic idea how to assess the cumulative environmental benefits of the subprojects to Swedish steel production is to start with a suitable material flow analysis (MFA) model of the Swedish steel cycle. Since the subprojects address issues of production as well as issues within the use phase of steel, the model has to take both these aspects into account. The model shall focus on those technologies and procedures that are being studied in the Steel Eco-Cycle project. These technologies must, however, be put into their proper context in the model. Figure A1 presents as a starting point an outline of such a model.

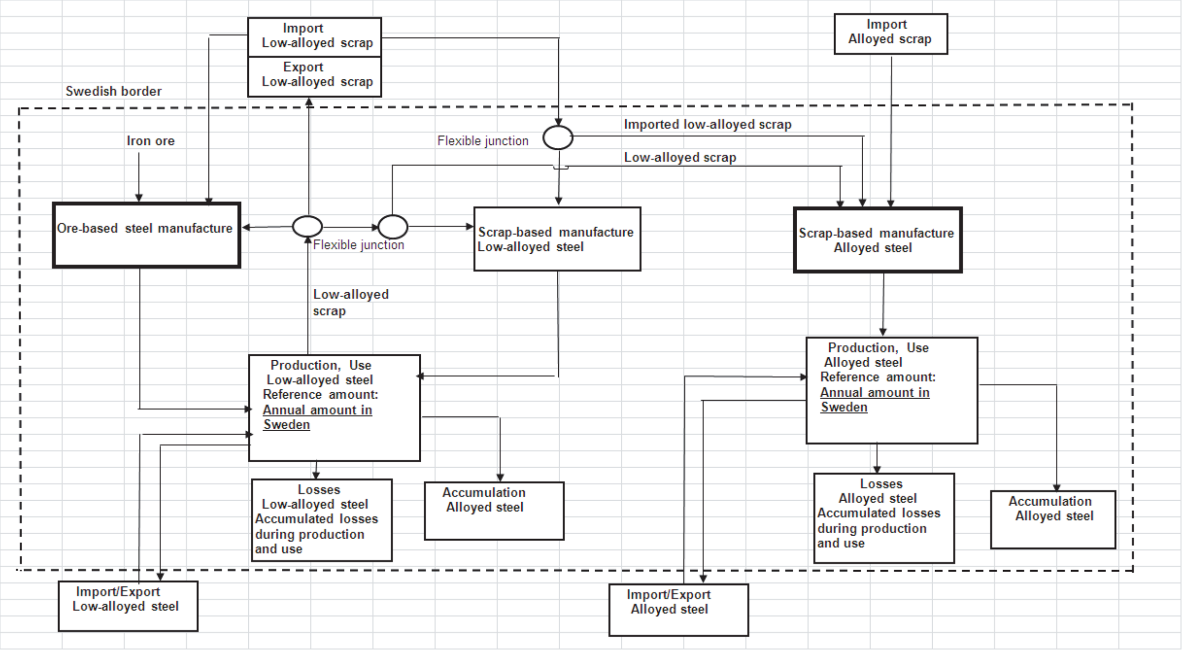


Figure A1. Outline of a MFA model of the Swedish steel cycle comprising manufacture, use, steel and scrap *flows. The small circles are junctions, where a flow may be split.*

The system boundary is the Swedish border (dotted frame). The system is divided into two parts, the low-alloyed and the alloyed cycle. The two cycles have a single, one-way connection, namely a flow of low-alloyed scrap from the low-alloyed to the alloyed cycle. Both cycles have a manufacturing process chain, in figure A1 symbolised by a single bold-framed module for each cycle. The steel flows from manufacture to the use phase, on each side symbolised by the modules Production, Use. These modules summarise the production and use of steel goods. The modules exchange steel with Import/Export of steel goods from and to the technosphere outside the system boundary. The result can be a net influx to or a net outflow of steel from the Swedish steel cycle. There are also losses from the steel cycle in the form of goods which are discarded irregularly or accumulated in the Swedish technosphere (abandoned equipment and long-lived equipment).

Steel from regularly discarded and scrapped steel goods is recirculated as steel scrap. Low-alloyed scrap may be used as addition to the steel furnace (the BOF) in the ore-based steel process, or it may be remelted at a scrap-based steel plant for low-alloyed or alloyed steel. Finally the scrap may be exported. Alloyed scrap is recirculated to remelting. Additional scrap, low-alloyed as well as alloyed, is imported for remelting or as addition to crude steel in ore-based steel manufacture.

The environmental performance of the entire Swedish steel cycle is determined by the efficiency of the manufacturing processes, by the service life and the service weight of the steel goods in the use phase, and by the choices made at the junctions of the scrap flows. The latter choices are determined by technical and financial factors.

The next step in the modelling is to transform the outline of the model into an LCA-model. This can in principle be done by building a model in GaBi around the two basic steel models (ore-based and scrap-based, section 3.1). These models are supplemented with the GaBi models constructed for the subprojects according to the assessment procedure described in section 3.2. A possible result is shown in figure A2.

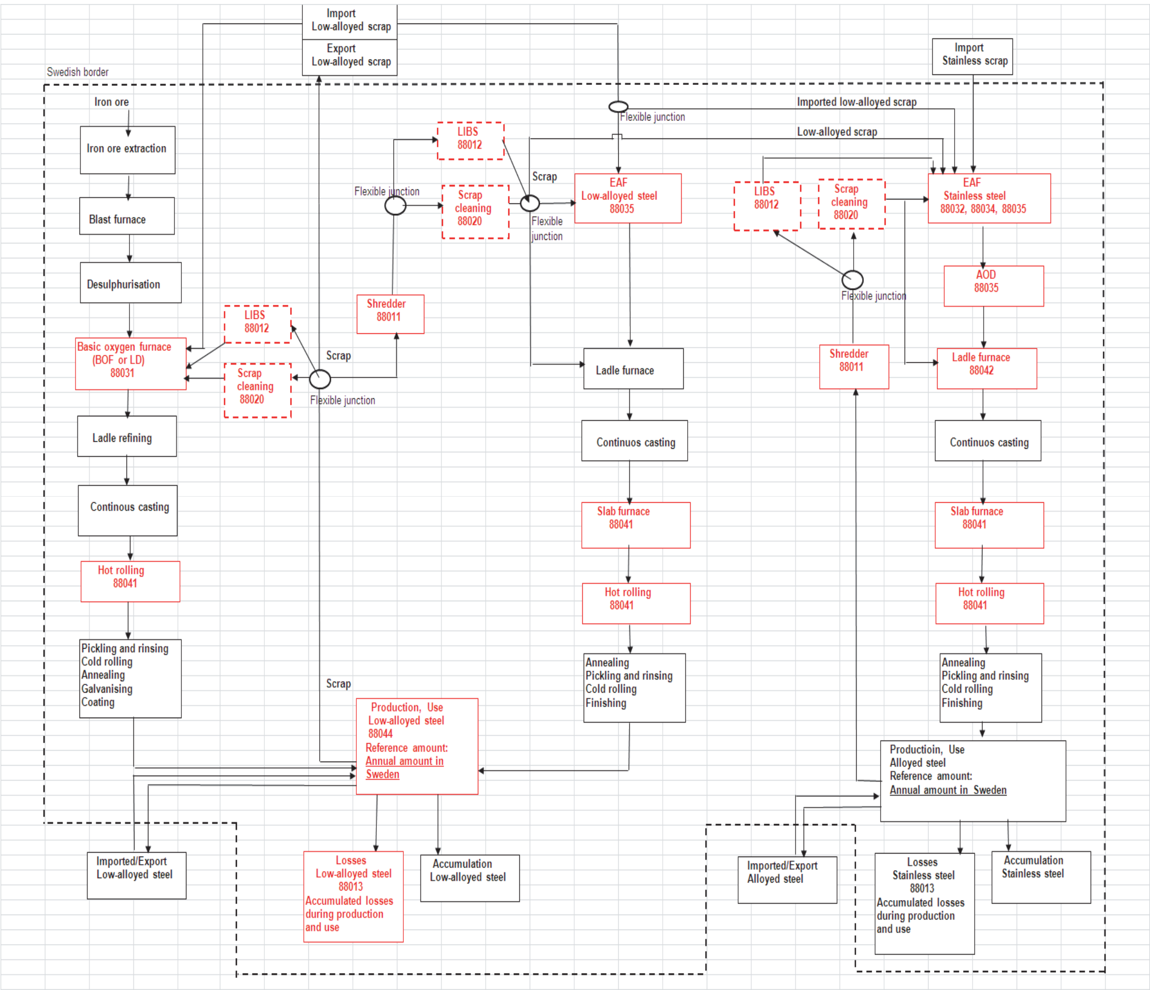
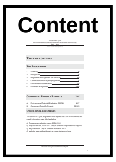


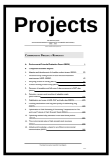
Figure A2. *LCA model of the Swedish steel cycle. The boxes symbolise processes modelled in GaBi. Red boxes are processes which have been modified by research and development work during the Steel Eco-Cycle programme, either directly or by modified auxiliary processes. Dashed boxes represent new processes.*

In figure A2 the steel manufacturing modules (ore-based and scrap-based) have been split into their separate process steps, and scrap-treatment processes have been introduced. All processes, which are directly or indirectly affected by the research and development work of the Steel Eco-Cycle programme, are marked with red boxes. Processes, which are entirely new, are symbolised by dashed boxes. In each red module the project or projects affecting that process are indicated.

As a start we suggest that the annual amounts of low-alloyed and of alloyed steel being supplied to the Swedish market are selected as a functional unit (or reference units). It will probably be necessary to make the simplification, that the two steel types are represented by fictitious steels of some average composition, if we want to calculate the impact from the entire Swedish steel cycle. The reference case will be the situation today, including the process technologies existing now, the flows of steel and scrap within the system and across the system boundary, and the amounts of steel being accumulated in Sweden as durable, abandoned and discarded products.

For the assessment of the cumulative effect of the Steel Eco-Cycle programme the modified and the new processes will be introduced in the model, including changes of the amounts of lost steel and changes of the impact on the use phase from the replacement of existing steels by new alloys. Suitable assumptions about the scrap flows and the use of the scrap will have to be made and introduced at the flexible junctions of the model.



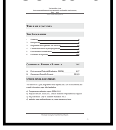


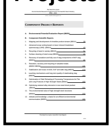
APPENDIX 2: Classification of projects according to development status

Table B2. *Classification of projects according to development status.*

	Classification[1]
88011 Mapping and development of the shredder product stream (Shredding) Increased yield of steel from shredded scrap.	2
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS): Stainless steel	3
88012 Advanced scrap sorting based on laser induced breakdown spectroscopy (LIBS): Low-alloyed ore-based steel	3
88013 Recycling of steel in the society (Recycling of steel): Low-alloyed steel	3
88013 Recycling of steel in the society (Recycling of steel): Stainless steel	3
88020 Surface Cleaning of Steel Scrap: Ore-based steel	1
88020 Surface Cleaning of Steel Scrap: Scrap-based steel	1
88031 Recovery of vanadium and full use of the slag components in BOF slag (Vanadium recovery)	1
88032 Retention, recovery and recycling of valuable metals (New melting processes EAF): Modified addition of Mo	1
88034 Retention, recovery and recycling of valuable metals from slag by salt extraction and electrolysis	3
88035 Properties of slag. Stabilisation and reuse of AOD slag as substitute for gravel in constructions.	1
88041 Improving high strength steels with energy efficient process routes (Optimisation of hot rolling)	1
88042 Optimising retained alloy elements in new steel sheet products (Tolerance of recycled elements)	2

[1] According to:
1=Technology developed and tested under conditions close to application, low uncertainty.
2=Experiments in lab scale or other conditions not fully representative for industrial application, medium uncertainty.
3=Based only on theory or experiments that are not representative for industrial application, high uncertainty.





MAPPING AND DEVELOPMENT OF SHREDDER PRODUCT STREAM (88011)

(How to Improve the Quality of Recycled Products)

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Abstract

Recycling is a requirment for sustainable development of our society. End-of-life vehicles (ELVs), obsolete appliances and industrial wastes have become important resources for producing iron and steel, aluminium, copper, and other metals. These obsoletes are firstly shredded into pieces and then processed for reuse and recycling. Shredding plants currently recycle waste to mainly produce raw material for metallurgy.

Within this study possibilities to increase the recycling rate and to reduce the amount of disposal were sought. Part of this study was dedicated to investigating shredding plant facilities and looking for avenues to improve the quality and quantity of the shredding product streams. The aims were to improve the quality of ferrous scrap by increasing its density, $\rho>0.9\ t/m^3$, and reducing its copper content, $Cu\leq0.25\%$, as well as having better quality of non-ferrous metals through the recycling schema, and finally to treat shredder residue (SR) to recover metals and plastics to reduce the amount of disposed material.

This report summarizes all activities from literature review, mapping shredding plants to find bottle necks, sampling and laboratory/pilot tests to recover ferrous, non ferrous, and composites from the shreds in an environmentally sound manner.

Key words: *shredding plant, ferrous scrap, steel scrap, recycling, end-of-life vehicles (ELVs), obsoletes, magnetic separation, eddy current separation, electrostatic separation, shredding residue (SR), recovery, sampling, environmental protection, energy conservation*

1. INTRODUCTION

Nowadays, recycling is an important part of supplying materials and accounts for a growing share of total metal production due to introducing new technologies and other cost reduction innovations.

In today's metallurgy, recycling plays a vital role in reducing energy consumption and production costs as well as in environmental protection. For example, in iron and steel production up to 74% of the total energy consumption can be conserved by recycling [1-5, 6, 7].

To recycle metals and other materials from complex end of life consumer products, shredding plants are built. A shredding plant essentially consists of a heavy fast-turning rotor to crush the scrap fed into the rotor house, an air cleaning system for primary and secondary de-dusting, a range of separating devices including magnetic, eddy current, heavy media, as well as hand or mechanical sorting to split the shredded materials into more or less clean streams of ferrous and non-ferrous scrap as well as coarse and/or fine residue that must be treated further, incinerated, or dumped. There are other systems, including screening and classification systems, to size the fragments to facilitate separation processes (Fig.1).

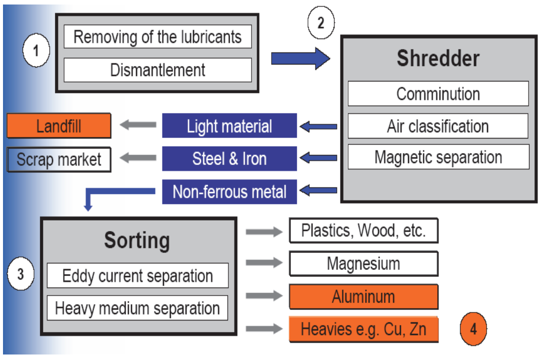

Fig.1. Shredding plant configuration and its constituents

Ferrous scrap is the main commodity from shredding plants. However, non-ferrous metal scrap is counted to be another valuable product all to be used by metallurgical plants. Table1 depicts the EU's standard quality for the ferrous scrap being used for steel production. However, higher scrap quality, i.e., ρ>0.9 t/m^3, and Cu ≤ 0.25%., is much favourable.

Table1. EU shredded steel scrap specification

Name	Density (t/m)	Fe, wt%	Cu ≤ wt%	Sn ≤ wt%
E40	0,9	> 92	0,25	0,02
E46	0,8	> 92	0,50	0,07

In EAF operation the scrap density is of major importance. Using low density scrap may increase the incidence of back-charge to the EAF and can be difficult to handle when charging the furnace. Low density scrap also tends to sit up in the furnace, making it difficult to close the furnace, so that the roof may be swung. In some cases it may be needed to remove some of the scrap from the furnace [3, 8]. Scrap size is another determining factor, although the acceptable size is normally defined by the size of the furnace and the power rating of the transformer. Scrap size also contributes to the scrap density. This means that the scrap density can be controlled by scrap size.

Furthermore, environmental demands, with increasing costs for land-filling, are other motivations to improve the quality and quantity of the recycled scrap and reduce the amount of waste products. Therefore, there is motivation for improving the performance of shredding and recycling plants and this still needs further work for better recycling through comprehensive understanding of the available technologies and even introducing new green technologies for recycling and waste management to conserve resources and protect the environment.

Note that up to 5450 BTU (~1373 kcal) per pound of product can be conserved in steel making by using scrap. Moreover, recycling conserves 1400 lbs coal, 2500 lbs of iron ore, and 120 lbs of limestone per ton of steel [1].

Advanced steelmaking technology has contributed substantially to reducing energy consumption and CO$_2$ emissions in the last decade(s); for example, Michaelis and Lackson [6-7] reported that for the period of 1954 to 1994 twofold reduction in both the annual energy consumption and the energy consumption per tonne of steel had been achieved in UK. However, it is not impossible to speculate on additional future cutbacks. Additional reduction in energy consumption and CO$_2$ emissions would be gained from optimizing and integrating existing steelmaking processes, implementing emerging technologies and technology efficiency, higher scrap quality, better scrap utilization, and developing eco-steel products while hot metal production via BF and conversion via BOF and EAF remain as the base for steelmaking in a projected future.

Since shredding plants are mainly constructed on the basis of mineral processing technologies, i.e., comminution (shredding), screening and classification, and finally physical separation including magnetic, eddy current and heavy media technologies, detailed knowledge in mineral processing is vital to improve the separation efficiency and product quality in the shredding plant.

Currently, the rate of recovery for obsolete goods, especially ELVs, in shredding and recycling plants, around the world, reaches to maximum 75-80% and about 25% of the scrap is deposited in land fills. However, due to social, economical and technical view points the recycling rate must be increased in an environmentally sound and technically viable manner [1, 5]. For example, in order to meet the EU targets for ELV recycling, it will not be possible to obtain very high recycling rates without considering recovering valuables from SRs. As shown in Fig.2, in order to achieve the goals for the recycling rate for ELVs in 2015, (i.e., to gain 95% recycling rate) up to 80% of the shredding residues must be recycled. This is not an easy task, especially when fine size (<8mm) SRs are considered.

Mapping and Development of the Shredding Plant is part of the "Steel Eco-Cycle" project in optimizing and improving metal recycling for the Iron and Steel industry in Sweden by implementation of mineral processing technologies with the general aim to produce high quality scrap for metallurgical uses and improve recycling rates. Another overall aim is to construct a roadmap for an environmentally sound, economically viable, and technically innovative procedure for fragmentation and physical separation in shredding plants in order to create a more efficient recycling scenario for the present and future.

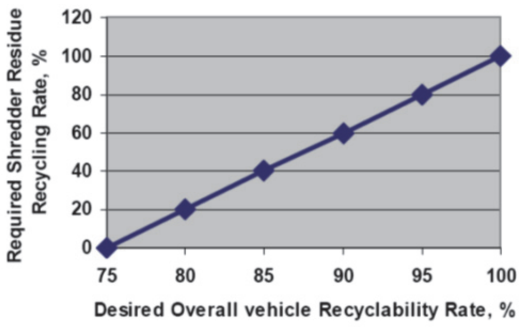

Fig.2. Requirements for recycling SRs as a function of overall recovery for ELVs [9]

2. OBJECTIVES

The main objectives of this project were to increase recycling rates of shredding plants and increase the bulk density for ferrous scrap, i.e., $\rho>0.9$, and Cu content, $\leq 0.25\%$, which is favourable for the steel industry, to improve the precision of separation, to reduce the total amount of waste disposal and to decrease the environmental impact of shredding plants, and finally to deliver findings and applied method to the industry (technology transfer). Therefore, efforts were made in order to investigate how the quality and quantity of the ferrous metals, as the main product, and other metals, in particular Al, as the second product could be improved and the amount of final residues (SR) could be minimized for environmental conservation through a comprehensive test schedule.

Moreover, since SRs must be treated to recover both materials and energy due to EU legislation, it was aimed to treat SRs from Swedish plants to recover mainly the metal fractions.

To achieve these goals it was planned: to study the shredding plants and the technologies available for treating the shredded products in detail, to map present shredding plants to identify bottle-necks, to investigate possible ways to improve separation efficiency and increase recycling rates, to look for new separation technologies available that suit the shredding plants, to test some new technologies available and to construct a roadmap for the present and future on the basis of ***green technology.***

3. METHODS

It was planned to obtain enough information and provide a thorough understanding of how the quality and quantity of the recyclables could be improved and the environment be better protected through a comprehensive study plan. Accordingly, the project commenced with a comprehensive review to provide information in detail regarding shredding plants and trends for improving their performance around the world, to understand general problems and to define the bottle-necks, etc., within the plants.

The second stage was concentrated on the mapping of 4 different Swedish shredding plants. Accordingly, three Stena plants, i.e., Halmstad, Hallstahammar, Huddinge, and the Skelleftehamn plant owned by Kuusakoski, were visited and mapped. Furthermore, two main strategies for development of the shredding plant streams and improving quality of the products were introduced and discussed [2].

Within third stage, samples were taken from a shredding plant (Halmstad) to characterize the shredded waste samples, to size the samples and to conduct magnetic and eddy current separation tests to produce high quality ferrous products in line with the needs of the metallurgical industry.

For the forth step, it was decided to further investigate shredded residue as a means of identifying ways to recover metals from the residue (SR) and to reduce the amount of final residue to be land filled.

All these steps were systematically planned on the basis of clear objectives and a precise research plan. Moreover, cooperation and support from Stena in providing information, access to the plants, and sampling completely satisfactory.

3.1 A literature review to configure shredding plant facilities and performance

A comprehensive review of the literature was completed which covered the metal recycling, shredding plant and its constituents, identification, sorting and separating techniques for different size fractions of shreds, and also processes for shredding residue. Finally the recycling scenarios with respect to the new EU legislation for ELVs and changing in cars composition by substitution of lighter materials like aluminium and reinforced composites instead of iron and steel were explained and discussed.

3.2 Mapping of four shredding plants in Sweden to identify ways of improving plant performance

Within this part of the study, four different shredding plants were visited and mapped with the aim to evaluate their performance, including material streams, their sizes, and technologies employed, to characterize the bottle necks, and to define their similarities and differences, etc. Two main strategic scenarios/schemes were addressed for higher recovery of materials through the shredding plants. Accordingly, the recycling can be improved either by intensive dismantling of obsoletes and wastes or by optimal use of current processing technologies through intensive and precise size reduction and liberation as well as separation optimization.

3.3 Conducting separation tests on representative samples to improve the recovery (quality & quantity)

Representative samples were collected and characterized. Then, different standard separation tests were conducted. Due to the need for steel-making companies of reduced elemental impurities, such as Cu, Zn, Mo, etc., and increased bulk densities for ferrous scrap, these were sought as the main goals. In addition, attempts were made to have quality products for non-ferrous metals, especially Al and its alloys, as well.

This part of the study included making representative samples from bulk scrap, sizing and classifying the comminute scrap by screening and finally, conducting magnetic and eddy current separation tests to produce high quality ferrous and non-ferrous metal fractions.

3.3.1 Representative sample

In order to have reliable data that can be verified, it is important to have a representative sample. Representativeness is of paramount importance since it is a measure of the degree to which the data accurately and precisely represents a characteristic of a population.

There are two main parameters in defining the amount of representative samples needed for experiments. These are particle size and the density of material to be considered by any sampling method.

Sampling was completed on the basis of Gy’s theory on bulk material sampling. Based on the sampling statistics presented by Gy, representative samples were collected according to the following equation in order to conduct separation tests [10].

$$M_{sample} = \left(\frac{1}{S^2}\right) f\rho \left(\frac{1}{a_c} - 2\right) d_c^3$$

where, S, M_{sample}, ρ, f, a_c, d_c, are maximum tolerate of standard deviation, mass of sample to be taken in gram, material density, shape factor, critical constant to be determined (0-1), and particle size at a_c centimetre.

The S can be defined according to the accuracy needed for standard deviation and the shape factor can be explained and defined by roundness or other shape characteristic factors. However, the a_c is defined by the maximum amount of impurity elements in final product after recycling the scrap (for example the 0.25% is considered for Cu). Finally, the d_c is defined according to the sieving system used and/or discharge grate size design of the shredding machine.

For our sampling campaign, 7, 0.4, 0.25%, 10 and 0.5 were considered for ρ, f, a_c, d_c, and S respectively.

It must be noted that the d_c size is defined based on the discharge grate design for the shredder machine. Accordingly 5 tonnes of the raw material was collected as the sample for running tests.

3.3.2 Screening and sizing of the collected sample

Previous studies indicated that it is very important to size the shred particles for physical separation since all physical separation processes, to some degree or another, are sensitive to the size distribution and shape factor for the feed.

This gives an idea about the size distribution and shape factor for the shreds. It is also helpful to determine the accumulation of different components within different size fractions that can finally lead to defining the optimum procedure for the separating step(s).

The shreds from the plant were, therefore, sieved to have three main classes or size fractions for particles. The raw material was classified as P >50mm, 32mm<P<50mm, and P<32mm categories.

3.3.3 Magnetic separation tests

A series of magnetic separation tests, using a Sala dry Magnet, were carried out to improve the quality and quantity of the iron scrap for metallurgical use. Tests were conducted on three size fractions, i.e., P>50mm, 32mm<P<50mm, and P<32mm.

From a theoretical view point, in traditional magnetic separation, magnetic force is the dominant external force and since this force is proportional to the magnetic field strength of the separating device, it is often claimed that by increasing the magnetic field, the performance of the magnetic separator improves. Although this is a valid explanation for some cases, in a real matrix situation the role of the magnetic field strength is more complicated and an increasing of magnetic field strength can often have a negative effect on the performance of the magnetic separator. Furthermore, the feed content and the feeding mechanisms as well as the configuration of magnetic separator are highly important in separation efficiency. Another effective parameter is particle size.

3.3.4 Eddy current separation tests

After separating the ferrous fraction by magnetic separation technique, the non-magnetic fractions were passed through an eddy-current separator to separate non-ferrous metals within the feed. Eddy-current separators are usually the next step at the shredding plant after the magnetic separation stage.

In the eddy-current separator, particles are separated due to their conductivity through the influence of a magnetic field. In fact, when a conductive object is passed across a changing magnetic field, an eddy current will arise in that object, generating a magnetic field that opposes the applied field by the separating device. Thereby, eddy currents can be generated in a conductive particle by changing the electro-dynamic magnetic field or by moving permanent magnets.

Fig.3. Particle trajectory on eddy-current separator

Drum-type eddy-current separators have been widely employed in waste recycling plants; however, the main problem in eddy current separation is associated with the separating of fine particles, e.g. particles smaller than 5 mm or finer. In the last two decades, eddy-current separators with permanent magnets represent a class of separators substantially improved. In current drum-type eddy-current separator permanent magnets are placed alternatively, N-S and S-N oriented around a drum, parallel to its axis [11]

When particles are fed to the eddy-current separating device they are affected by different forces, i.e., gravitational, centrifugal, frictional, inter-particle, drug, magnetic deflecting and repulsive forces (Fig.4).

These forces are changed by changing particle size and its shape, the particle density and its conductivity, as well as parameters with respect to the separating device like drum speed, magnetic field intensity, feeding mechanism and feeding rate.

Investigations revealed that when the magnetic rolls remain stationary, which means that the magnetic deflecting force should be negligible, the deflections of all materials including metals and non-metals appear to be similar, regardless of the rotational speed of the external shell. This implies that gravitational, centrifugal, and other mechanical forces cannot result in selective deflections of various materials. Nevertheless, when the magnetic rolls rotate, the magnetic deflecting and repulsive force act on conductor particles, resulting in selective separation of conductors from insulators or even different conductors from each other.

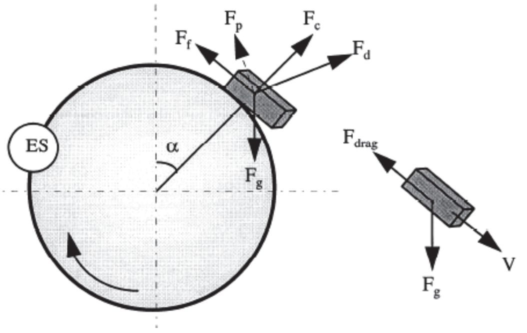

Fig.4. Forces acting on particles when they are fed to the separating device

3.4 Auto shredder residues (ASR) and its recycling by physical separation techniques

Some of the main concerns of shredding companies is the recovery of metals and plastics from shredding residues (SR) in order to improve the recycling rate, conserve energy, and protect the environment. According to the detailed studies, between 18 to 25% of the feed to the shredding plants is considered shredding residue (SR). Most of this fraction is not treated and disposed. A higher percentage of shredding residue is achieved if the feed to the shredding plant consists of more ELVs. Usually, particles finer than 8 mm in size are not processed and are disposed along with part of the lighter fractions that are vacuumed during shredding (comminution). This is almost a rule within the Swedish shredding facilities.

SR is a heterogeneous product of shredding plants that consists of mixed materials including small particles of ferrous and non-ferrous metals, different plastics, glass, stones, wood, ceramics, etc.

Methodology for treating the SR consists of characterizing of the SR sample, sizing, further grinding of the SR, and using electrostatic (Fig.5) and magnetic separation techniques to sort and separate the ground SR.

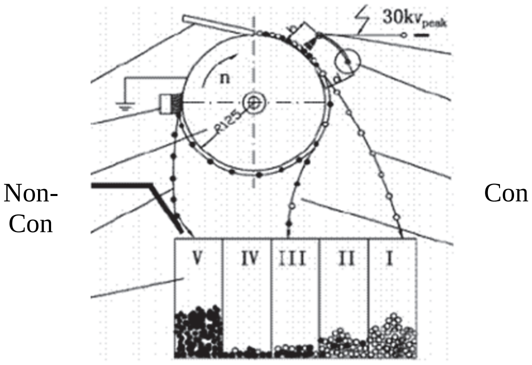

Fig.5. Electrical separator for separating conducting from non-conducting particles within the SR

4. RESULT AND DISCUSSION

The following are results from different steps of this comprehensive study.

4.1 Out comes from the literature review

Detailed studies of the shredding plants and their performances have been reported [1]. Some significant findings are highlighted as:

a- It is important to have a good dismantling procedure prior to shredding obsoletes. Also, dismantling by itself is a profitable process.

b- Liberation plays a vital role in having better recycling of different streams. So, an optimal liberation size must be defined. However, it is important to avoid having too much fine material. During size reduction parameters such as residence time, anvil and discharge grate design, feed rate, circumferential speed, etc., must be optimized.

c- Shreds should be sized for separation stage(s). Thus, it is important to optimally design the screening facilities that fit the downstream processing. In some circumstances, if the sizing is done perfectly, part of the scrap can be used directly without having any need for the separation stage.

d- A narrower size fraction facilitates the downstream processing and thereby the recovery rate improves.

e- For the eddy-current separator, the size fraction of the feed plays an important role and the pole size for the eddy current magnet must be chosen accordingly. Sink-float separation is also affected by particle size. Too much fine material creates problems in processing and leads to losses.

f- Studies revealed a need for quality control in plants to avoid the uptake of problematic contaminants. Thereby, a reliable quality control system must be considered and implemented to precisely detect shredding products, and control quality.

g- Shredder residue (SR) is another concern, especially from an environmental point of view. SR/ASR can make up to 25% of the total feed to the shredding plant, which is mostly land-filled nowadays. However, this must be avoided in the future due to environmental concerns.

h- Substitution of lighter materials, like aluminium and composites, instead of iron and steel in manufacturing, in particular for vehicles, revealed that aluminium is a favourable material for iron and steel replacement. In this case not only is the energy consumption decreased and both environment and natural resources protected, but also dismantlers, shredders, and recyclers benefit. However, the substitution of iron and steel by composites is not an ideal option.

i- Design for recycling is another determining factor to allow better recycling of the end of life products. From a recycling and recovering point of view, it is important in designing and manufacturing goods to [12]:

Make use of incompatible material combinations as much as possible

Avoid chemical joints and use of physical joints. Preferably, use of one big physical joint instead of many small joints, minimizing the number of joints used in term of join mass.

Choose joints and shredding parameters that produce a joint size distribution out of phase with the particle size distribution. (Fig.6)

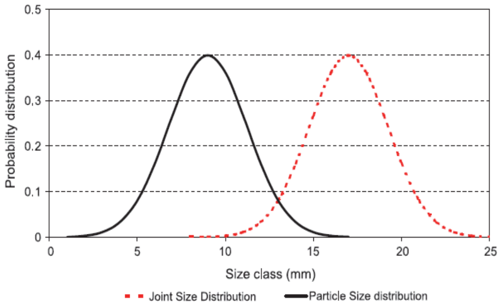

Fig.6. Joint and particle size distributions out of the phase for higher liberation and lowest contamination [12]

4.2 Out comes from mapping Swedish shredding plants

Mapping four shredding plants in Sweden indicated, although they generally perform acceptably, that there are some issues to be considered for better plant performance and achievement of goals according to the new EU legislation, in particular the EU directive for car recycling, which indicates a reuse and recovery of 95% on the mass basis (minimum recycling 85%) for vehicles 95% by 2015, which currently are far from being realized.

a- It seems investigation in detail must be conducted to characterize the particles after shredding and their liberation on the basis of different components.

b- There are no rules for sizing after comminution. This must be considered seriously. There must be a logical concept for screening and sizing the shreds to improve the recovery. However, sizing must be completed on the basis of the material liberation and downstream processing stages [2

c- Having high density scrap in EAF metallurgy is desired. Improvement in density can be achieved for the recycled ferrous scrap by different ways. One way is sizing the shreds (before or after separation).

d- Another challenging area is the heavy media separation process (if exists). For this stage again precise size classification is needed. One plant does not treat the particles finer than 10 mm in size during media separation. Re-consideration may be needed by investigating this size fraction, i.e., -10 mm, in greater detail.

e- There are two main strategic schemes for obtaining high recycling rates and meeting the targets established by authorities [2-3, 13]. These strategic tactics can be used for recycling ELVs and other end of life manufactured products (Fig.7). As can be seen in the figure, recycling and recovery of materials can be improved either by intensive dismantling of obsoletes and wastes (scheme 1) or by optimal use of current processing technologies through intensive and precise size reduction and liberation as well as separation optimization (scheme 2). However, innovation and the emergence of new processing technologies play a vital role in the latter.
Of course, the optimal case would be a combination of both strategies. This must be sought through completely identifying and understanding the key parameters determining technical, economical and environmental feasibility of the two strategies.

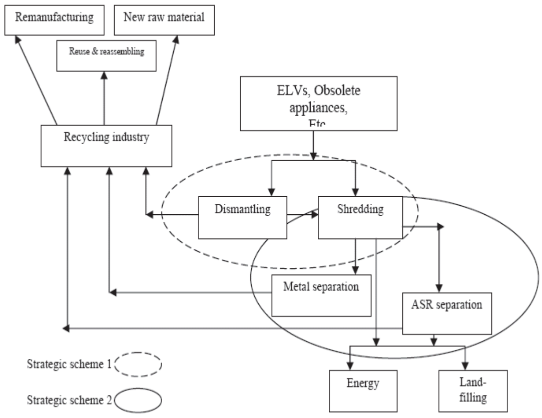

Fig.7. Two different strategic schemes for treating the shreds (scheme 1 intensive dismantling and scheme 2 focusing on separation)

4.3 Physical separation tests on samples obtained from shredding plants

4.3.1 Sampling and sizing of the collected sample

In the third step, sampling of the shreds was completed from a heavy fraction of the shreds by making use of Gy’s theory for sampling. Accordingly 5 tons of raw material was obtained. The sample (raw material) was then screened and sized in three different fractions, i.e., P>50 mm, 32<P<50 mm, and P<32 mm. This gives an idea about the size distribution for the shred stream. Sizing the shreds helps to determine the accumulation of different components within different size fractions that finally leads to choosing the appropriate separation steps. On the other hand, it has been confirmed that the narrower the size distribution, the better the separation efficiency.

Sizing of the shreds also leads to knowledge about the shape factor during the shredding process as well as the distribution of different components within each size fraction. This may lead to consider other physical separating techniques to be used in future. During the study it was found that majority of non-metals is of the finer size fraction, i.e., P<32mm. This is due to that fact that they exhibit lower strength and plastic properties; thereby they are comminuted to finer particles. In addition, the degree for liberation increases by decreasing the size fraction. Table 2 indicates the size distribution of the sample.

Table2. Size distribution of shreds

Size (mm)→ % total↓	P > 50	32 < P < 50	P < 32
100%	38.77%	27.45%	33.77%

4.3.2 Magnetic separation tests

In magnetic separation the separation is affected by the magnetic susceptibility of the particles. This magnetic susceptibility decreases with increasing the applied magnetic field. Reduction in the magnetic susceptibility that accompanies the increase in the magnetic field strength can often result in decreasing the recovery. This must be noted in ferrous metal separation.

Usually ordinary magnets, having fixed magnetic fields, are used for recovering the ferrous fraction. However, if high intensity magnetic separators are used some mixed particles will be recovered as well. For example, irony aluminium, a complex material consisting of aluminium and magnetic parts that are mechanically connected, can be recovered by a high intensity magnetic field.

A series of magnetic separation tests were conducted on three different size fractions to improve the quality and quantity of the iron scrap for metallurgical use.

As shown in Table 3, for each size fraction, separation tests were conducted in two stages for improving the recovery (i.e., 1st and 2nd stage in table 3). This means that the non-magnetic part of the first stage was passed through the separator one more time.

Table 3. Magnetic separation results on different size fractions of the shreds (two- stage separation)

Magnetic tests on P>50mm			
Product	Weight% in fraction*	Weight% in total #	Density (t/m^3)
1st stage	90.5	35.1	
2nd stage	2.4	0.9	
Total Magnetic (1st +2nd)	92.9	36.0	0.998
Non-Magnet	7.1	2.75	
Magnetic tests on 32<P<50mm			
Product	Weight% in fraction	Weight% in total	Density (t/m^3)
1st stage	90.4	24.8	
2nd stage	0.8	0.2	
Total Magnetic (1st +2nd)	91.2	25.0	1.095
Non-magnet	8.8	2.4	
Magnetic tests on P<32mm			
Product	Weight% in fraction	Weight% in total	Density (t/m^3)
1st stage	78.7	26.6	
2nd stage	1.2	0.4	
Total Magnetic (1st +2nd)	79.9	27.0	1.06
Non-magnet	20.1	6.8	

** W% of the material in specific size fraction & # W% of the material from total feed*

As indicated in Table 3, recoveries were considerably improved and the total recovery reached to 88%; however, higher recoveries were achieved for coarser particles. The results of separation tests also indicated that a higher bulk density for ferrous product can be achieved by sizing the feed prior to the magnetic separation.

The distribution of the ferrous fractions and non-ferrous fractions are 41% and 22.9%, 28.4% and 20.1%, as well as 30.5% and 56.7% for coarse (P>50mm), middle (32<P<50mm), and fine (P<32mm) size fractions of the shreds, respectively. Complete test results indicated high quality of ferrous products, having higher density favourable for steel producers, can be achieved by sizing the feed and then separation of narrower size fractions. It must be noted also that the separation results are dependent on how the raw material is fed into the separating zone.

At last, about 12% of the feed was rejected as the non-magnetic fraction. This non-ferrous fraction consists of both non-ferrous, non-metal, and in some cases, steel particles that must be treated further to recover the metal content.

Fig.8. High quality ferrous fraction for metallurgical application (P>50mm)

4.3.3 Eddy current separation tests

Most often within shredding plants for recycling wastes, the eddy-current separation process is the second procedure to separate the non-ferrous metals, especially Al and its alloys, from the non-ferrous fraction after magnetic separation.

The non-ferrous fractions obtained from magnetic separation were treated by an eddy-current separator. Again, separation tests were conducted for three different size fractions. Tests were also conducted for different conditions, e.g. different roll and belt speeds. The results are summarized in Table 4

Table 4. Approximation for metal and non-metal recovery by eddy-current separator

Size	**Non-ferrous % in**		**Non-metals % in**		**Ferrous (steel) % in**	
	fraction	***Total***	***fraction***	***Total***	***fraction***	***Total***
P>50	38	1.1	54	1.5	7.5	0.2
32<P<50	53	1.3	36	0.9	10.5	0.25
P<32	35	2.4	54	3.7	9	0.55

In concluding the results it must be noted that:

a- Tests on P>50mm indicated about 35% of the feed can be recovered as the Al product. The separation campaign indicated that by increasing the belt and roll speeds the recovery of the material in non-metal fraction increases.

b- For middle range particles, 32mm<P< 50mm, more than 50% of the feed can be recovered as quality Al product, more than 35% of the feed contains mainly non-metals, and the remaining includes ferrous metals (steel), non-metals, etc.

c- Tests on the finer fraction, P<32 mm, revealed that it is possible to obtain a high quality Al fraction with recovery up to 42%. However, the recovery diminishes by decreasing the roll and belt speed. Again the separation efficiency is governed by adjusting the roll and belt speed.

Fig.9. From top to bottom: Al and its alloys, non-metals and ferrous fractions after eddy-current separation
(for the size fraction of 32 < P < 50mm)

Accordingly, about 5% of total feed can be recovered as the non-ferrous metals, mainly Aluminium and its alloys by eddy-current separation.

4.4 Recycling of shredding residue (SR/ASR) by physical separation techniques

The SR received from shredding plant was treated as follows:

4.4.1 Characterizing SR

In general, oversized SRs, i.e., residue having a particle size bigger than 8 or 10 mm, from different plants mainly consist of polyurethane foam and rubber. These materials can be economically recycled by chemical recycling techniques, including pyrolysis, because the less inert materials are associated with this size fraction which leads to less ash production during processes. This means that larger fractions would be more suitable for chemical recycling, pyrolysis, and energy recovering [5].

In contrast, within fine SR streams more than 40% (statistically between 45-65%) of particles are smaller than 2 mm, and thereby, they are probably useful for making composites, of course, after removing ferrous particles from the stream.

Most of the dirt, rocks, glass, and metals which are broken into smaller pieces are found in smaller size SR/ASR streams. Therefore, streams with smaller particle sizes have a significantly larger amount of “sinkables” than “floatables”.

The raw material, i.e., Swedish SR, was characterized before conducting separation tests. It has been noted in the first report that in most Swedish shredding and separation facilities, especially those of Stena, the particles finer than 8 mm are not treated and considered as residue [1]. This means that our sample contained particles with the size of P<8 mm.

The raw material was treated by air jigging to sort the feed as dust (very fine), light, and heavy fraction categories. Then, materials were screened to have four different size fractions, i.e., 4<P<8 mm, A, 2<P<4 mm, B, 1<P<2 mm, C, and P<1 mm, D, in size. The results are shown in Tables 5 and 6.

Table 5. Characterizing SR by size

SR Product	*A*	*B*	*C*	*D*	*Total*
Very Fine(dust)	*na*	*na*	*na*	*na*	*3.8*
Light fraction	*6.2*	*15.1*	*11.2*	*21*	*53.5*
Heavy fraction	*4.2*	*20.2*	*14.2*	*4.2*	*42.7*
Σ	***10.4***	***35.3***	***25.4***	***25.2***	

Table 6. Characterizing SR by components

SR Product	*Glass*	*Metal*	*Organics*	*Misc*	*Total*
Very Fine(dust)	*0.9*	*0.2*	*2.7*	*0*	*3.8*
Light fraction	*11.8*	*2.3*	*39.5*	*0*	*53.5*
Heavy fraction	*18.3*	*19.1*	*4.7*	*0.6*	*42.7*
Σ	***31.0***	***21.6***	***46.9***	***0.6***	***100***

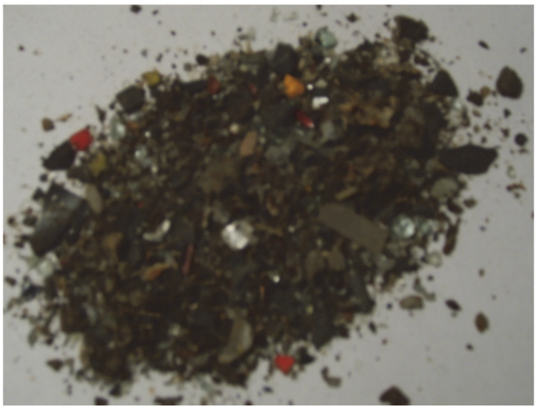

Fig.10. SR as received from the shredding plant (feed)

From the above tables, it can be concluded that about 50% of the SR is finer than 2 mm in size. Particle size analysis indicated d_{50} for heavy and light fractions to be about 1mm and 2.5mm, respectively. More information is given in a related report [5].

4.4.2 Separation Process for SR

Reasonable amounts of ferrous and non-ferrous metals are contained in SRs. Metals are mixed with non-metal particles. These non-metal particles are non-conductors (e.g., plastics, rubber, and glass). So one possible method of separation would be to separate the metals, i.e. conductors from non-conductors in a finer mix of SR. Even fine metal particles are valuable to be recovered in order to increase the recycling yield as well as reducing the final residue to be land-filled.

An electrical separation technique was used to separate the metals from non-conductors, mainly plastics and polymers. Two products having a higher content of metals and a higher content of polymers were achieved. However, in-depth studies revealed that one issue for separating metals and non-metal fractions would be the liberation. So, the SR was ground further by hammer mill to bring about better liberation of different components.

In the first stage, the particles were sorted by electrostatic separation to render three different products. Detailed observation indicated that under optimal conditions, 15% of the SR could be recovered as a high quality metal fraction. About 35% of the feed is recovered as the non-conducting materials, including plastics and polymers, and the remaining, i.e., about 50% is the middling.

Further treating of the middling fraction (second stage separation) resulted in recovering 30% and 45% of middling as the conducting and non-conducting fractions, respectively. These results revealed the possibility to recover about 30% of the SR as conductors (mainly metals) and 58% as non-conductors.

Fig. 11 depicts the conducting fraction of the SR after stage two treatments with an electrical separator.

Fig.11. Conducting particles (mainly metals)

Fig.12 and Fig.13 depict the middling and non-conducting fractions after electrical separation. As can be seen from Fig.12, the middling fraction contains mainly non-liberated particles.

Further tests on conductor fractions using high intensity magnetic separation indicated that two fractions consisting mainly of ferrous and non-ferrous metals are produced. However, the distribution is nearly 50%-50%.

Further separation of non-conducting particles can also be carried out by the triboelectric separation technique on the basis of the electro-physical properties of the contents. However, the decision must be made after characterization of the non-conducting fraction in detail and evaluation of its thermal capacity and heating value. Sorting and separating different components from SR still is a challenge.

Fig.12. Middling fraction (mixed- middling)

Fig. 13 Non-conducting particles

5. CONCLUSIONS

Sustainable development requires an optimal use of all resources and environmental conservation. Recycling is an important part of supplying materials and accounts for a growing share of total metal production due to the introduction of new technologies and other cost-reducing innovations. High costs for disposing of and depositing waste materials in landfills, the need for raw material, as well as other environmental and economical concerns due to new legislation all provide strong motivation to reuse and recycle globally. Nowadays, a wide range of different complex multi-component products is manufactured. These goods must be manufactured, used, and handled to the end of their life cycle, and finally recycled properly. Recycling not only conserves resources but saves energy and protects the environment.

Shredding plants play a major role in the recycling chain, in particular for supplying raw material to the metallurgical industry. It is believed that recycling would be improved and optimized through thoroughly understanding all of the technical, economical, and environmental aspects that affect recycling processes.

The finding from this study includes:

1. A high recovery (88%) for ferrous scrap from the heavy fraction of shreds can be achieved if the shred is sized prior to separation (e.g., p>50mm, 50<P<25mm, and P<25mm). However, the highest recovery of 93% was achieved for the coarse size fraction.
2. A higher scrap density, that is favourable for steel producers, was achieved for the recycled ferrous metals (i.e. densities of 0.99, 1.095, and 1.06, respectively, for p>50mm, 50<P<25mm, and P<25mm size fractions). These densities for ferrous scrap are considerably above the standard (i.e., between 10 to 20% higher than that of quality scrap for European standards).
3. A high quality of non-ferrous metal fraction, mainly Al and its alloys, was obtained by eddy-current separation. Again, the sizing of scrap improves the recycling rate. The total recovery was ~5% which was very promising.
4. Beneficiation of the Shredding Residue (SR) was completed after characterization of the material. Further comminuting of the SR led to increased liberation and thereby improved separation.
5. Electrical separation was found to be the most cost effective separation technique for treating SRs. Separation, in two stages, resulted in recovering 30% of the feed as the metal fraction (however, the distribution of the ferrous and non-ferrous metals was almost 50%-50%).
6. In total about **93%** of the heavy fraction of the feed to the shredding machine (shredder) can be recovered as metal scrap (**88%** of ferrous, **5%** non-ferrous metals). This is between 5 to 8% above the current recovery for shredding plants.

This study showed the value and importance of classification of the feed prior to separation and optimizing other process parameters to achieve high recovery rates and product quality..Steel producers may thus be able to improve the efficiency of furnace (EAF) production by sizing the scrap. This can be also achieved by installing comminution equipment to further grind the ferrous scrap to provide high density ferrous scrap for the EAF. Therefore, this is recommended for steel plants that desire ferrous scrap of a higher density.

On the other hand, there may be a need for low density scrap for producing some special steels. Again sizing the scrap is beneficial.

There are generally two main strategies for obtaining high recycling rates. One is the intensive dismantling of obsoletes and the other the optimal use of current mineral processing technologies through intensive and precise size reduction and liberation. However, the most successful scenario would be a combination of both strategies. In addition, the role of design in manufacturing should be taken into account more seriously in future.

There is a lack in material balancing for shredding plants around the world that must also be considered seriously in order to precisely control the input, output and losses both qualitatively and qualitatively.

The author also believes that separation efficiency can be maximized and problems can be minimized if each shredding plant deals with specific obsoletes. This means, for example, one plant can be considered to shred and process ELVs while another one deals with obsolete appliances. By doing so, each plant would have a relatively homogenous raw material that can be processed more efficiently.

Findings from this comprehensive study also indicate that in using currently available technology, the 2015 targets for recycling ELVs in the new EU legislation will be very difficult to meet. In other words, if they are not impossible to achieve, they at least cannot be accomplished easily using current technology. Further investigation is therefore needed to optimize the technologies available in order to maximize recovery as well as the design of new equipment for treating SRs effectively and efficiently.

6. FURTHER RESEARCH

Further research must be dedicated to optimize the separation parameters and work on dense media separation to recover steel and other non-ferrous metal fractions. In addition, SRs must be studied in more details and technologies must be developed to deal with this fraction in order to meet EU legislation targets for ELVs.

6.1 Dissemination and publications within the current project

6.1.1 Submitted manuscripts

Five comprehensive reports and one submitted paper are outcomes from this study (No. [1] to [5] in reference list)

6.1.2 Conference publications, refereed

1- Mapping and Development of Shredding Plant Stream to Improving Quality and Quantity of Recycled Materials and Protect Environment, (paper accepted for 24th International mineral Processing Congress, Beijing, Sept 2008).

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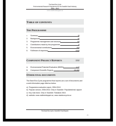

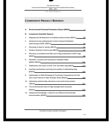

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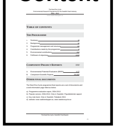

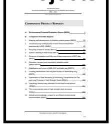

ADVANCED SCRAP SORTING BASED ON LASER INDUCED BREAKDOWN SPECTROSCOPY (LIBS) (88012)

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Abstract

Classification and quantification of steel scrap is developed using Laser Induced Breakdown Spectroscopy (LIBS). The technique is very well suited for scrap sorting thanks to its possibility for rapid non-contact analysis, up to several meters distance. Also, a high flow of scrap pieces to be analysed is possible by means of single shot analysis at high repetition rate. The technique complements the capability of today's eddy-current based sorting in ferromagnetic and non-ferrous metals. Unwanted elements in the scrap, e.g. Cu and Sn, can be minimised and more precise sorting of stainless steels is enabled. An improved knowledge about the composition of steel scrap will increase the use of recycled steel, also in specialty steels. Furthermore, alloy elements in the scrap, e.g. Cr, Mn, Mo and Ni can be used more efficiently in metallurgical processes.

In the first phase of this project, the possibility to classify and quantify the composition of steel scrap pieces using LIBS was investigated in a laboratory setup. The most suitable spectral lines for LIBS analysis of steels was studied with a high resolution optical spectrometer. Special attention was given the accuracy of repeated analyses with very few laser pulses. The information from 150 laser pulses, as is used in bulk analysis, was compared with that of the very first 1 - 3 laser pulses. It proved possible to use the three very first laser pulses for classification of scrap, also in classes within the steel category, e.g. mild steel, cast iron, stainless steel, etc. It was also found that more work is still required to handle classification of dirty and surface coated samples. Finally, the feasibility of the technique to analyse a continuous stream of scrap was demonstrated at the first field trials at Stena Recycling, Huddinge. This work was carried out in cooperation with Fraunhofer-Institut für Lasertechnik (ILT), who designed and built a field demonstrator unit as part of a European RFCS project.

In phase two of the project, the main objective was to develop, build and evaluate a more compact and low-cost field demonstrator LIBS system. In comparison with the system from ILT, this system is based on a compact, low-resolution, low cost CCD optical spectrometer and a much simpler detection and ranging system.

The prototype, complete with hardware as well as custom designed software, was constructed and tested in field at Stena Recycling in Hallstahammar and in Huddinge as well as at Outokumpu Stainless in Avesta during 2011/2012. The prototype is capable of analysing up to 30 scrap pieces per second from a distance of almost 1 meter without the need for sample preparation.

1. INTRODUCTION

Direct classification and quantification of recycled steel scrap is a new, challenging application of the rapidly developing LIBS technique. The technique can be used e.g. after eddy current based sorting of shredded ferro-magnetic and non-magnetic fractions in order to provide an online continuous chemical analysis. This opens up entirely new possibilities for the use of recycled steel also in high quality steel products typical for the Swedish steel industry, mainly for the following reasons:

1. Valuable alloy elements included in the scrap delivered to the steel plant, e.g. Mn, Cr and Ni, can be used more efficiently in the process, reducing the need for pure raw materials.

2. The level of undesired elements, e.g. Cu and Sn, can be better controlled and reduced.

The LIBS technique is based on laser pulses directed and focused onto a surface, which induces a plasma emitting element-specific optical emission from the sample material. The spectral information is recorded with an optical spectrometer and the signal can be used to deduce the elemental composition of the analysed scrap piece. The two major strengths of the technique are foremost the almost instantaneous analytical response and the capability for remote analysis.

Scrap sorting of aluminium using LIBS has already proven to work very well. One American project [1] and a European one [2] have been carried out. Cast Al-products can be sorted from wrought parts with the elemental knowledge of the silicon content. The challenge with steel is the larger variety of steel categories and the complex spectrometric properties of iron and the alloy elements in steel.

Some of the technical challenges associated with using LIBS for steel scrap sorting are listed below.

1. The surface of scrap pieces may be dirty, or coated with a galvanising layer and/or paint.
2. Shredded scrap pieces come in a large range of geometries.
3. The emission spectra of Fe as well as several alloying elements are very line-rich, making the data evaluation more complex than e.g. for Al-base alloys.
4. The throughput of ferro-magnetic scrap on a conveyor is up to 50 tonnes per hour at a speed of 0.5 m s^{-1}. At this flow rate, analysis of all scrap pieces is not technically feasible and it is necessary to “sample” the scrap flow with LIBS, providing an average of the scrap composition.
5. The environment of a scrap shredding site is characterised by dust, vibrations, heat, fumes and cold weather. This is an extremely harsh environment for a high precision device filled with optical components and electronics. A major challenge is therefore to make the device sufficiently robust for these conditions.
6. In applications where the system will be used for rapid screening in a scrap yard, the system must be highly mobile, yet comply with all safety regulations for laser radiation.

The first phase of the project provided vital parts of the know-how needed for the design of a system for industrial real-world applications. The second phase of the project involved substantial laboratory investigations with the aim to determine the limitations inferred by the use of a low resolution spectrometer. A technological solution to the problem of automatic detection of samples was also developed and implemented into the setup. The final prototype constructed is a moveable instrument constructed from commercially available components and designed for fully automatic operation without the need for operators.

2. OBJECTIVES

- To develop a robust, affordable LIBS instrument for analysis and sorting of steel scrap, static or moving on a conveyor belt
- To develop fast, effective data evaluation algorithms for alloy identification based on complex low-resolution spectra
- To test and evaluate the complete LIBS system for selected industrial applications

3. METHODS

The work involves system design, laboratory tests, software development and finally field tests and evaluation. The following work packages have been defined for the completion of the project.

1. Investigation and definition of the specific applications for the system
2. Investigation and selection of spectrometer systems and detectors for the intended applications
3. Investigation and selection of laser systems
4. Development of the optical system for guiding the laser beam and signal collection
5. Development of intelligent data evaluation for classification and quantification of material categories present in the scrap flow
6. Development of analysis procedures of actual steel scrap
7. Construction of a prototype LIBS instrument
8. Testing of the prototype LIBS system in "real-world" applications

In order to ensure a compact final prototype the optical design of the setup was very important. The single most important feature of the system is the light collection. A high signal to noise ratio is of the uttermost importance if both the quantitative as well as the qualitative analysis is to be as accurate as possible. In order to avoid large investment costs and long experimental evaluation periods in the laboratory a theoretical ray tracing of the future system was performed. This allowed the design of the system to be optimized with respect to light collection before being physically constructed. An imaging setup using a spherical mirror with an aperture of 75 mm was chosen and the mirror was given a coating designed for optimal reflectivity in the wavelength range 200-400 nm. Together with the spectrometer chosen, an Ocean Optics HR2000+ sensitive in the range 220-440 nm, the system has sufficient signal to noise to function without compromised quality on a sample distance of up to 700 mm.

Unlike the laboratory LIBS instrument used in phase one of the project, the final prototype was designed to work in a fully automatic mode. Technology for automatic triggering of the laser pulses therefore needed to be developed and implemented. An approach was chosen in which a continuous laser distance meter measures the distance from the setup to the surface of the scrap flow. This was achieved by implementing a M9i-750 laser distance meter from MEL sensors having a 50 micro meter resolution. This solution allows the LIBS-setup to be stationary unlike other systems in which the optical design of the laser instrument is constantly compensating for the varying instrument to sample distance. By instead feeding the output voltage of the distance sensor to a pulse generator and triggering the same on a certain level, a fully automatic system was constructed. In practice the LIBS prototype constantly monitors the distance to the samples shown to it and as soon as a sample is in the focus of the laser a pulse is triggered and an analysis is performed.

This technical solution has a number of advantages compared to systems using adjustable optics. Most importantly, the cost of the system is low while the stability of the system is high. The downside is that the laser instrument is less flexible, this is however unimportant in this particular application. Figure 1 shows the layout of the final prototype constructed during phase 2.

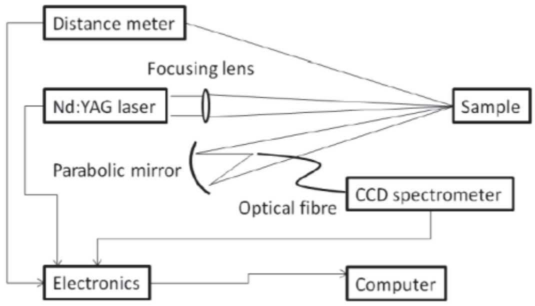

Figure 1. Schematic view of the LIBS instrument

Once constructed, several laboratory tests were performed in order to determine the limitations and possibilities of the system. In order to calibrate the spectra several certified reference materials were studied. Extensive searches were performed in attempts to correlate channel intensity ratios to actual elemental abundances in the spectra of reference materials. Figure 2 shows a typical spectrum recorded when firing the laser onto a high alloy steel. Figure 3 illustrates an attempt to correlate and calibrate channel intensity ratios to actual elemental abundances.

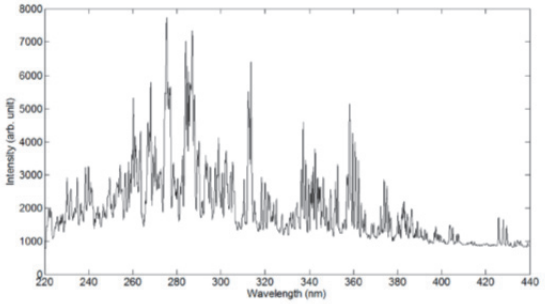

Figure 2. Typical high alloy steel spectrum recorded with the LIBS-setup constructed during phase 2 of the project

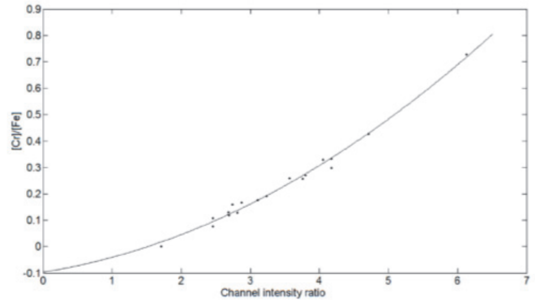

Figure 3. Cr/Fe calibration curve based on the correlation between several channel intensity ratios and the actual chromium/iron content ratio for 18 different certified reference materials. Each data point corresponds to 40 laser shots and materials with Cr contents between 0 and 27% were used.

The process of calibration is not trivial since the resolution of the spectrometer is relatively low, approximately 1.5 nm. The number of spectral lines from iron rich material is very large and the chance to find well isolated spectral lines suitable for calibration is in practice often impossible. Therefore a random search among all possible channel ratios was performed and the channel pairs with the strongest correlation to actual relative elemental concentrations were used in the final version of the analysis software. The software was designed and developed in a LabVIEW environment which offers great flexibility and possibilities to tweak the software to suit several similar applications. The software is capable of either performing a semi-quantitative analysis or to be trained to recognize certain user-defined material classes. When used in a quantitative way, the method is strongly dependant on the number of laser pulses used for each analysis. Given time, the accuracy of the quantification procedure can be greatly enhanced compared to the accuracy obtained when the quantification is based on a single laser shot.

One question raised early in the project was whether or not it is a problem that the LIBS method samples the surfaces of the investigated samples. In order to investigate this matter in more detail, a second laser was installed in the laboratory setup. The technique to use a second laser pulse in order to first ablate and clean the surface of sample and then probe the bulk content with a second pulse has been used by several research groups prior to this study. After the studies it was concluded that the results were not significantly improved by applying a second pulse and in order to keep costs as low as possible it was decided to construct the final prototype from a single laser approach. The prototype during operation can be seen in Figure 4.

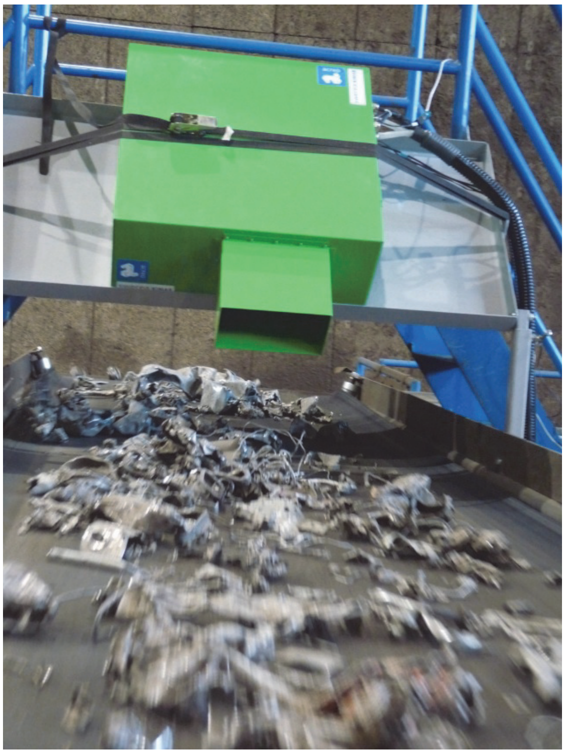

Figure 4. The final LIBS prototype mounted and operating over a conveyor belt transporting shredded scrap at Stena Recycling in 2012.

4. DEFINITION OF THE SPECIFIC APPLICATIONS FOR THE SYSTEM

The main industrial partners are Stena Recycling and Outokumpu Stainless. Researchers from both Swerea KIMAB and Acreo have visited both companies and held meetings with their representatives. Field tests at both sites have also been performed.

At Outokumpu Stainless Avesta, numerous possible applications have been identified, both in the scrap yard and the rolling mill. Automatic identification of internally produced scrap from the cutting line was identified as a first objective. The objective of the field test was to classify a number of scrap pieces as belonging to one of the steel grades produced by Outokumpu in order to avoid mix-ups of material. This was to be performed in a fully automatic mode online. The instrument used was not the final prototype but an earlier version of the same using the same components and analysis algorithms. Figure 5 shows a photograph from the field tests.

Figure 5. A photograph from field tests at Outokumpu Stainless in Avesta, Sweden. An early version of the LIBS instrument is used to classify internally produced scrap pieces on a conveyor belt.

The results from Outokumpu Stainless showed a correct classification rate of 94% when performing 2000 single shot analyses on four different steel grades.

At Stena Recycling in Huddinge/Hallstahammar, the first objective was to monitor an average composition of the shredded scrap flow. A number of field tests were performed in order to tests the different components and features of the instrument such as the automatic triggering mechanism, the light collection principle, the software analysis time and also the stability of the whole system. After a number of runs during both 2011 and 2012 it was concluded that the aim of the final prototype should be to monitor the levels of Fe, Cr, Ni, Mn and Mo in the scrap flow.

6. CONCLUSIONS

The following conclusions can be drawn from the present work.

- For a good LIBS analysis of steel scrap the following instrumental parameters are proposed: pulse energy 0-330 mJ, working distance 0,5-1 m, laser repetition rate 0-30 Hz.
- Elemental calibrations based on 50 laser pulses preceded by 100 pre-burn pulses, display about the same standard deviations as in conventional spark-OES for bulk analysis.
- A two-step classification of steel scrap has been developed and evaluated. The first step is a semi-quantitative analysis, aiming at categorization of material type, e.g. coated steel, uncoated steel, copper, polymer, etc. The second step is adopted in case the sample is categorized as steel in the first step, and is based on a dedicated steel calibration, in order to classify the type of steel, e.g. mild steel, cast iron, transformer steel, etc. Software including algorithms for this analysis has been developed and tested in the laboratory as well as with the final prototype in field. Laboratory tests on clean samples under well controlled conditions have shown very promising results.
- Steel classification of relatively rusty scrap pieces and of Zn-coated samples has been achieved with just 3 laser pulses. This is a major technical breakthrough, which shows that LIBS has a high potential also for demanding steel scrap sorting.
- It is shown that an echelle spectrometer is a very useful tool for the purpose of choosing spectral lines, because of its combined large spectral range and high spectral resolution. This study also indicates that spectral channels normally suited for conventional OES sources are not necessarily the most suitable for LIBS measurements. Computer software with the ability to search for correlations between channel intensities and known mass contents of the samples has been developed. A multivariate analysis of the experimental data in combination with collection of data from a large number of certified reference materials show strong potential for the possibility to perform quantitative mass content measurements.
- The feasibility of the technique to analyse a continuous stream of scrap has been shown at field trials at Stena Recycling in Huddinge, Stena Recycling in Hallstahammar and at Outokumpu Stainless in Avesta.
- First results from a fully automated in-field attempt to identify different steel alloys using single shot LIBS at Outokumpu Stainless resulted in a correct classification in 94% of the 2000 measurements performed, see Figure 6.

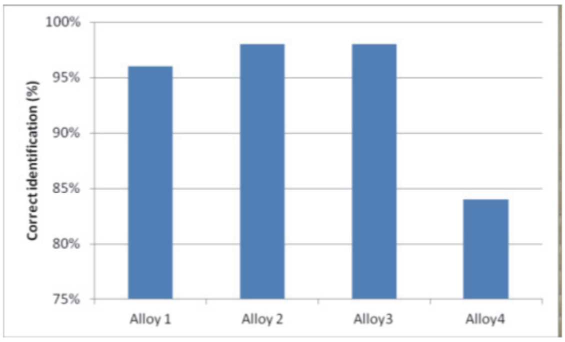

Figure 6. Performance of fully automatic online classification of four different steel grades during the first field tests at Outokumpu Stainless

- Continuous elemental analyses of shredded steel scrap from Stena Recycling have not yet been fully quantified due to lack of ways of calibrating the measurements. However, automated field measurements have been performed and a clear correlation between measured content and actual content seem to be apparent in the latest preliminary results. Automatic evaluation algorithms are currently being developed. The preliminary results of online measurements of manganese during one campaign at Stena Recycling are shown in Figure 7.

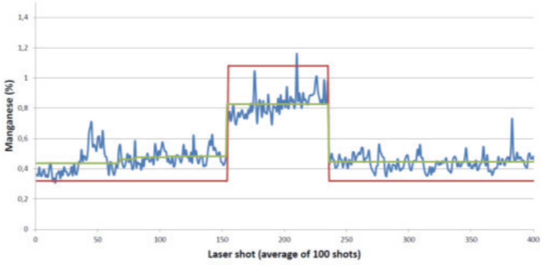

Figure 7. Figure showing manganese content over time during one measurement campaign at Stena Recycling in Hallstahammar, Sweden. The blue line shows the LIBS measured manganese content and the green line the average of the same measurement. The red line shows the manganese content estimated by Stena Recycling with the help of x-ray analysis of random samples.

7. FURTHER UTILIZATION

Field tests have been conducted at Stena Recycling and at Outokumpu Stainless with very promising results regarding analysis and sorting of scrap. Evaluating the results from Stena is not trivial due to the lack of additional measurement results available for comparison. Without the possibility to calibrate against measurements performed with a complimentary technique, quantifying the quality of the measurements is difficult. Additional attempts to do this with the help of e.g. x-ray fluorescence analyses are on-going. The research regarding steel scrap recycling with the help of LIBS will continue until 2015 financed by a four year full-time grant awarded to Jonas Gurell by Formas in 2011. In addition, contacts established during conferences and meetings have expressed a strong interest in evaluating the prototype at several private companies such as Harsco Metals, SSAB, SIMS Recycling Solutions, H. J. Hansen etc.

The now available prototype will also be utilized for additional recycling-related research purposes. Two research projects related to LIBS for aluminium analysis and recycling have received funding from VINNOVA and will be performed during the period 2012-2013. Another interesting prospect with this technique is to enable sorting of polymers, e.g. PVC, EPDM, PMMA, PE, etc, currently a hot topic in the scrap industry.

8. DISSEMINATION AND PUBLICATIONS WITHIN THE CURRENT PROJECT

Peer-reviewed scientific publications

1. J. Gurell, A. Bengtson, M. Falkenström, and B.A.M. Hansson, Laser induced breakdown spectroscopy for fast elemental analysis and sorting of metallic scrap pieces using certified reference materials, Spectrochimica Acta B: Atomic spectroscopy, 74-75, pp 46-50 (2012)

Conference publications, non-refereed

1. T. Björk and A. Bengtson, Analytical Aspects of Scrap Sorting With LIBS, Proceedings of the 7th Int. Workshop on Progress in Analytical Chemistry in the Steel and Metal Industries, 16 – 18 May 2006, Luxemburg.
2. T. Björk, Automatisk sortering och kemisk analys av stålskrot i fragmenteringsanläggning, Stål 2007, Borlänge, Sweden.
3. T. Björk, A. Bengtson, Quantitative analysis of steel scrap using LIBS with very few laser pulses, EMSLIBS 2007, Paris, France.
4. J. Gurell, A. Bengtson, M. Falkenström, and B.A.M. Hansson, Development of a laser based system for fast elemental analysis and sorting of metallic scrap pieces, CleanTech 2011, Budapest, Hungary
5. J. Gurell, A. Bengtson, M. Falkenström, and B.A.M. Hansson, Development of a laser based system for fast elemental analysis and sorting of metallic scrap pieces, Conference on laser ablation 2011, Cancun, Mexico
6. J. Gurell, On-line classification of steel scrap using intelligent evaluation from a CCD spectrometer equipped LIBS, Skrotgårdsmetallurgidagarna 2011, Gävle, Sweden
7. J. Gurell, P. Lundin, M. Falkenström, A. Bengtson and B. Noharet, Fast and remote analysis of metals for efficient recycling, SOPO12, Shanghai, China
8. J. Gurell, and A. Bengtson, Online classification of steel scrap using intelligent evaluation from a CCD spectrometer equipped LIBS, Scanmet 2012, Luleå, Sweden
9. J. Gurell, and A. Bengtson, Online classification of steel scrap using intelligent evaluation from a CCD spectrometer equipped LIBS, APWC 2012, Jeju, South Korea
10. J. Gurell, Efficient recycling of scrap using online laser spectroscopy analysis, Skrotgårdsmetallurgidagarna 2012, Hallstahammar, Sweden

Additional publicity

1. Article in Ny Teknik 2011 http://www.nyteknik.se/nyheter/automation/article3100073.ece
2. Article in Gjutaren 2011
3. TV interview in TV4 Vetenskap 2012, http://www.tv4play.se/program/tv4-news?title=vetenskap_3_oktober&video_id=2225712
4. Article in International Innovation, in press November 2012

Awards received

1. H.M. King Carl XVI Gustaf 50 year fund for science, technology and environment (Jonas Gurell, 2011)
2. The Greentech award from the Swedish Association of Graduate Engineers (Jonas Gurell and Arne Bengtson 2011)
3. Invited speaker regarding LIBS to the 2nd annual conference of AnalytiX 2013, Suzhou, China (Jonas Gurell 2012)

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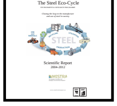
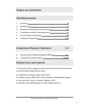
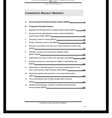
by S.K. Das TMS (The Minerals, Metals & Materials Society), 2003.

[2]. Ü. Aydin, J. Makowe, R. Noll, VDI-Berichte Fast identification of light metal alloys by laser-induced breakdown spectroscopy for material recycling, 1844, (2004) 401-412







RECYCLING OF STEEL IN THE SOCIETY (88013)

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Abstract

For the purpose of understanding and describing the"Recycling of steel in the society" the flows of steel at different stages have been studied in detail. Two different models, the "KTH-model" (Model 1) and "KTH steel scrap model" (Model 2) have been developed for describing the results. The models are Material Flow Analysis (MFA) models with the geographical border of Sweden. The models don't use the conventional cradle to grave concept but a product to product concept which is thought to be more appropriate for a real recirculation situation. Another characteristic of the models is that it is built not only on statistical data on different flows but also uses analyzed data on losses. The Model 1 illustrates the stocks and flows of steel in the society and points out where improvements in recovery can be made. Focuses has also been put on defining different recycling rates and compare them towards each other based on results from Model 2. For example the question of redundant material, losses and average circulation time of steel were answered with these two models.

A study to investigate the alloy content in steel scrap deliveries was also performed in purpose of increasing the yield in the reactor and to decrease the usage of alloy substitutes. For this the development of best praxis for random sampling of alloy content in steel scrap deliveries were evaluated to find a fast and cheap analyzing method compared to test melts. Random sampling could also be used by steel mills as a method to verify the alloy content of steel scrap, narrow the margin of analysis and to be able to purchase cheaper steel scrap with unknown composition.

Incinerator scrap and similar low valued Fe products have been identified as a large single loss area in the MFA and consequent reduction of the recirculation rate. A specific investigation of this area is therefore being performed within the project.

1 INTRODUCTION

Recycling of steel is obviously important for sustainable production of steel. However the availability of iron ore on the earth crust is so good that sustainability question of the raw material is academic.

More critical for a sustainable production and use of steel is the necessary energy use in conjunction with its production. This is especially important because the primary production of steel in the blast furnace route generates considerable CO_2 emissions. There is no doubt that there will be an increasing pressure from political side towards limitations of the CO_2 emission both locally and globally. In spite of promising research programs to reduce specific CO_2-emission for primary steel production, if global steel production will increase it will lead to increased CO_2-emissions.

The expected increased pressure on all CO_2 emitters to reduce emissions will certainly also be valid for European and Swedish steel producers. However there are strong arguments for continued production of steel in the World, in Europe as well as Sweden. Steel is most likely a material that is CO_2-effecient compared to other material choices for most applications. But in order to prove these assumed circumstances rather complicated LCI/LCA has to be made. An important base for such analysis is knowledge of the material flow of steel.

A strong argument for scrap based steel production is the possibilities of circulating steel because it gives lower CO_2 emissions when material is recycled. For steel industry it is of importance to be able to present data on recirculation of steel and also to show how to improve the yield in the reactors.

Due to today's very strong emphasis on the global warming challenge it is natural that it is the main driving force to learn more of the steel recycling. For the steel industry another interest is to assure a good quality of the scrap. It is therefore of importance for the recycling industry and the society to know the recycling rates and how to affect them.

In order to describe the recycling of steel it is relevant to use an appropriate model. The demand on a model is that it can describe the circulation rates in the system, show distribution of losses in the system and yearly stock changes for steel in use and redundant. Instead of the usual cradle to grave perspective the model should start and end with the product.

Academic work on describing and modeling the steel circulation flow has a rather short history. Emphasis has since long been put on improving efficiency in steel production but in the last decades increasing interest have been given to the recycling issues. This is due to an increased interest to find cheap and high quality Fe-units in form of scrap but it is also driven from the environmental challenges.

Pioneer works in the 1990´s have been done at Arcelor led by J.P. Birat [5-6]. Important work with emphasis on the economical and trade side has also been published from J.Aylan et al [7-11]. Lately interesting articles have been presented by Japanese researchers [12-13] . Arcelor and J.P. Birat have continued their pioneer work by leading ULCOS which is a large European program on CO_2 reduction. They have also started a large European research program called SOVAMAT with the aim to investigate different aspects on the value of materials in the society.

JISF, Japan [14] produced a detailed MFA type of steel flow in Japan for the year 2001. Eurofer in Europe [15] has presented a similar one for Europe 2004. The European steel flow according to Eurofer is shown in Figure 1.

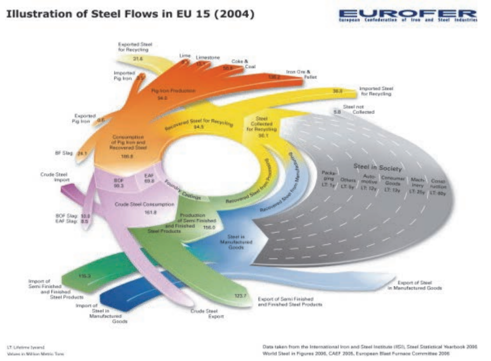


Figure 1 Steel flows in society in EU15 (2004). Source: Eurofer 2007

This presentation contains a lot of information but is limited compared to the MFA models presented in this work. The Eurofer model does not contain analyses of losses or stocks. It can therefore neither be used for describing the important circulation rate nor for describing the yearly change of stock of material in use.

2 OBJECTIVES

The overall objective is to increase the knowledge and establish actual figures of the recycling of steel in the society. The result is planned to be a base for analyzing the influence of economical and technical variables on the degree and appearance of the recycling of steel.

Primary stakeholders are steel industry, recycling industry and production industry for steel containing goods. Other important stakeholders are the state in its role as legislator and the society e.g. environmental lobbyists. A goal is that the work should contribute to an establishment of methods and strategies to direct the scrap usage in the society towards an optimum from a viewpoint of resource conservation and decreased environmental effect.

More specific goals are:

- Create new practical and academic tools to treat information on the recycling of steel.
- Create a necessary foundation for LCI/LCA analysis´ of steel compared to other material choices.
- Description of losses in real figures in the recycling in order to optimize efforts to improve recycling rates.
- Create a model for forecasting future recycling figures and available Fe-units.
- Create a model for forecasting future scrap quality and generation.
- Calculate average circulation time of steel in the society.
- Defining mathematical equations for recycling ratios to standardize ways to calculate the rates.
- Evaluating random sampling of alloy content in steel scrap deliveries to optimize process in reactors.

3 METHODS

3.1 Development of the KTH model (Model1)

3.1.1 The MFA model 1

The MFA (Material Flow Analysis)-model 1 programmed with the MFA-tool STAN is showed in Figure 2. Since the main focus in this project is to describe the steel flows in the society in order to find recoverable losses or other possible hidden sources of scrap, the focus is on steel consumption rather than on steel production and manufacturing of products.

The model treats the different stages in the circulation loop in eight processes starting with the marketing of products and the usage phase. The products eventually become redundant and are collected, upgraded and used as raw material in steel production. Finally the new steel is produced and fabricated and manufactured to new products that are fed to the market. There are import and export flows to/from all processes and three internal recycling flows.

The system border is the steel flow system in Sweden. The base unit is “steel equivalents” meaning the amount of Fe, Cr, Ni, Mn etc. in steel, raw materials or losses, in tonnes.

C and Si are assumed to be 0,02% and 0,2% in steel when necessary. This means that iron making is located outside the system and the hot metal is recalculated to an import flow of steel with this carbon and silicon content.

From all processes a loss flow is defined. The losses are collected in a loss process without a stock and exported from the system.

Three flows are especially important to estimate. The steel content in product export and product import together with the export of steel in used goods is of great importance for the steel balance. Economical data on export and import are available. Main assumptions are therefore based on extrapolated data from known specific data on certain products on steel equivalents in ton per value expressed in US dollars. The error introduced to the model from these estimates are considerably reduced by the fact that import data are almost of the same size as export data and the net has rather small impact in terms of ton.

Accumulation of steel is first of all important in the usage phase and the redundant phase and to some extent in material stocks in the metal working, fabrication and manufacturing phase.

3.1.2 The MFA-tool STAN

STAN is software for Substance Flow Analysis, SFA, developed at the Technical University of Vienna under the supervision of Professor P Brunner. Prof. Brunner was a pioneer in the development of the MFA concept and is today a leading expert in the area,[16]. STAN can model flows of goods together with its components and the system has algorithms for balancing a given system from input data. Calculated data are separated from input data which simplifies maintenance and each flow and process can be documented within the system. The tool is distributed as a freeware.

A special Excel interface is developed for data documentation and calculation to make it possible to use estimated data in STAN.

Another reason for choosing STAN is that it is good enough and free. This means that it is possible to distribute the model to participating parties at low cost.

3.1.3 Data Acquisition

Data acquisition is a critical task since data is initial collected by official institutions for other reasons than to study material flows. Official data available for steel is trade statistics, production data and scrap usage data reported to the EU. Other data has to be collected from the market actors like Jernkontoret [17], importers [18] and JBF [19] or estimated from secondary sources.

The acquisition work encounters two major obstacles:

- Data is not collected by anyone with an interest of a broader use and is therefore not easily acquired
- Data is considered a trade secret and is mostly not shared

The acquisition work is supported by two factors:

- Major companies already produce an environmental report together. Introducing recycling in this report is a logic next step.
- The focus on greenhouse gases increases the demand on companies to show environmental responsibility regarding all activities including recycling of materials.

3.1.4 Losses and recirculation rates and their definitions

Our definition on recovery rate is based on the idea that what is not defined as irrevocable losses is eventually recycled. The recovery rate is therefore defined in percent as 100% minus the irrevocable losses in percent. This definition is valid and useful for each process in the model. The definition is in accordance with the basic principles of the MFA model that material is not possible to destroy within the borders.

The irrevocable losses are defined as steel atoms which are no longer in use, have gone lost and have a higher cost to bring back to the recycling chain compared to the value of scrap at that level.

The data for losses fed into MFA model 1 is based on a mixture on own research, figures and opinions from literature on losses and recycling rates, see fig 2. Ongoing research on losses will hopefully improve the accuracy of the losses data and by that especially improve conclusions from the MFA model 1 on recovery rates.

Each process in the model is built up from input and output figures and the balance between them represents the loss. Important data is also the figure of the loss itself because it can create the balance in a process even if one other input or output figure is missing. This means that the model is able to describe and quantify all paths at each stage with a high degree of accuracy. For the same reason the model can quantify changes in stocks and recovery rates at each stage as well as for the whole circulation.

3.2 Development of the KTH Steel Scrap Model (Model 2)

To obtain a picture of the material flow of iron and steel in Sweden from beginning of iron and steel making until today, a dynamic MFA model called the KTH Steel Scrap Model (Model 2) was developed. The model is a combined mass flow and mass balance model that offsets statistics to calculate external scrap consumption, Swedish scrap, internal scrap and net flow of steel into the Swedish society. By obtaining a continous data set back in time, the potential scrap generation, average life time of steel, different definitions of recycling ratios could be calculated, analyzed and discussed.

External scrap consumption was calculated based on mass balance analysis´ for different years and applied on production figures from 1889-2010 with additional estimations and assumptions. The mass balances were calculated for the following scrap consuming processes; Martin converter, Electric arc furnace, oxygen blowing processes and foundries. Swedish collected steel scrap, internal scrap and net flow of steel into the Swedish society was also calculated and compared to statistically obtained data.

3.3 Recycling ratios and potential scrap generation

Recycling ratios of iron and steel can be defined in many different ways depending on the specific use of the information. The recycling ratio is according to the United Nations environmental programme (UNEP) defined as the proportion of end-of-life scrap that is successfully recycled [20]. This rate is called the End-of-Life recycling rate (EOL-RR) and can also be read as the ratio of collected scrap to potential scrap generation.

However the potential scrap generation is hard to measure due to that steel scrap are not registered until it has been collected, upgraded and obtained an economic value. Moreover the stocking of the redundant phase before collection is hard to measure in the society. Also that it is difficult to measure when a material is no longer in-use anymore. Due to these reasons many studies have been based on mathematical models to investigate forecast values of the potential scrap generation [21-22]. The potential scrap generation can be calculated in different ways and are sensitive to the input data and assumptions in the models.

Thereby it is for great interest to standardize ways to calculate the recycling ratios. New mathematical equations to calculate the recycling rate was investigated and defined. These recycling ratios were further on calculated from different time perspectives; i) apparent recovery rate, ii) average true recycling ratio, iii) total recycling ratio. These ratios have been calculated based on data from the beginning of iron and steelmaking in Sweden in 1889 to 2010 and compared to the EOL-RR.

3.4 Life time of steel in the Swedish society

To be able to calculate the recycling rate, the life time of steel had to be investigated. Based on output data from the KTH steel scrap model (Model 2) the average circulation time of steel was calculated by a new method called volume correlation. By looking at a certain year, the total amount of iron and steel that had entered the society was calculated. Thereafter, the year when the same amount of Swedish collected scrap had been taken out of the society was calculated. The difference in years between the volumes will represent the average circulation time of iron and steel in the Swedish society. This life time of iron and steel can be calculated by assuming a full recovery or by considering losses in the society.

3.5 Random sampling of alloy content in steel scrap

A separate study to investigate the alloy content in steel scrap deliveries was also performed in purpose of increasing the yield in the reactors and to decrease the usage of alloy substitutes. Due to this reason the development of best praxis for random sampling of alloy content in steel scrap deliveries were evaluated to find a fast and cheap analyzing method compared to test melts. Random sampling could also be used by steel mills as a method to verify the alloy content of steel scrap, narrow the margin of analysis and to be able to purchase cheaper steel scrap with unknown composition.

Development of best praxis for random sampling of alloy content in steel scrap was evaluated for two different scrap types, Old steel scrap and Auto bundle scrap in Sweden. Deliveries from different deliverers were chosen to represent the regular consumption at the steel mill. A total amount of 6 deliveries were analyzed.

With the equipment of a benchmark, 2 ropes each ca 30m long, a spray can, rubber bands and cutter, a network of 100 random samples were marked and cut out. The 100 random samples were analyzed in Optical Emission Spectroscopy (OES) for alloy content. Furthermore out of these deliveries 3 melts were created by mixing half Old steel scrap and half Auto bundle scrap, where after steel and slag samples were taken after direct melt and evaluated in OES. Thereafter massbalance calculations were performed.The input data from random samples were compared to output data from steel, slag and dust analysis.

4 RESULTS AND DISCUSSION

4.1 *The different processes*

4.1.1 Process: Market

The results from the KTH model (Model 1) showed that in 2006 products containing 3 940 kton of steel equivalents were put on the market and consumed. Out of this was 503 kton imported. No stock built up was occurring. Export and losses are neglected for this process.

4.1.2 Processes: In use and Redundant

The results from KTH models (Model 1) showed that in the year 2006 stock is obviously increasing with 984 kton which is a remarkable result which will be discussed later on in this report. Stock has been set to 90 mill ton for in use and redundant according to international opinion and experience [23], [24] and [25]. For the moment we don’t have enough facts from our research on the Swedish circulation to be able to establish own produced data on total stock in use. We expect to be able to produce ideas on the size of the stock after finishing ongoing studies on stratified flows.

Calculations of irrevocable losses are 11.0% for in use process and 3.5% for redundant process which makes a total of 556 kton.

The steel content in product export and import has to be further investigated. At present a steel content corresponding to a car is assumed for a number of selected sectors.

4.1.3 Processes: Collecting and Upgrading

In the year 2006 in Sweden 2 300 kton is collected and 2687 kton upgraded. Irrevocable losses in the collecting phase are 80 kton (3.5%) but the flow is increased by the internal secondary circulation from the process fabrication and manufacture by 467 kton. Irrevocable losses from upgrading process are set to 67 kton (2.5%).

From the upgrading process there is a significant country export of 853 kton while other product exports and imports have been neglected.

Stock is unaffected and is set to 10% of the flow for both processes.

4.1.4 Process: Steel production

Incoming scrap flow to steel production process is 1 767 kton while total import of virgin steel equivalents, alloys and country imported processed scrap amounts to 3 872 kton. Irrevocable losses are set to 122 kton (2.0%) while other exports are neglected. Stock is unchanged and estimated to 10% of outgoing flow.

4.1.5 Process: Working

In this process semi-finished steel is physically processed to steel products. Product export is therefore larger and amounts to 4 245 kton while incoming flow from steel production process is 5 925 kton. Finished steel for fabrication and manufacture is 1 018 kton. The yield loss in the process is divided into final irrevocable losses amounting to 177 kton (3.0%) and an internal secondary recycling of steel units back to the steel production process of 467 kton.

4.1.6 Process: Production, (Fabrication and manufacture)

The largest flow in the Production process is product import of 3 585 kton while the local primary flow is 1 018 kton. This process has also a rather large product export of 774 kton which should be compared to a product import of 503 kton..

The yield loss in this process is divided in final irrevocable losses of 92 kton (2.0%) and an internal recycling of estimated 400 kton is recycled to the collecting process.

Stock is set unchanged and estimated to 20% of the flow which means 920 kton.

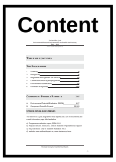
4.2 Steel circulation in Sweden 2006 described in the MFA-model

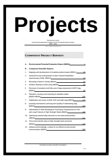
The MFA model is built on the idea that the circulation of steel can be described as an ongoing loop. Eight defined phases followed by each other has formed eight processes in the model. The idea to present the circulation model as a product to product flow works well. It is not only more logic and interesting but also practical because the stratified flows for natural reasons start with the newly marketed product.

Although the circulation loop in the model is congruent and theoretical correct there are some conditions which should be noticed.

The time for stocking in each process is very different. The stock for steel in use and redundant together is kept from month to hundreds of years but typically 10 years to 50 years. All other stocks are turned over in as most a couple of months. This means for example that the irrevocable losses are of a different kind and size for the in use and redundant stocks.

Another incongruence to be noticed is the large import of raw steel over the model boundary. An amount of 3 872





kton is imported compared to 1 767 kton coming from the main flow in form of scrap. To outweigh this import the export of steel products over the geographical border is 4 245 kton. That figure can be compared with the main flow of Swedish steel to fabrication and manufacturing which is 1 018 kton. In order to meet the demand for Swedish produced products with a steel content of 3 337 kton a geographical import of 3 585 kton is necessary. This means that the scrap circulation in terms of tonnage plays a rather small role for Swedish steel production as well as for Swedish fabrication and manufacturing. However the scrap flow is very essential for scrap based steel production in Sweden and for scrap recycling industry. In future the MFA model can be used for analyzing trends in the different flows affecting the mentioned industries.

Already without deeper analysis the model illustrates a number of facts, more or less recognized:

- Sweden accumulates steel in the usage phase.
- The bulk of steel recycled in Sweden is not produced in Sweden and consequently,
- Steel produced in Sweden is recycled else ware.
- Sweden is a net producer of steel.
- Scrap represents a rather small part of the sources of new produced steel in Sweden but is important for the scrap based industry.

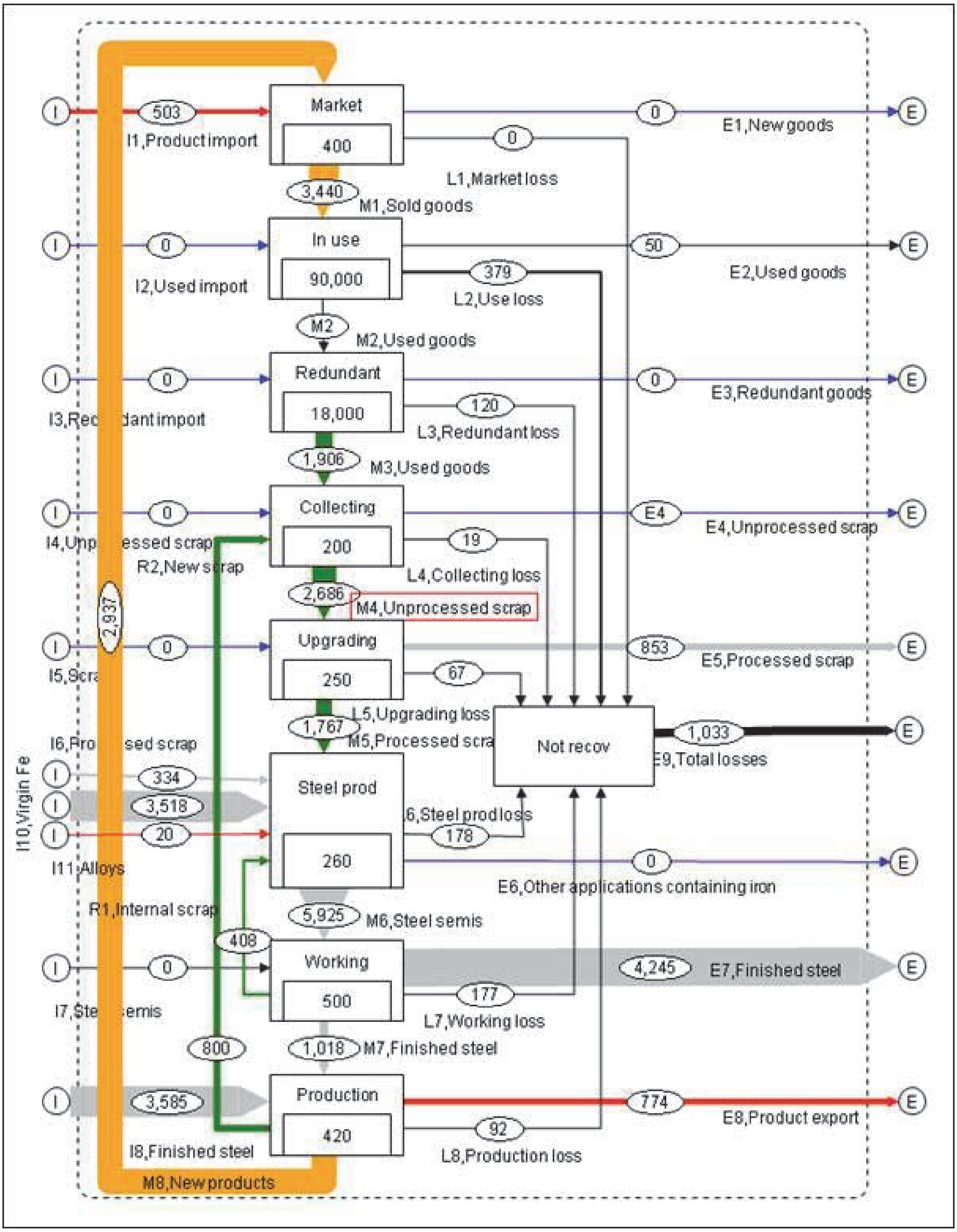


Figure 2 The KTH model for Sweden 2006

4.3 Redundant material

In order to understand the circulation of steel in the society it is important to follow the steel when it goes from being used to not being used any longer. For several reasons it would have been desirable that the material not in use had gone directly further in the chain to the collecting phase. However this is not the case, on contrary a large part of not used material is stocked as redundant material. The importance of this phase in the circulation is so large that we have given this phase an own "process" in the MFA model.

Compared to the other phases or processes in the MFA model, there is very little economical or other type of pressure upon keeping the redundant stock low. This is unsatisfactory because this stock should be kept low to reduce further irrevocable losses, to improve towards a cleaner environment and generally reduce capital employed.

A typical redundant stock is the private stock of not used equipment and other things stored in garages and cellars. The society has here a responsibility to facilitate the collection. Also large sources for redundant material are industrial buildings. Again the society has a possibility to facilitate recycling by reducing legacy which today holds back the demolition work.

The presented model is rather weak in precision due to weak data on the redundant material. It is possible to increase these data by analyzing stratified flows which now is going on.

4.4 Changes in stock for steel in use and redundant

There is an interesting and significant increase of the stocks in use and redundant of total 984 kton for the year 2006. There are no signs that this increase is special for 2006 and we therefore conclude that this increase is similar for the last years. A part of the increase can be explained by the increase of the population. On average the population has increased in Sweden with around 50 000 people per year corresponding to a need to build up a stock of 500 kton. Still there is an increase in stock by 484 kton of steel corresponding to around 0,5% of the stock.

There are several factors leading to increase or decrease of stock of which the most important are:

1. Increase in standard of living which leads to increase of consumption.
2. Increase of redundant material and non-recoverable material are not defined as losses in time.
3. Dematerialization due to better steel performance per weight of steel will decrease demand.
4. Material substitution, steel can be replaced by plastics, paper packages and so on while steel also can replace other materials like concrete etc.

In spite of the increase of the stock we believe that dematerialization is a strong factor but it is counteracted by the increased standard of living and material caught in redundant stock. It is an important task for further research to get more data on the factors controlling the changes in used stock of steel.

4.5 The circulation rates and losses

Improved data from ongoing research on losses will make it possible to draw conclusions on recovery rates and identify areas for improvements of the recycling. First of all it is important to simplify the recycling model shown in figure 2. An attempt is shown in figure 3 where only four processes are used and figures are given per capita.

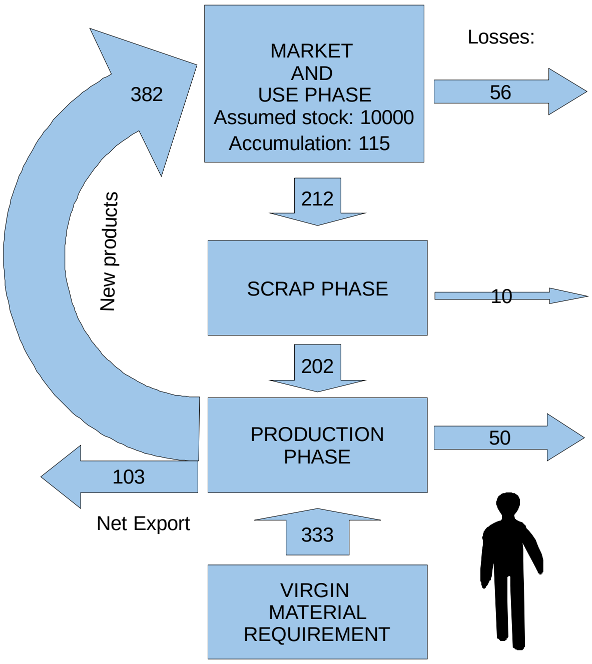


Figure 3 Recycling machine for Sweden 2006 with figures per capita. [26]

When discussing recycling rates it is important to take into account the life times of steel products. The 212 kg of scrap collected represents steel between 100 to 1 years old. It is therefore not directly possible to compare with the 382 kg steel coming into the use phase in 2006.

A simple calculation using data for market shares from a British study [27] gives the result shown in table 1.
The main assumptions are:

- steel consumption the final year is indexed 100
- national steel consumption has increased in average 1, 2 or 3% per year over the period.
- steel content in products are constant over time
- relation between different product types is constant and production is equal to consumption
- life times of products are constant over time

- products enter the scrap phase immediately when the life time is over
- no losses are accounted for

Table 1. The fraction of a years steel consumption that come back from steel produced earlier years for 1, 2 and 3 % assumed market increase. In the table the value for ship is set to 1% though it was 0 in the study.

These data can be compared to the values in figure 3. The scrap flow/consumption ratio is 0.55 and if this value is compared to table 1 it gives a recycling ratio of 74%, 96% and 120% for the year 2006. None of the figures are unrealistic for a single year with high scrap prices. This simplified approach is promising and shall be investigated further.

4.6 Improving the Recycling Machine

When improving a system it is important to understand where you are and being able to point out where to go. This endeavor is in the project encapsulated in the metaphor “Lubricating the Recycling Machine”. Possibilities to improve the system are shown in figure 4.

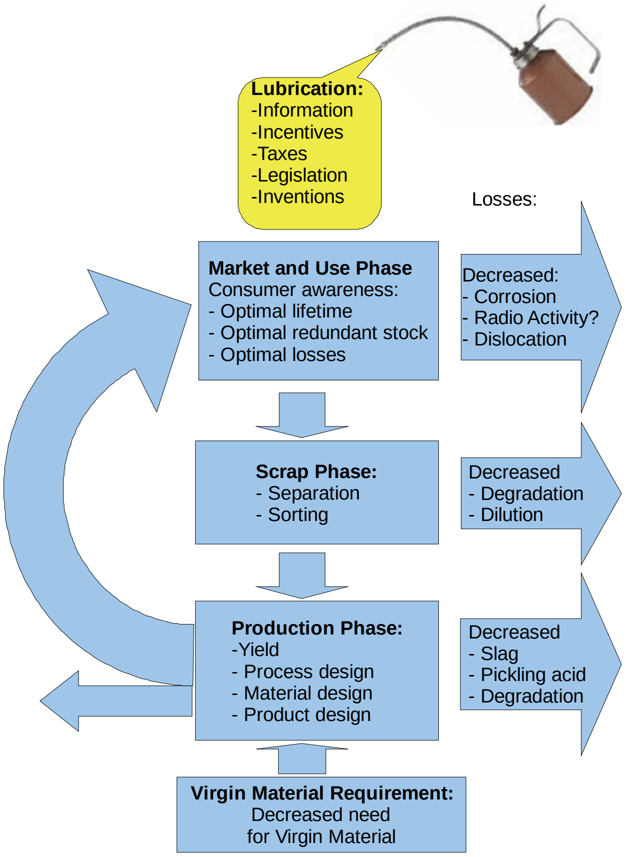


Figure 4 Possible improvements in the Recycling Machine [26]

It remains an important task for the project to quantify the improvement potential and invent ways to make the improvements come true.

4.7 Incinerator scrap

By studying the loss data it was found that some Fe-containing scrap was so low valued that it was at least partly sent as land fill. Assumption is that around 60 000 ton of incinerator scrap and another 60 000 ton of grinding material both with rather high Fe contents are produced yearly in Sweden. It is discussed to use more of these materials in Swedish EAF- furnaces and some trials have been performed.

4.8 The KTH Steel Scrap Model (Model 2)

Results on the output from the KTH steel scrap model (Model 2) were compared to an earlier analysis done by Jernkontoret for the timeline 1980-2009. For the total external scrap consumption in steel mills, the trend correlation coefficient between the KTH steel scrap model and Jernkontoret´s analysis was 0,83 while the area correlation was 0,91. For Swedish scrap arising the trend correlation coefficient was 0,95 and the area correlation was 0,91.The result shows that mass balance and mass flow calculations is area wise well correlating to consumption figures based on trade statistics. The difference in trend is assumed to be mainly due to stocking effect. Deviations are also assumed to be due to uncertainties in estimating internal scrap arising by process type and Fe bearing substitutes over time. Overall conclusion is therefore that mass balance and mass flow models could be used as a tool to calculate apparent scrap consumption based on crude steel production figures by process type. The KTH Steel Scrap Model was shown to be a good model to offset statistics prior to use them as important indicators

4.9 Life time of steel in the Swedish society

Based on results from the KTH steel scrap model (Model 2) the average circulation time of iron and steel in the society from 1900-1972 was calculated to 27 years and 22 years, assuming full recovery and losses of 17% in the society. The variance in the average life time of steel was for the same timeline calculated to 25 and 20 years respectively. Table 1 shows the average circulation time of iron and steel from 1900-1970 with the assumption of full recovery and 17% losses in the society.

Life time	Life time

unit: years	17% losses	Full recovery
1970	28	36
1965	20	29
1960	15	21
1955	15	18
1950	16	20
1945	19	21
1940	20	23
1935	21	25
1930	23	26
1925	24	28
1920	26	31
1915	27	30
1910	26	30
1905	23	27
1900	17	22

Table 1. Average circulation time of iron and steel in Sweden 1900-1970

4.10 Recycling ratios and potential scrap generation

The recycling ratio in this study was defined as the amount of collected steel scrap to the iron and steel consumption. The recycling ratio was further on defined from different time perspectives; i) apparent recovery ratio, ii) average true recycling ratio, iii) total recycling ratio;

$\mathrm{f(x)} =$ Collected scrap
$\mathrm{g(x)} =$ Iron & steel consumption
$\mathrm{h(x)} =$ Losses
$\mathrm{i(x)} =$ In use
$\mathrm{j(x)} =$ Redundant

$$\varepsilon_{(\mathrm{Apparent})} = \frac{f(x_1)}{g(x_1)} \qquad (1)$$

$x_1 =$ Year

$$\varepsilon_{(\mathrm{Average\ true})} = \frac{(x_3 - x_2) \times f(x_1)}{\int_{x_2}^{x_3} g(x)dx} \qquad (2)$$

$x_1 =$ Year, $x_2 =$ Year − Life time − var(Life time),
$x_3 =$ Year − Life time + var(Life time)

$$\varepsilon_{(\mathrm{Total})} = \frac{\int_0^x f(x)dx}{\int_0^x g(x)dx - \int_0^x i(x)dx} \qquad (3)$$

$$\int_0^x i(x)dx = \int_0^x g(x)dx - \int_0^x f(x) + h(x) + j(x)dx$$

$$\varepsilon_{(\mathrm{Total})} = \frac{\int_0^x f(x)dx}{\int_0^x f(x)+h(x)+j(x)dx}$$

The apparent recovery ratio in Sweden was calculated to 66% in 2010. The apparent recovery ratio can be intepreted as the recycling ratio for materials and products with a short life time of 1 year. Since steel has a long life time of average 26 years, the redundant phase has to be considered. The average true recycling ratio was calculated to 69% in 2010. Furthermore the Average true recycling ratio was calculated back in time and compared to the EOL-RR, see Figure 5. The results shows that the average true recycling ratio can be intepreted as the EOL-RR since it consideres the redundant phase in the society.

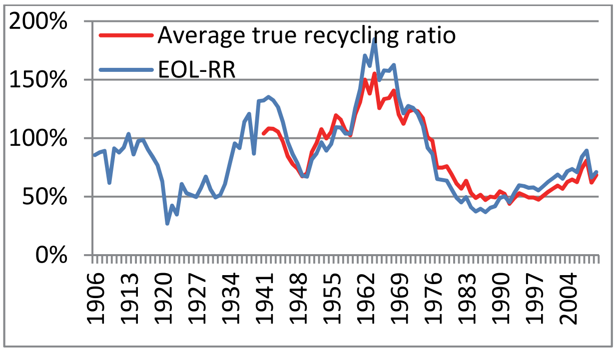


Figure 5 Comparison of EOL-RR and Average true recycling ratio

Furthermore the Total recycling ratio was calculated to 71% in 2010. The Total recycling ratio is a steady ratio that could be used to compare recycleability of different materials in the society.

By defining the recycling ratios by mathematical equations, it would be possible to standardize the way of calculating them. Also by avoiding input data of analysis, it would be possible to calculate the ratios based on data on circulation time of steel.

Further on the potential scrap generation in Sweden was calculated with the assumption of 17% losses in the society, shown in Figure 6. The results indicates that the potential scrap generation will stabilize around 3000kt the coming 10 years from 2010.

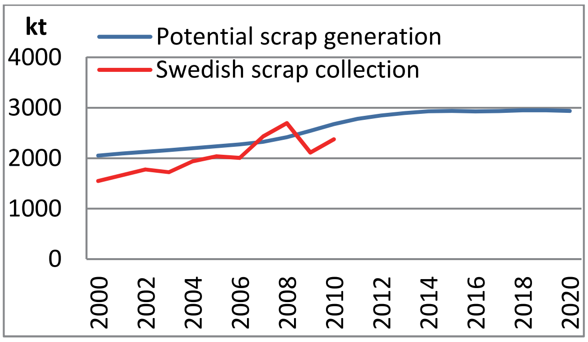


Figure 6 Swedish scrap collection and potential scrap generation with 17% losses

4.11 Random sampling of steel scrap

Results from the random sampling of alloy content in steel scrap deliveries showed that both scrap classes of Auto bundle and Old steel scrap fulfilled the requirements of alloy content according to the Swedish Scrapbook. The results also showed that Old scrap had a higher variance in analysis compared to the Auto bundle scrap. Furthermore separate analyzing methods for evaluating the Zn content had to be performed due to sample preparation before OES analysis and was shown to be approximately 3,1% in existing Auto bundle scrap.

The random sampling was accurate or close in analysis to the steel, slag and gas analysis for the following elements; Mn, P, Cr, Ni, Ti, Co, Nb, Sn and Fe.

The overall conclusion from the results shows that random sampling of steel scrap seems to be a good method to analyze alloy content in Auto bundle and Old scrap deliveries. Furthermore random sampling could be a good method to evaluate alloy content in scrap deliveries with unknown alloy content, whereby expensive test melts could be replaced. Also random sampling could be used to verify the composition of steel scrap deliveries and narrow the margin of analysis to optimize the process in the reactors.

Based on data on limestone-, flux-additions and composition and amount of slag withdrawal, the annual losses of Fe atoms to landfilling were estimated for an annual production of 99 heats. The annual losses of Fe atoms were calculated to 192 ton. With the assumption of Fe price of 3 SEK/kg, this corresponds to approximately 577 205 SEK per year which is lost in landfilling. This is a large loss both from an environmental as well as economical point of view and a great potential in savings.

4.12 Scrap charge model RAWMATMIX

Within this project a model for prediction of the cheapest mix of scrap for steel production with as low energy consumption as possible was made. The model also include calculation for the carbon footprint of the material. The model have been used for education and thesis work at KTH. It is now valible at www.rawmatmix.com. In figure 7 an example from RAWMATMIX is shown.

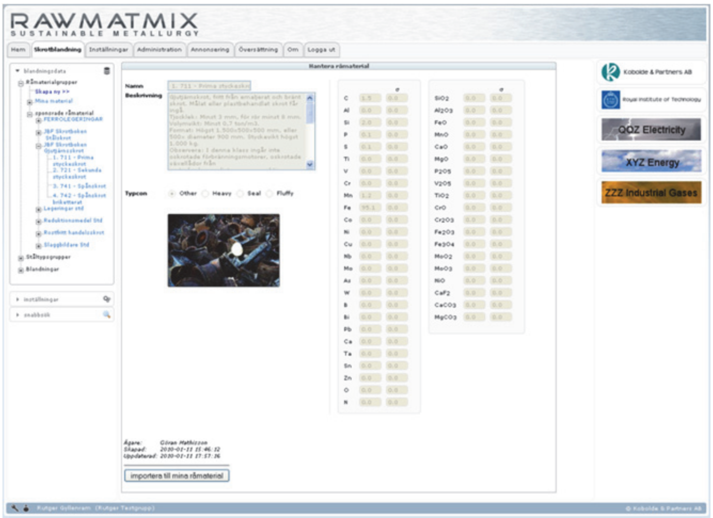


Figure 7. An example from the model RAWMATMIX

5 CONCLUSIONS

Two different MFA models were created to describe the circulation of steel in Sweden. Some of the conclusions from these works are:

- The critical data acquisition has been successfully performed by using good statistical data and excellent personal contacts within industry.
- Together with the technique to use researched data for irrevocable losses the model is able to describe and quantify all circulation paths and other paths, as well as changes in stocks and recycling rates.
- The KTH model can in future, as planned, be a base for analyses of the influence of economical and technical variables on the degree and extent of the recycling of steel in the society.
- In future implementation calculations can be carried out for several scenarios application both for Fe-balances and for balances including Ni and Cr.
- The model results are expected to have a high precision after validation and adjustment and are also expected to be widely accepted. The results can be successfully implemented in Swedish steel companies.
- Model results can be used to initiate, allocate and support work for decrease irrevocable losses and increase recirculation
- A scientifically based theoretical model of losses and recycling rates for stratified flows has been developed.

- An extensive amounts of plant trials have been carried out to determine the incoming composition of scrap
- Mass balance and mass flow models is a good method to offset statistics prior to use them as important indicators in the society and industry.
- Volume correlation between the steel consumption and collected scrap gave an average circulation time of 27 years with assumption of full recovery.
- New definitions of mathematical equations for recycling ratios were introduced as a suggestion of standardizing a way of calculating the ratios.
- Random sampling of alloy content in steel scrap was shown to be a competitive method of evaluating the alloy content in steel scrap deliveries at the steel mills compared to expensive test melts.
- Continue to develop and use RAWMATMIX on order to minimize the energy consumption and carbon footprint during scrap steel production.

6 FURTHER UTILLISATION

To continue this research and use of the new knowledge from this research program, following is suggested to be done:

- Continue to integrate the concept “Scrap yard metallurgy”. This is done both in the education at KTH as well as between researcher and industry during the annual seminars “skrotgårdsmetallurgidagarna”

- Development and use of the KTH-models. Both as a research tool but also as an information tool for practical use.

- Continued development of random sampling. This in order to have a better selection and analytical prediction of scrap content at the steel plants.

- Use of RAWMATMIX, also here use the model as a research tool and in education at KTH.

7 DISSEMINATION AND PUBLICATIONS WITHIN THE CURRENT PROJECT

The research team has given a couple of presentations for the sake of dissemination but also to get some feedback. The presentations are shown below followed by a list of reports and publications in progress:

1. Stålcirklationen, Sven Ekerot, Ståldagarna maj 2005 Borlänge[1]
2. Vad driver stålåtervinningen, Sven Ekerot, Svenskt Avfall, Årsmöte okt 06
3. Skrotflöden, Rutger Gyllenram, Metallurgmötet dec 2006
4. Stålets nio liv, Rutger Gyllenram, Ståldagarna maj 2007 Borlänge [2]
5. Hållbarheten hos världens stålprod., Sven Ekerot Ståldagarna maj 2007 Borlänge [3]
6. Lubrication the steel recycling machine, Rutger Gyllenram, Sam 1 Sovamat Sevilla, mars 2007 [4]
7. Framtida stålflöden, Rutger Gyllenram-Sven Ekerot, JBF90 maj 2007
8. Stålcirkulationen, Rutger Gyllenram, Stålbyggnadsdagarna sept 2007
9. Lubrication the steel recycling machine 2, Rutger Gyllenram, Sven Ekerot, Pär Jönsson Sam 2 Sovamat Nantes, may 2008 [23]
10. Lubricating the recycling machine 3, Rutger Gyllenram, Sven ekerot and Pär Jönsson, at SAM3,april 2009.
11. Presentation on the Stålbyggnadsinstitutets “Steel construction prize”, ”Stålets miljöegenskaper”, Rutger Gyllenram, May 2009.
12. Norska Stålförbundet, Rutger Gyllenram, Oslo Oct. 2009.
13. Vad kan vi lära av stålkretsloppet, Pär Jönsson, återvinningsdagen, Stockholm Nov 2010
14. KTH Steel Scrap Model – defining different recycling rates and calculating average circulation time of iron and steel in the Swedish society, Alicia Gauffin, Anders Tilliander, Pär Jönsson, SCANMET IV, 10 June 2012, Luleå Sweden
15. KTH Steel Scrap Model – iron and steel flow in the Swedish society 1889-2010, Alicia Gauffin, Sven Ekerot, Anders Tilliander, Pär Jönsson, MOLTEN12, 31 May 2012, Beijing, China
16. KTH Steel Scrap Model – iron and steel flow in the Swedish society 1889-2010, Alicia Gauffin, Sven Ekerot, Anders Tilliander, Pär Jönsson, Journal for manufacturing science and production, 2012, Under review at the moment

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[3] Sven Ekerot ”Hållbarheten hos världens stålproduktion och –konsumtion” Stål2007, Jernkontoret Borlänge maj 2007,s5
[4] Rutger Gyllenram, ” Lubrication the steel recycling machine” Sam 1 SOVAMAT Sevilla, mars 2007

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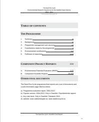

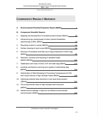

SURFACE CLEANING OF STEEL SCRAP (88020)

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Abstract

This paper describes the work carried out within the project 88020, “Surface cleaning of steel scrap”. The goal of the project was to develop a process for simultaneously preheating of scrap and removing surface coatings. The work has been conducted at Swerea MEFOS Swerea Swecast and SSAB EMEA funded by the “Steel Eco-Cycle” program. The project has been carried out in close cooperation with a steering committee of representatives from the industry.

The project idea was to evaporate impurities (organic coatings and Zn coatings) in a gas phase for treatment in small and effective filters. Chlorine has been shown to be an effective reagent to remove zinc as $ZnCl_2$. The zinc removal in small scale experiments has been as high as 99% at preheating temperatures of 700 ºC. A large scale pilot plant for the suggested concept have been designed, erected and taken into operation successfully. High zinc removal efficiency has been indicated from the pilot trials.

In this project a new innovative process concept, developed based on experimental work and pilot tests was presented and discussed.

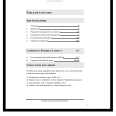
Key words: Steel scrap, scrap cleaning, surface cleaning, zinc removal, zinc recovery scrap preheating

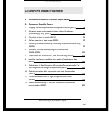
1. INTRODUCTION

In order to increase the corrosion resistance of steel, a surface coating is often applied. The share of coated steel produced today is globally increasing, resulting in an increasing amount of re-circulated scrap with different types of coatings. Therefore, the scrap used in steel making tends to be a more complex material with increased amounts of organic and zinc contaminants. In conventional scrap melting processes (steel converters or EAF’s), these impurities evaporate and leave the system with the off gas or the filter dust. This is not environmentally acceptable, since it results in problematic landfills or harmful air emissions. Recirculation of the electrostatic filter dust and briquetting of dust are today commonly used practices to handle the problems of zinc. By dust recirculation, it is possible to accumulate the Zn content to concentrations attractive for zinc recovery.

The costs for energy and anticipated effects on how emissions of anthropogenic greenhouse gases from human activities are affecting the climate are today important factors steering the development of the metallurgical processes. It is well known that an effective means of decreasing the global emission of greenhouse gases is the increased use of scrap in steelmaking. Thus, a desirable development should strive towards widening the scrap base together with the development of a more effective scrap melting process. However, with the increased use of scrap, more undesirable chemical elements and compounds follow, which can result in disturbances in product quality, to the process or emissions of harmful substances to the environment. Hence, the development of a method to remove coatings prior to melting is of great importance.

In the literature there are several methods described to remove coatings from the surface of scrap. These can be divided into two main principles: leaching and thermal treatment. Research regarding leaching based on acid solutions (HCl, H_2SO_4) and basic solutions (NaOH) are covered in the literature [1,2,3,4,5]. When removing zinc by basic leaching, Zn is transferred to Zn^+ and recovered either in the form of sodium zincates (Na_2ZnO_2 or $NaHZnO_2$) from a saturated solution or electrolysis. In Acid leaching, zinc is recovered via a saline solution ($(Zn(NO_3)_2$, $ZnSO_4$, or $ZnCl_2$). Both methods have advantages and disadvantages. Basic leaching is a selective process and does not affect





the iron, but is a time-consuming process, while acid leaching is less selective but much faster. A key factor in effective leaching is the area contact between the solution and the steel scrap. The zinc rinsing is much faster for shredded scrap than for bundles. In an article by Niedringshaus et al.[2], a basic leaching process with electrolysis recovery of zinc is described. The zinc removal degree was high, > 90 %, with a treatment time of 6h. The formation of cyanide was indicated as one possible problem with the recovery of zinc by electrolysis. One commercialised process (the Meretec process [6]) based on this concept is in operation. The process is continuous and produces scrap suitable for foundries. The concept appears to be competitive and fully functional*.

Several studies can be found regarding the thermal treatment of scrap. In an article by Dapper et al.[7] the possibility to evaporate Zn, Ni, Cr, and Sn from coated materials using chlorine was examined. In a phase diagram, it was shown that e.g. $ZnCl_2$ was more stable than $FeCl_2$. Furthermore the $ZnCl_2$ was more volatile. The vapour pressure up to 670ºC was close to zero, which will result in suppressed formation of $FeCl_2$ as long as there is metallic Zn present. Chlorinated rinsing of non-iron oxides and metals using HCl from the combustion of PVC was further addressed by Fray [8]. Further studies by Tee and Fray [9,10,11] have been concentrated on the possibility to vaporise coatings with an air and chlorine gas mixture. They indicated that it is of great importance to control the O_2:Cl_2 ratio in the gas mixture. A 10:1 ratio is found to be sufficient in order to suppress iron losses.

Zn vaporisation in CO/CO_2 and N_2 gas mixtures is very rapid at temperatures higher than 950ºC. Ozturk and Fruehan[12] showed that almost all Zn is vaporised in a close temperature interval after 850ºC and that the rate of vaporisation decreased at lower temperatures. In an article by Granström et al.[13], the pros and cons of combined scrap preheating and the surface removal of organic compounds and Hg is discussed. The concept is a stand-alone process resulting in high flexibility and operability. Increased productivity, cleaned scrap and decreased emissions are advantages described.

Vacuum treatment has also been tested for removing coatings. In an article by Okada et al.[14], a method to clean scrap by heating and vacuum treatment was suggested for a temperature interval of 700 – 900ºC. The method showed high removal efficiency already at 700ºC compared to preheating with CO/CO_2 gas mixtures. An almost 97% zinc recovery was achieved.

Several suggestions and solutions for surface cleaning and the removal of zinc coatings have been presented. Most commercial solutions are found based on the leaching concept for shredded scrap. Only a few articles based on high temperature cleaning have been found. The advantage with a thermal process is mainly that the reaction time is much faster than for leaching processes. Some solutions are based on the chlorinated rinsing of galvanized steel scrap. However, no industrial applications have been reached. For an industrial scale application, it is of great importance to control the corrosion of the steel construction by careful design and by control of the O_2:Cl_2 ratio. It is furthermore important to find effective methods for recovering zinc from the dust as well as for handling hazardous emissions (e.g. dioxins) in the gas cleaning.

A great possibility for energy saving and to improve the energy efficiency of the scrap melting process is to preheat the material prior to melting. With preheating it is also possible remove a large number of chemical components from the scrap. Studies on combined surface cleaning and scrap preheating have not been found reported in the literature. This makes the concept to an emerging project including studies both from an environmental and economic point of view.

In this project an experimental study as well as pilot tests of a new innovative process for the simultaneous surface cleaning and preheating of scrap with chlorinated gas to be melted in the EAF or converter has been performed.

2. OBJECTIVES

This paper descries the method based on simultaneous surface cleaning and preheating of scrap for further use in the steel or foundry sector developed within the project. The method has

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* In July 31 2008, driven by the technology developed to removes zinc from scrap galvanised steel, the CMA corp. Ltd. acquired the Meretec Ltd,

primarily been developed for shredded scrap. The main goals are:

- Design of a new innovative technique for simultaneous preheating and surface cleaning,
- Reduced energy use by utilising energy-containing waste or by-product gases as fuel in preheating and surface cleaning

The industrial and environmental goals are:

- Reduced environmental load from dust and gas emissions,
- Reduced primary energy use (electricity or coke)
- Improved scrap utilisation and improved quality of scrap,
- Minimised risk of explosions causing personnel and mechanical damage due to snow and ice free scrap,
- Simplified recycling of internal dust and sludge (free from Zn), decreasing the amount sent to landfill.

3. METHODS

The work has been divided into both fundamental experimental studies regarding the mechanisms of the surface cleaning of scrap and into pilot trials of the proposed method with subsequent melting in an induction furnace and LD converter. The purpose of the pilot trials was two-fold: firstly to test the concept on large scale; secondly to measure the impact on emissions from having cleaner scrap in a scrap melting process.

Small scale testing as well as pilot testing of scrap preheating and surface cleaning was conducted by Swerea MEFOS. Melting tests of treated material was conducted by Swerea SweCast.

Industrial companies have actively participated through a reference group that discussed the results and the development of the proposed concept.

3.1 Small scale studies

An experimental furnace has been used for the small-scale fundamental tests. The principal of the setup is shown in Fig 1 and Fig 2. The test rig consists of a gas mixing station, a pebble shaft (filled with Al_2O_3 ceramic balls) and two different top sections, one with a burner for heating the pebble shaft and one for material testing.

The heating of the pebble shaft is achieved by directing the gases from the burner downwards through the shaft. When the pebble shaft has been loaded with energy, the section for material testing replaces the burner section. The gas mixture is heated in the hot pebbles shaft passing upwards. The gas is then led through the top section containing the test material. The gas mix is sampled before and after passing the test material. The composition is determined by a mass spectrometer, an AirSense 2000.

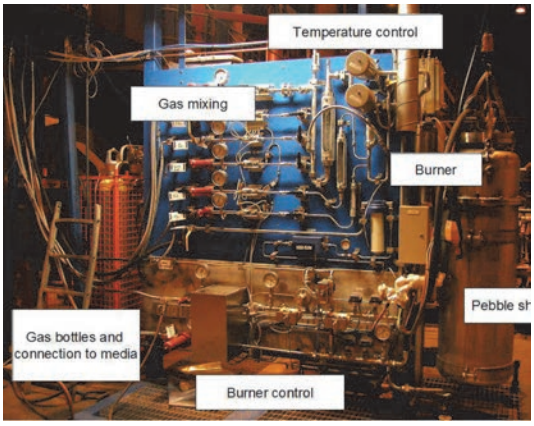


Fig. 1 - Gas mixing station with burner top

The inlet gas temperature before passing the sample can be controlled by distributing gas through the hot pebbles shaft or through a cold by-pass to the top section, Fig 2.

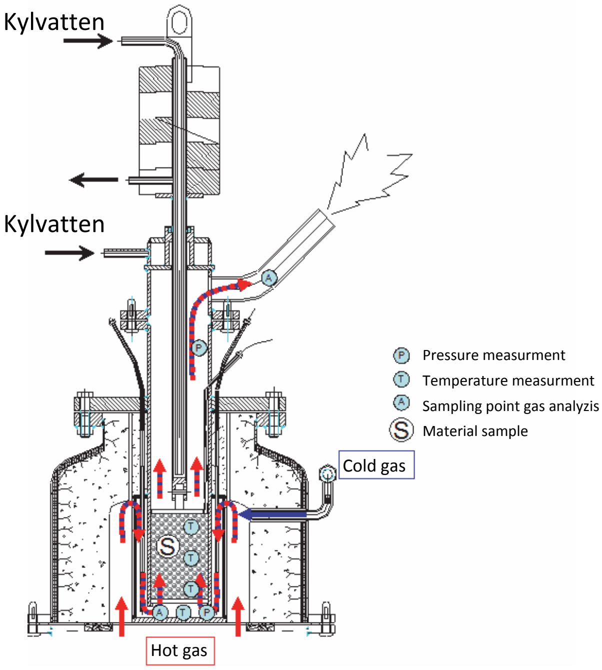


Fig. 2 - Material testing top

The gas for heating can be a mix of gases. The gas grades and designed flow-rate ranges are:

N_2	30 – 1500 ln/min
O_2	4,9 – 245 ln/min
Air	5 – 250 ln/min
CO_2	5 – 250 ln/min
$H_2O_{(l)}$	0,004 – 0,2 kg/min
CO	5 – 250 ln/min
H_2	5 – 250 ln/min
Cl_2	1-20 ln/min

Water for moisture formation is partly vaporised before entering the pebble shaft. For safety reasons, CO and H_2 can selectively be led without passing through the shaft.

3.1.1 Test material

In each experiment, six different steel qualities and three pieces of each material were tested. The different qualities tested, Table 1, were cut and twisted into small 20*60 mm pieces. One of the materials was free from all types of coating.

Table 1 - Test materials (SSAB strip steel qualities)

Steel quality	zinc coating, g/m2
HDG Z275	275
HDG B500	275
Nova	275
DOCOL	0
Plastisol	275
Polyester	275

Approximately 1 kg steel scrap was charged into the material testing top together with the test materials. Ceramic Al_2O_3 balls are charged in the bottom of the material holder to ensure a reasonable gas distribution. The purpose of the "bulk steel" is to imitate a real industrial application where the Zn-containing scrap is in a steel environment. On top of the material surface, a 30 kg stamp is applied, corresponding to a pressure of 3.4 ton/m^2 or a shaft height of 2-4 m, which is a normal height of a scrap basket. The level of the stamp was recorded during the preheating sequence, indicating softening in the materials.

3.1.2 Dust emissions

A partial flow of exhaust gas was passed through a dust collector, paper filter. The filter was analysed to determine the dust emissions from the test.

3.2 Pilot tests

It is expected that the economy of an industrial application is strongly depending on a low amount of vent gas caused by demands for advanced downstream filters. In the development it was thus fundamental to test technical solutions for recycling of flue gas.

The downscaling to pilot setup was made with a priority to maintain a realistic heat load on the cross section surface of the shaft and to have a full height. By keeping these dimensions it was possible to operate the pilot close to the expected industrial working points for heating rates, temperatures, specific gas volumes, compositions etc.

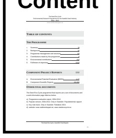
3.2.1 Scrap treatment Pilot, 1st generation

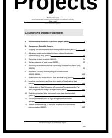
A pilot test facility has been set up to test the surface cleaning/preheating shaft in large scale, Fig 3. The unit is a ceramic lined shaft with a height of 3400 mm and a diameter of 1090 mm. Energy is supplied to the shaft by a top-placed combustion chamber. The hot gases from the combustion are led through the charged scrap burden and exhaust by suction through a side mounted exhaust pipe in the bottom of the shaft. After a finished trial, the scrap was cooled with nitrogen, and the scrap was discharged through the bottom of the shaft.

A large variety of measurements are collected in the pilot plant (temperatures, pressures, gas flows). A standard process computer equipped with National Instruments software platform Lab View was used for control and data logging of this information.

3.2.1.1 Measurement

Temperature measurement was carried out at different levels of the shaft as indicated in Fig 3. In each level two mantled thermocouples are placed. The temperature measurements give an indication of the temperature profile propagation in the shaft.





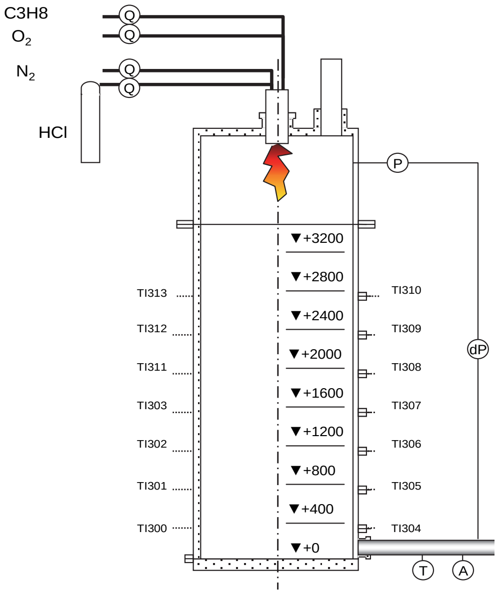


Fig. 3 – Pilot shaft setup

The hot gas was analysed before and after passing through the scrap. The exhaust gas was continuously analysed for:

CO	0-20%
CO_2	0-15%
H_2	0-10%
O_2	0-30%

The pressure in the flame chamber and the pressure difference over the charge was measured, indicating a change in permeability of the scrap.

3.2.1.2 Scale formation

Preheating of scrap was performed at conditions that might promote high metal losses, i.e. high temperatures and a gas of relatively high oxygen potential. Preheating with a chlorine-rich gas might promote even higher metallic losses, unless the O_2:Cl_2 ratio is controlled.

The degree of steel losses due to scale formation can be of fundamental economical importance and a method to determine the losses g/m2 was developed. The selected method was based on weight loss of rinsed thermocouple steel mantle (Ø12 mm) before and after each test.

3.2.1.3 Test material, scrap

The scrap used in the tests was commercial shredded scrap supplied from Stena Metal Group in Hallstahammar, Sweden. The scrap was typically a 100 mm steel piece with 1-10 mm in thickness, as shown in Fig 4. The bulk density for this scrap was ~600 kg/m^3.

Fig. 4 – Shredded scrap used in the experiment. The picture shows surface-cleaned scrap.

3.2.1.4 Test procedure

The scrap was charged into the shaft with a tractor. Scrap was filled to the first level of the thermocouples (+400 mm) after which the conduits for the level are mounted. This operation was repeated for each thermocouple level until the shaft was filled, +3200 mm. At two levels, 400 mm and 1300 mm, steel baskets with material for melting tests were charged. At other positions also smaller test baskets were charged. These baskets held the same material as used in the small scale studies.

The preheating cycle was approximately 60 min. During the experiment, HCl gas was manually regulated to simulate ASR combustion, e.g. the HCl concentration in the preheating gas. The other media, N_2 and O_2, were regulated through the control system. After a completed test, the scrap was cooled with a low flow of nitrogen. When the scrap was cooled the shaft was emptied.

3.2.2 Scrap treatment pilot, 2nd generation

The pilot plant was redesigned to operate in continuous mode with shredded scrap and to work together with a dedicated off-gas treatment system, capturing the ZnCl product for subsequent zinc recovery. A separate combustion reactor was used to simulate combustion of chlorine rich energy containing waste.

The design includes basic engineering and process strategies. The following design criteria were judged as critical:

- Continuous operation for high throughput enabling processing of scrap for industrial tests,
- Handling of the exhaust gases recycling,

- Safe handling of scrap, both charging and emptying of scrap from the shaft,
- Safe handling of all gas streams (Heating gas, off-gas, recycled gas and bleed-off gas),
- Safe handling and addition of HCl liquid.

3.2.2.1 Zn recovery Gas scrubber

The objective for the gas treatment plant is to cool down the gas to below 70 °C and to wash out $ZnCl_2$, particulates and acid gases to a caustic water solution. Cooling is made directly at the gas entrance by high pressure water spraying. After cooling, the gas is led through a packed bed tower scrubber. The formed $ZnCl_2$ solution and sludge are stored in a tank at the bottom of the scrubber.

Depending on the cleaning efficiency some excess of HCl might be present the gas and has to be neutralized by mean of an alkali, such as NaOH.

$$HCl + NaOH \Leftrightarrow NaCl + H_2O \qquad 1$$

The off-gas is fed to the scrubber where it is contacted with a solution continuously added with NaOH to keep the pH slightly acidic but around the neutrality. In this solution the HCl is neutralized according to the reactions 1 while metal, that can be in form of oxides and/or chlorides, are complexed and taken in solution according to the general reactions 2 and 3.

$$MeCl_x + yNaCl \Leftrightarrow Na_yMeCl_{(x+y)} \qquad 2$$

$$Me_2O_x + 2xHCl + 2yNaCl \Leftrightarrow 2Na_yMeCl_{(x+y)} + xH_2O \qquad 3$$

The metals to be found in this gas phase are supposed to be Zn, Pb, Cu, Fe and sometimes some traces of Ag. The scrubber fluid was analysed with respect to Zn concentration.

3.2.2.2 Measurement

Temperature measurements were carried out at different levels of the shaft, gas entering the preheating shaft and exhaust gas temperature.

The gas was analysed before and after passing through the scrap. The exhaust gas was continuously analysed for:

CO	0-20%
CO_2	0-15%
H_2	0-10%
O_2	0-30%

The pressure in the flame chamber and the pressure difference over the charge was measured.

The concentration of the caustic solution was monitored by a pH measurement. One batch of liquor has capacity for several scrap treatments.

3.2.2.3 Test material, scrap

To control the zinc amount in the charged scrap synthetic shredded scrap were produced. Three lots of shredded scrap were prepared at the STENA site in Hallstahammar. The scrap lots were defined by origin:

- SSAB galvanized steel coils 26ton (known zinc load)
- SSAB uncoated sheets 66ton
- Mix of galvanized road fence and galvanized SSAB sheets, 31ton

- The separate shredded grades allows for a controlled charge of zinc to individual tests.

3.3 Melting tests

Two different types of melting tests have been performed. Melting in induction furnace at Swerea SWECAST and industrial melting at SSAB EMEA in the LD converters.

3.2.1 Inductive melting tests

A 100 kW induction furnace was used in the melting test. During the melting cycle the exhaust gas was collected in a hood. A measuring probe was used to analyse the exhaust gas with regards to dust and zinc gas. The collected dust was further analysed for metals.

For each trial the material from the large material baskets are used. Totally eight material baskets were melted. Each basket contains 100-140 kg material.

3.3.2 Industrial Melting trials

Two industrial melting trials were conducted in the LD converters at SSAB EMEA Luleå works.

Campaign 1: Totally four trials were conducted where treated and untreated shredded scrap was included in the scrap mix and two reference heats. The amount of shredded scrap used in the trials was 5 ton. Measurement of the total generated dust amount and analysis of the generated dust was analysed.

Campaign 2: Totally 6 heats were followed measuring the present zinc load in normal operation practise and scrap mixes.

Additionally trials with treated and untreated scrap are pending.

4. RESULTS AND DISCUSSION

4.1 Small scale tests

In total, 17 small scale tests, with different gas mixtures, final temperatures and gas flows were conducted Table 2.

Table 2 – Experimental setup for surface cleaning and preheating tests

No	Temp ºC	flow nl/min	N2 %	O2 %	CO2 %	CO %	H2 %	H2O %	HCl %	Cl2 %
1	700	500	99							1
2	700	500	78	21						1
3	700	500	100							
4	700	500	79	21						
5	700	500	89	10						1
6	700	400	75		5	10	6	4		
7	700	400	75		5	10	6	4		
8	700	500	79	10	6			4		1
9	700	500	87	2	6			4		1
10	700	500	80			12	8			
11	700	500	79	10	6			4		1
12	700	500	69	20	6			4		1
13	350	500	79	21						
14	350	500	78	21						1
15	500	500	78	21						1
16	700	500	77	21					2	
17	500	500	77	21					2	

During the tests the gas temperature were increased according to a standard temperature profile simulating a full scale process, Fig 5. Tests 6-7 were made with a smaller gas flow rate than the other experiments. In tests 13 – 17 the effect of final temperature and HCl as a chlorine source were analysed.

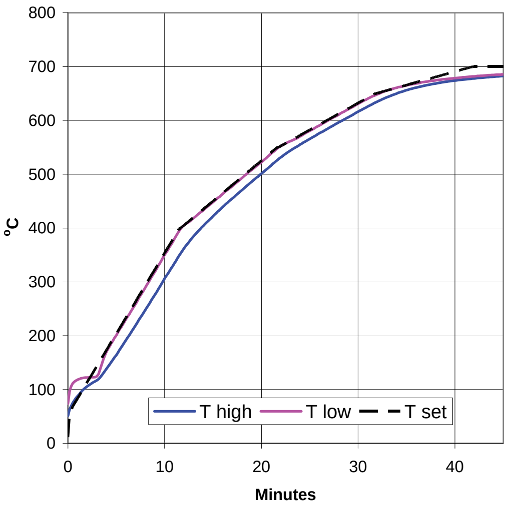


Fig. 5 – Temperature profile during pre-heating experiment. "T high" respectively "T low" is measured temperature in the material testing top.

In the experiments containing Cl in the gas, high dust formation was observed. In experiment 1, without O_2, severe dust formation was seen. The white Al_2O_3 ceramic balls showed a discolouring from dust. The test material was discoloured and had a varying mill scale thickness, Fig 6.

Fig. 6 – Test material from experiment 1. Severe dust formation was observed during the experiment, which can be seen on the white ceramic balls.

Dust formation was clearly observed in the experiments containing Cl_2, or HCl gas. Pre-heating in air and O_2 gas mixtures generated much less dust.

The weight difference of the materials before and after the preheating is shown in Table 3. The amount of residual Zn on the test material was determined by dissolving the remaining zinc coating in HCl. The Zn^+ in acid solution was analysed by AAS (atom absorption spectrometry). Based on the analysis, the residual zinc on the test materials were determined. The theoretical zinc removal efficiency during the experiment is shown in Table 4.

Table 3 – Calculated weight difference of test material [mg]

	HDG Z 275	HDG B500 Z100	NOVA	Docol	Plastisol	Polyester
1	-1210	-1220	-1660	-180	-2530	-1610
2	-1000	-930	-1680	70	-2680	-1720
3	-290	-220	-610	30	-1430	-440
4	-60	-70	-230	-50	-1080	-260
5	-1210	-1210	-1920	-430	-2680	-1920
6	-110	30	-260	10	-1110	-190
7	-50	10	-340	0	-1080	-140
8	-850	-960	-1370	110	-2070	-1170
9	-890	-950	-1300	100	-2060	-1380
10	-250	-260	-470	50	-1360	-290
11	-1130	-870	-1390	180	-2020	-1240
12	-860	-990	-1210	130	-2130	-1250
13	0	-30	-190	-10	-1090	-180
14	0	-10	-130	30	-960	-80
15	-490	-730	-620	70	-1530	-610
16	-550	-200	-830	430	-1650	-910
17	-640	-670	-770	40	-1570	-470

Table 4 – Calculated zinc removal efficiency

1	HDG Z 275	HDG B500 Z100	NOVA	Docol	Plastisol	Polyester
1	97	99	96	n.a	98	98
2	100	100	98	n.a	100	100
3	49	48	17	n.a	20	12
4	5	9	0	n.a	11	2
5	99	99	100	n.a	99	99
6	5	-8	-16	n.a	-3	-12
7	-3	-29	8	n.a	-6	-13
8	98	99	99	n.a	99	99
9	85	87	83	n.a	83	92
10	38	39	28	n.a	28	23
11	97	99	98	n.a	96	97
12	97	99	98	n.a	98	98
13	8	8	2	n.a	11	5
14	0	5	43	n.a	11	7
15	66	79	52	n.a	85	45
16	100	99	99	n.a	99	98
17	67	76	54	n.a	76	35

For the pure hot galvanised test materials, HDG, the weight of zinc corresponds to the total weight loss of the material. For the materials with paint or plastic coating on top of the galvanised steel, the loss of weight is greater due to the organic coatings removed. For the DOCOL steel sheet material, only small changes can be seen. An increase in weight indicates oxidisation, negative weights indicate $FeCl_2$ dusting.

In the experiments with a lower final temperature (350ºC), test 13-14, both weight loss and removed zinc was low, indicating that the reaction time was insufficient. In the test with a final temperature of 500ºC, test 15, the zinc removal increased, however not to the same level as for the 700ºC final temperature. In the experiments with HCl as a chlorine source, tests 16-17, the same zinc removal degree was achieved as in the case with Cl_2 as a chlorine source.

The tests show that the zinc removal rate is greatly dependent on the gas composition. Chlorine is a good reagent to promote high zinc removal. A reducing gas has less zinc-removing potential than one containing a chlorine source. The removal efficiency is temperature dependent. But at a temperature of 500ºC, the removal efficiency is 60-80 %. At a final temperature of 700ºC, the removal efficiency is almost 100 %.

The gas composition seems to be of less importance for removing organic coatings. More important is the final temperature. However, already at 500ºC, a high removal rate of organic coatings was achieved. At 700ºC all of the coating was burned off or left as a loose scale surface which was easily removed.

When preheating using a gas containing chlorine it is important to control the O_2:Cl_2 ratio. This is clearly shown in test 1, where Docol, and the HDG steel sheet material had nearly 20% more weight loss than can be explained by the removed zinc. A likely explanation is that iron reacted with chlorine gas, forming $FeCl_2$.The phase stability diagram, Fig 7, shows that with an O_2:Cl_2 ratio of 10:1, zinc exists as $ZnCl_2$ and iron as hematite, Fe_2O_3. This condition is preferred in the pilot setup.

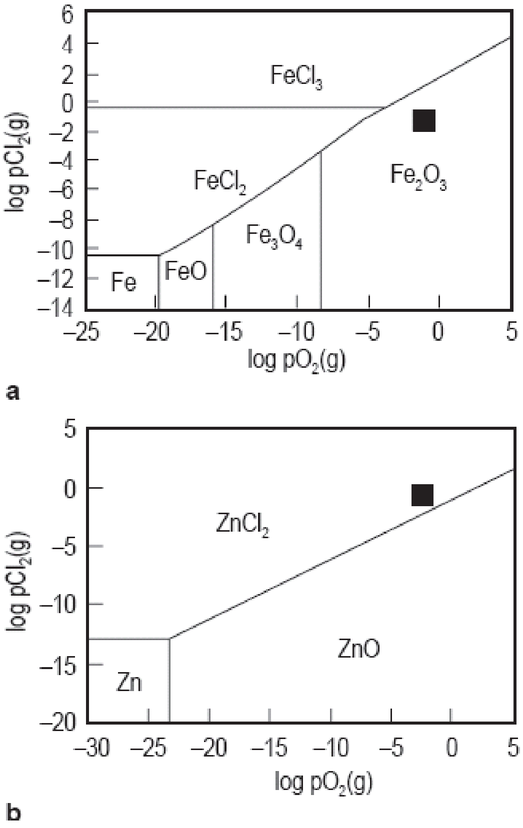


Fig. 7 – Phase stability diagram for the systems Fe-O_2-Cl_2 and Zn-O_2-Cl_2

4.1.1 Gas analysis and dust generation

Mapping of the dynamic cleaning process based on gas analysis was not possible due to the high dust generation resulting in clogging of the gas analysis apparatus which resulted in only short measuring periods.

An estimation of the dust formation based on a total mass balance is shown in Table 5, where the difference is assumed to be dust.

Table 5 - Calculated dust generation from mass balance of Zn.

	in (g) Sample	out (g) Sample	mill scale	Diff=dust	Zn cleaning efficiency
1	5,4	0,1		5,3	98
2	5,6	0,0		5,6	99
3	5,4	3,8		1,5	29
4	5,4	5,1		0,3	5
5	5,4	0,0	0,1	5,3	99
6	5,4	5,8	0,0	-0,4	-7
7	5,4	5,9	0,0	-0,5	-9
8	5,5	0,1	0,2	5,2	99
9	5,5	0,8	0,1	4,6	86
10	5,5	3,8	0,1	1,6	31
11	5,4	0,1	0,2	5,1	98
12	5,4	0,1	0,3	5,0	98
13	6,0	5,6	0,0	0,4	7
14	5,7	5,1	0,0	0,6	13
15	6,0	2,1	0,0	3,9	65
16	5,4	0,1	0,0	5,3	99
17	5,3	2,1	0,0	3,3	62

The tests with high zinc removal efficiency show the highest dust formation. This calculation supports the theory that Zn has reacted with Cl_2 and is found as dust in the exhaust gas.

In analysis of the generated dust, high traces of chromium were found. This is an indication of erosion of the test equipment, since the Cr found is unique for the steel from the test equipment

4.2 Pilot tests

4.2.1 Pilot trials, 1st generation

Two pilot campaigns were conducted. In the first campaign totally four different pilot tests were performed, in Table 6. Each test used hydrochloride (HCl) gas as the chlorine source. The energy supplied to the preheating was varied depending on the amount of scrap in the shaft. The scrap rate varied between 1907 – 2145 kg.

Table 6 – Summary of supplied media in preheating tests

	Propan		Gas temp	O2	N2	HCl
Test id	nl/min	kWh	C	nm3/min	nm3/min	nl/min
#1	200	304	900	1,6	13,0	110
#2	200*	304	900	1,8	13,2	164
#3	175	265	900	1,7	11,6	164
#4	170	258	870	1,7	11,6	120

Test #1 was interrupted during the experiment due to leakage in the pressure safety valve. In test #2 the propane flow was decreased due to an unexpected high pressure drop in the shaft. Tests #3 and 4 were carried out without disturbances.

The Zinc removal efficiency was further analysed in the inductive melting trials.

In the second campaign the aim was to generate scrap to be melted according to the setup from the first campaign. Totally 20 ton of shredded scrap were used, 10 ton were treated and the remaining 10 ton were used as received in the following melting trials at SSAB.

4.2.1.1 Process efficiency

The temperature profile in the scrap, as indicated by the temperature measurements, Fig 8, shows an even distribution throughout the shaft at the end of the preheating cycle. The average temperature of the scrap in the end of the preheating cycle is about 650ºC. The energy efficiency varies between 0.8-0.9. The exhaust gas temperature varied throughout the experiment. The average temperature was in the range of 90-100ºC with a maximum at the end of the test of ~250ºC. The zinc removal efficiency based on the small material baskets charged at different levels varied between the different materials. The maximum removal efficiency was found for the hot galvanised material, HDG Z 275, where 80-90% zinc was removed.

The total dust in the exhaust was estimated to be between 5600 – 6100 mg/nm3 (corresponding to 0.5%). This is dust normally emitted in the scrap melting furnace. Dioxin was measured in the exhaust gas from the preheating shaft, indicating levels to be in the range of 200-1500 ng TEQ/nm^3.

4.2.1.2 Metal losses

Scrap preheating with a high oxygen-potential gas and containing chlorine have an imminent risk of high metal losses either through scale formation (FeOx) or through dusting ($FeCl_2$). The normalized weight losses from the thermocouples are shown in Fig. 8. The figure shows that the maximum weight losses are less than 160 g/m2 at a temperature of 800ºC and with chlorine as reagent.

For shredded scrap the specific surface area is higher than for bulk scrap. A reasonable surface area for shredded scrap is 40 – 60 m2/ton [15]. The corresponding metal loss would then be less than 0.9%.

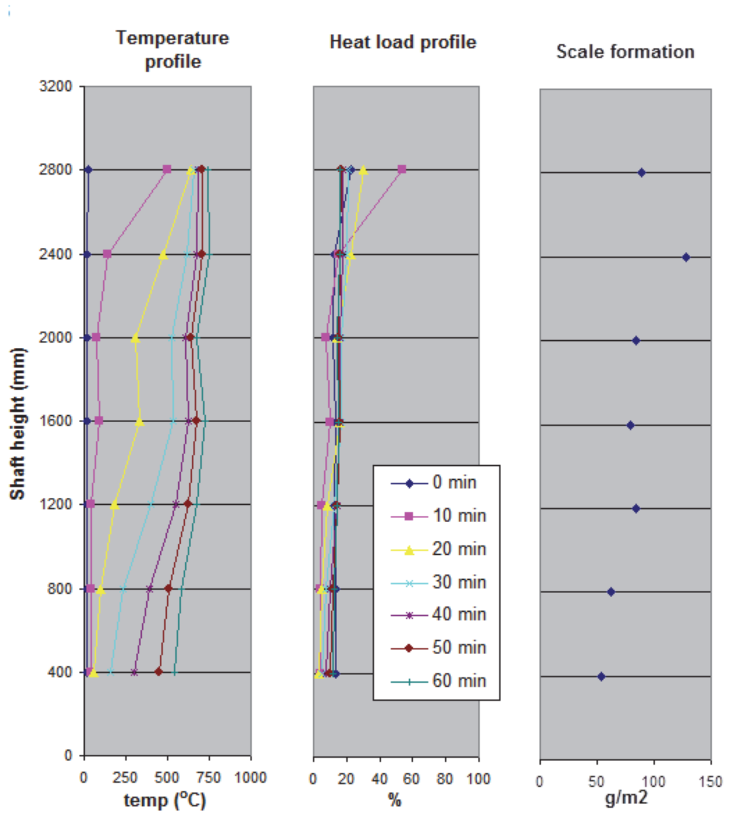


Fig. 8 – Summarised preheating results from pilot test 2 (2007-11-06)

4.2.2 Pilot trials, 2nd generation

The pilot constructed, Fig. 9 consist of a ceramic lined shaft with a height of 2500 mm and a diameter of 1090 mm.

The pilot plant has been successfully constructed, built and taken in operation. Hot and cold tests have been performed during 2012. In total 18 trials have been performed during 2012 in which important process behaviour have been identified. The initial hot commissioning period have been followed by activities concerning developments and improvements of the systems for evaluation of process performance.

Control of hot gas composition:

To be able to control the gas composition, mainly to control the oxygen potential in the preheating gas and to keep the O_2:Cl_2 ratio at 10:1 an alternative start-up procedure was derived. The air in the system is flushed by nitrogen before starting the gas recirculation and preheating cycle. The O_2 composition in the gas is instead gradually increased from almost oxygen free atmosphere to 10% instead of gradually reducing the composition from 21%.

Additionally, the preheating temperature profile is influenced by the heat losses in the system. The insulated and lined hot gas duct between the combustion chamber and the preheating shaft cannot practically be pre-heated before stating the first trials. This results in large temperature losses for the first trial in a sequence. Final temperature profile in the scrap (Fig. 10) showed that the scrap temperature is well above 800 °C which result in high mill scale formation. Additional thermocouples are installed in the top of the shaft to control the preheating temperature.

Handling of preheated shaft:

During transport, the shaft is completely open in the top while a steel grid in the bottom is keeping the scrap in place. Due to the design of the preheating shaft the high scrap temperature give rise to a chimney effect due to convection from air heated in the scrap bed. This results in unwanted iron oxidation, scrap ignition with unhealthy emissions of smoke and fumes. This

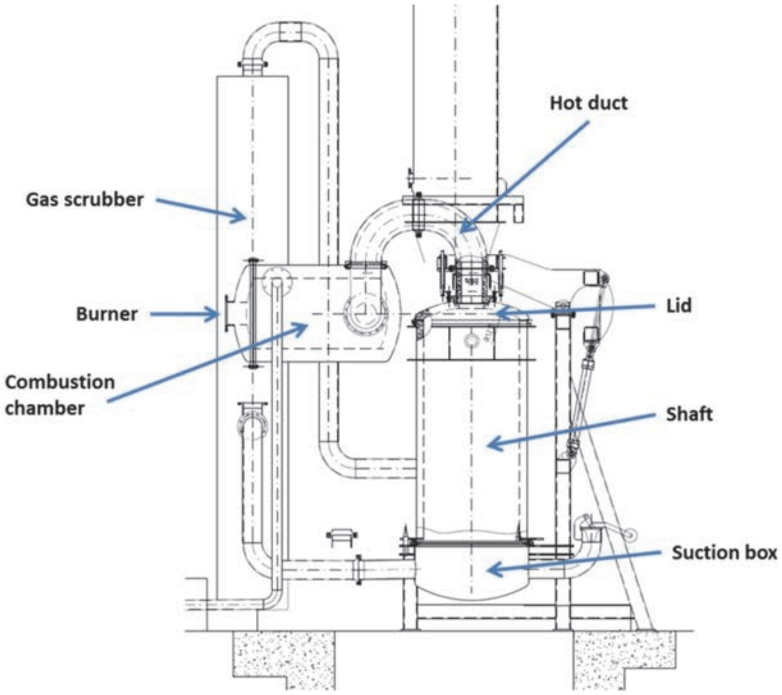


Fig. 9 - Surface rinsing station, sideview

needs to be redesigned for an industrial application. To manage handling issues the preheating cycle were followed by scrap conditioning consisting of a cooling cycle where nitrogen is flushed through the scrap to reduce the temperature below a temperature where the shaft can be moved without severe dust issues.

Operation practise

Energy is supplied to the shaft via separate combustion of propane in the combustion chamber. The hot gases from the combustion are mixed together with recycled gas and are led through the charged scrap burden and exhaust by suction through the suction box. The gas from the scrap is led to the scrubber with caustic solution were the chlorides including zinc are absorbed. The major part of the gas is recycled back to the combustion chamber while a smaller part is vented in order to maintain operational pressure in the process. The vented gas is cleaned in Swerea MEFOS gas treatment plant. The operation procedure is as follows:

1. Scrap is charged by a tractor and transported to the preheating stand or to the treatment position.
2. The shaft is placed in the treatment position by overhead crane. The lid is sealed to the shaft and the gas loop is closed.
3. Air is vented out by purging of nitrogen.
4. The burner is put into preheating mode and the desired O_2 content in the gas is tuned. The feed of HCl acid is started when the desired O_2 content is achieved. The burner is keep at constant power during the operation, Temperature is controlled by the circulation gas flow and the blower.
5. The pre-heating is stopped when the temperature of the outgoing gas has reached its set point. Scrap conditioning cycle starts.
6. The treated shaft is lifted by overhead crane and transported and emptied by tractor.
7. Next cycle can start

Fig 10 shows temperature profile from trial 15. It can be noticed that the highest scrap temperature in is significantly higher than 700 °C which from a mill scale generation perspective is very negative and also high risk of scrap ignition due to the O_2 in the preheating gas.

Zinc recovery

The operation of the scrubber unit to maintain the pH level suitable for the process was made by addition of caustic solution. NaOH is being feed continuously to the scrubber to neutralise the Cl$^-$ ions.

The zinc concentration in the scrubber fluid indicates how much zinc that has been removed from the scrap. Analysis of the scrubber fluid solution and sludge from test 14 and 15 indicates a zinc concentration about 174-265 g/kg TS in the sludge phase and 0.003-3.6 g/l fluid, Table 7. The scrubber contains approximately 800 l scrubber fluid, indicating that 19-22 kg Zn has been precipitated in the solid phase in the scrubber.

Cl is entering in the form of HCl acid solution (10M). The HCl concentration in the acid is 36% resulting in a corresponding Cl amount of 0.55 kmol. The theoretical Zn amount being removed is 21 kg/h. This corresponds corresponds to the recovered amount.

Table 7 – recovered Zn in scrubber solution (ALS analysis report)

Sample	Sludge Zn mg/kg TS	Solution Zn µg/l	kg Zn/charge (approx.)
14	265 000	3360	22.3
15:1	174 000	581 000	9.7
15:2	207 000	3 350 000	19.5
15:3	210 000	3 600 000	19.2

Depending on the pH of the scrubbing solution, $ZnCl_2$ reacts with H_2O and Zn^+ is expected to be found either in the sludge phase (ZnO) or the water phase ($ZnCl_2$). For acidic pH solutions, the Zn is found in solution while for alkaline pH solutions the Zn is found in sludge phase. This is in agreement with the analysis of the scrubber fluid reported, Table7.

Furthermore the results indicate that Zn removal rate is being additionally enhanced during the conditioning phase where nitrogen is used to cool down and homogenise the scrap. The samples 15:1 and 15:2, 15:3 represents samples after trial and after scrap conditioning.

Visual inspection of the treated material shows that some material have undergone a significant removal of Zn, other show a yellowish discolouring. The discolouring is on the zinc coated sheet material while the road fence material does not show this tendency. This indicates that the zinc removal efficiency is depending on the galvanising method. In the top of the scrap shaft high oxidation have been observed in trials with a high maximum temperature.

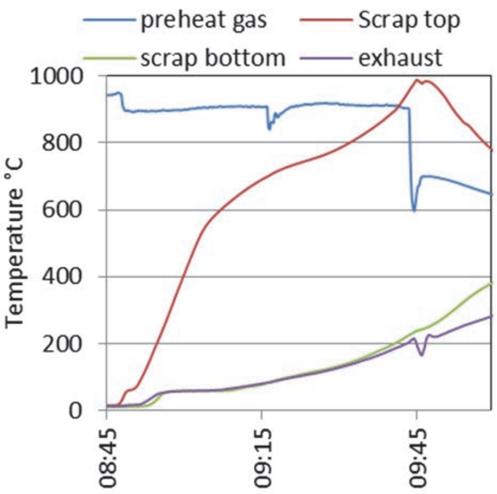


Fig.10 - Temperature profile during experiment (trial 15)

4.3 Melting tests,

3.3.1 Inductive melting test

From the first pilot campaign totally 10 melting tests were conducted, two reference melts with un-treated material and eight with treated material.

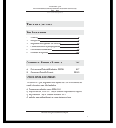
The first reference test showed that due to the low density of the scrap, the melting time was 3h. To shorten the melting time, heats 2-10 were made with a starting melt of 50 kg pig iron. This shortened the melting times to <1h.

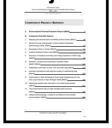
Table 8 – Results from melting trials

	weight kg	melting time hh:min	final temp °C	dust mg/m3ntg	Dust kg
1 Ref 1	200	03:02	1550	1410	1,68
2 Ref 2	110	00:42	1710	1966	5,9
3 071105-1	118	00:47	1 685	3036	2,91
4 071105-2	102	01:25	1690	960	1,67
5 071106-1	111	00:45	1712	1232	1,13
6 071106-2	121	00:52	1700	1122	1,28
7 071108-1	140	00:50	1690	2587	1,62
8 071108-2	116	00:49	1675	2508	1,51
9 071109-1	109	00:35	1724	1763	1,25
10 071109-2	109	00:25	1705	1260	0,64

From each surface cleaning test two material baskets were retrieved and sent to melting. The temperature history for the baskets is different. The first basket was at the lower level resulting in a shorter time in the high temperature region.

Smoke and dust formation was observed during the melting. During some part of the melting of





the un-treated scrap, a yellow/green smoke was observed which can be assumed to be caused by the zinc coating.

The effect of having cleaner scrap is shown in Fig. 11. Dust arising during melting was collected and analysed for zinc. The figure shows that the zinc can be decreased to less than 2 kg/t scrap compared to 17 kg/t scrap for untreated material. The test 071105 shows higher Zn content than the other. This is because the cleaning/preheating experiment was interrupted after 20 minutes at an average temperature of 350 ºC.

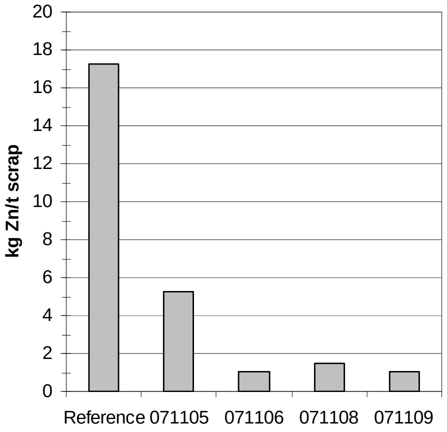


Fig. 11 – Results of the Zn measurement from melting trials (average Zn contents)

4.4, Industrial melting trials at SSAB EMEA

4.4.1 campaign 1

The overall aim of the campaign was to analyse the effect of treated shredded scrap in the scrap mix compared to the normal operation praxis. The dust generated during the different heats were recorded and analysed. Sludge samples were taken at 1, 2, 3, 4, 5, 10 and 15 minutes during the oxygen blowing. The dust generation was approximated equal between the different samples, e.g. from blowing start to 1 minute dust generation is approximated as the 1 minute sample, and between 1-2 minutes are approximated as the 2 minute sample and so on. The blowing time varies between different heats and was also recorded. Based on the blowing time and the dried dust generated the total dust generation are calculated, shown in Fig. 12. The figure also shows that the amount dust generated varies between the different samples (1, 2 ... 15 minutes).

From the analysis it is shown that the treated shredded scrap will result in less generation of dust. Substituting the external scrap amount by treated scrap seams to reduce the generation of dust by ~20%. A slight reduction in dust generation is noticed when treated shredded scrap is used.

No negative effects of the shredded scrap on the BOF operation were recorded. However the time between charging of scrap and hot metal is very important to take into consideration when analysing the amount of dust generated. The organics and zinc on the scrap will be removed early in the cycle. If the time between scrap charging and hot metal charging is too long,

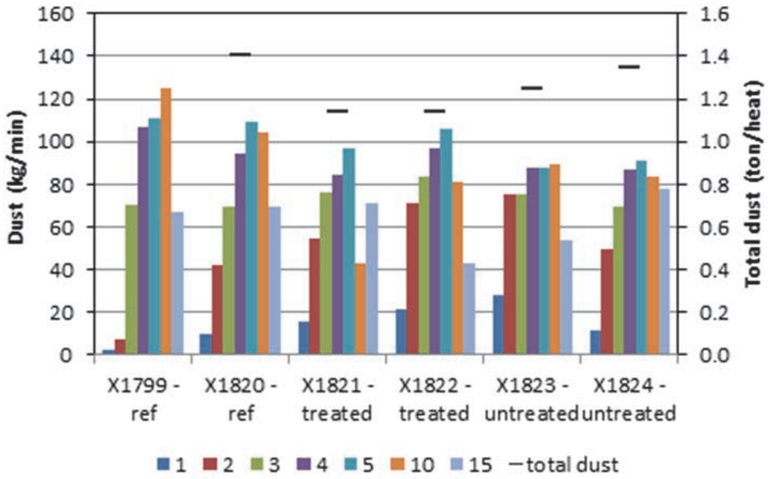


Fig. 12 – Results of the dust measurements from the industrial melting trials at SSAB (1st campaign)

organics and possible zinc will be removed in the secondary dust.

4.4.2 campaign 2

Additional reference trials at SSAB LD converter with the purpose of studying the zinc in primary and secondary dust from LD converter has been carried out. As a reference six heats was followed with respect to dust and zinc load in the primary and secondary dust.

During reference trials, samples were taken from 6 heats. The scrap mixes for each charge is shown in Table 9.

Table 9 – Scrap mixes used during reference trials at SSAB EMEA

Charge	Ext. “dirty”	Ext. “clean”	slabs	Steel sculls	HM sculls	Tot.
T-0751	-	5.8	8.2	3.4	6.3	23.7
T-0752	-	6.3	9.6	3.1	2.6	22.6
T-0753	6.9	-	5.3	9.3	3.4	24.9
T-0754	7.4	-	6.1	8.8	2.8	25
T-0755	-	-	11.4	11.3	2.7	25.3
T-0756	-	-	9.7	12.4	2.8	24.8

The external scrap,” Ext. dirty” has the highest observed zinc content. The rest of the scrap should be free of zinc. The dust content in the sludge water from venturi scrubber was between 5 and 60 g dust/dm3 of sludge water. This corresponds to a dust load between 25 and 250 kg dust/min. The total dust load was calculated to be between 2200 and 2600 kg dust per heat. Dust generation is greatest at the beginning of charge. Fig. 13 shows the dust load of primary dust during charging and blowing for the 6 charges. 0 minutes is start of the blow, ignition.

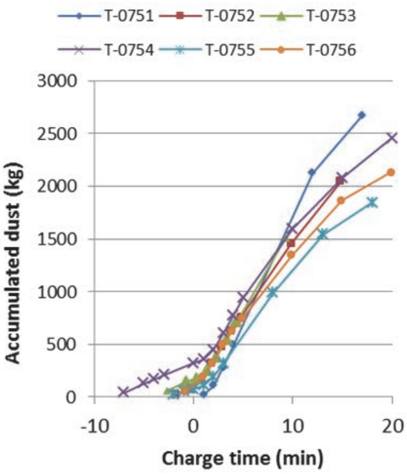


Fig. 13 Dust generation during LD process

The zinc load in the primary dust varies during the charge. The load is increasing from the start of the blow and reaches a maximum around 5 minutes into the charge. Then the zinc load decreases and is almost zero at the end of the blow. If the blow start is delayed after hot metal charging, zinc can be detected in the primary dust also before the start of the blow, charge T-0754. The zinc load in the secondary dust is very low in the 4 charges with “clean” external scrap. In charges T-0753 and T-0754, the zinc in the dust is 4 to 10 times higher than in the charges with only “clean” scrap. Fig. 14 shows indicative Zn load in the primary and secondary dust.

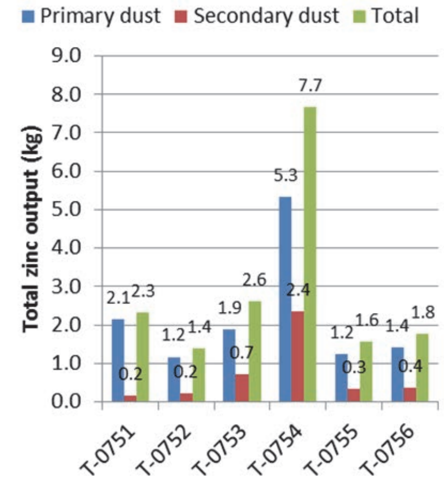


Figure 14 Zn in Primary and Secondary dust

The conclusions from the reference trials are:

- Zinc is found in both primary and secondary dust,

- The majority of the detected zinc is in primary dust,
- Zinc in secondary dust depending on scrap cleanliness,
- 50 % of the zinc to the primary dust leaves the converter in the first 5 minutes and 90 % of the zinc leaves in 10 minutes,
- The measurement method defined to analyse the zinc removal efficiency of the pre-treated scrap is suitable.

4.5 General discussion

All types of scrap preheating have the risk of forming environmentally hazardous components such as dioxin. The use of a “clean” fuel is not likely to improve the situation since scrap in itself is a very complex raw material. A fuel of similar complexity can consequently be used due to the already high demands on gas treatment on the exhausts. For industrial application, it is therefore important to minimise the exhaust that needs to be treated. A possible alternative to decrease the amount of gases is the use of oxygen. This can be achieved by using oxygen in a separate combustion chamber generating the hot gases for the preheating, e.g. from combustion of ASR (Auto shredder residue) or similar.

In the first program period small scale experiments have shown that it is possible to effectively remove surface coatings and preheat scrap to 600ºC using chlorine as reagent. No differences between the sheet qualities were observed. The use of chlorine in a preheating application will result in dioxin formation as well as possibly severe plant wear if not operated correctly. The small scale test showed that with an O_2:Cl_2 ratio in the preheating gas of 10:1, the metal losses are acceptable and the chlorine is selectively reacting with the zinc. This is a fast reaction resulting in high zinc removal efficiency at 700ºC. Nearly 100% efficiency was obtained. Hydrochloride shows the same good zinc removal properties. There is a clear temperature dependence on the zinc removal efficiency where a lower temperature, <450 ºC, results in a significantly reduced zinc removal rate.

The small scale experiments further showed that HCl has the same behaviour as Cl_2 gas. The HCl is a probable component from combustion of e.g. ASR (Auto shredder residue). Scrap preheating with energy waste such as ASR in combination with oxygen has several advantages:

- Fractions that today are sent to the landfill have a usage substituting electricity or coke
- Direct use of latent heat has high efficiency
- Environmentally hazardous dusts can be recovered and recycled in concentrated form
- Gas emissions can be treated in small effective filters

The concept was tested in initial pilot trials (1st generation) in two pilot campaign. The pilot tests and melting confirmed the results from small scale tests. In the induction furnace melting trials the collected dust showed that the zinc content could be significantly decreased. In the second campaign the treated scrap was charged into the LD converter, replacing the external part of the scrap mix, totally 5 ton/heat. The trials showed no negative effect on the LD operation, a significant decrease in total dust generated during the oxygen blowing cycle which was expected.

A process concept was suggested which is a stand-alone technique that utilises ASR as fuel with full oxygen combustion and treatment of the scrap in a separate scrap shaft, schematically shown in Fig. 15. The use of 100% oxygen reduces the total gas flow in the system, i.e. no nitrogen. The gas amount needed in the preheating of the scrap is achieved by gas recirculation. The use of 100% oxygen together with exhaust recirculation results in very low exhaust volumes going to the stack.

The suggested system setup contains a separate combustion unit (or gasifier) generating a hot gas (>1400ºC). The high-temperature combustion of ASR (or other by-product fuel) with oxygen results in a melted slag, which can be stabilised with lime additions. The temperature is controlled by recycling the exhaust. The preheating gas (maintained at a temperature of <900ºC) enters in the preheating shaft. During the passage of the cold scrap, energy from the gas is transferred to the scrap. After the passage the temperature of the exhaust will be below 200ºC. There will be a need of gas treatment (dust collection) before recycling of the exhaust gas. The gas going to the stack will require a sophisticated gas cleaning system to handle the dioxins. If the process is operated on ASR, the demand would be ~32 kg ASR/t scrap. The combustion would require 37 nm^3 O$_2$/t scrap. With gas recirculation, the gas volume to the stack would be ~50 nm^3/t scrap. This low volume to the stack allows for the management of hazardous components at reasonable cost.

During the second program period, together with financing through the Research Programme of the Research Fund for Coal and Steel (research grant RFS-PR-09028), Energimyndigheten, and Swerea MEFOS member companies a full pilot plant of the preheating concept has been designed and erected to test the suggested environmental- and process related effects. From the trials conducted, several important results for scaling up the process have been addressed. Some of these are a result of the pilot setup.

During the hot commissioning and initial trials conducted several alteration of the primary process setup was needed. To be able to control the O$_2$ potential in the gas, which is a key process parameter to make the Cl selective for Zn removal, purging of the system with N$_2$ to get rid of the air in the system is important. Controlling the O$_2$ potential and preheating temperature is also important to control the mill scale generation. A high O$_2$ content in combination with high temperature in the gas will result in severe oxidation and in worst case ignition of the scrap.

Integrating the dedicated gas scrubbing unit inside the process loop has both advantages and disadvantages. The main advantage is that the recirculation gas is cooled and cleaned when returning. All dust is collected in the scrubber. The disadvantage is that the gas is saturated with water, resulting in large gas volumes and potentially a risk of forming H$_2$ when the humid gas is passing the 700 °C scrap. The gas composition must always be monitored,

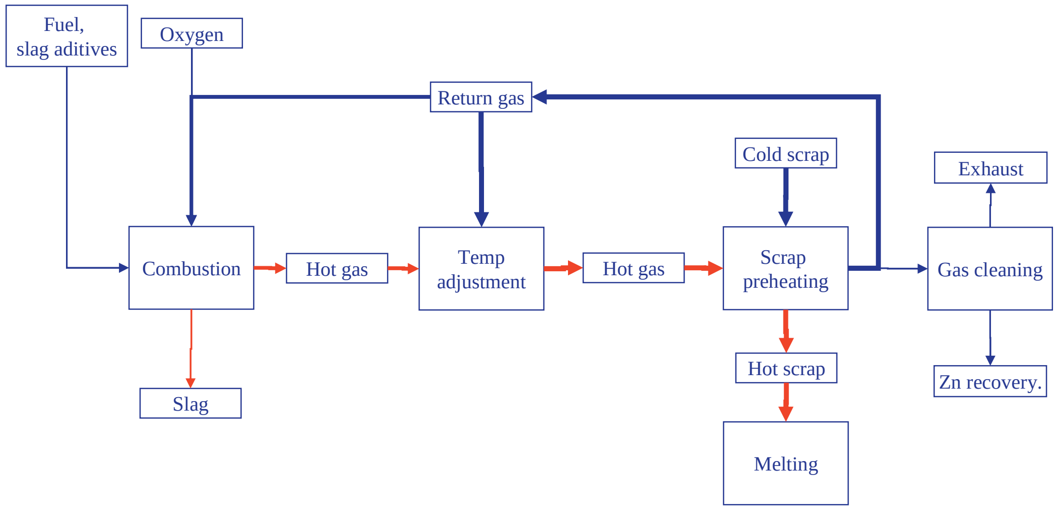


Fig. 15 – Industrial system scale up based on chlorine as reagent

furthermore must the recirculation at all times be turned off if the main burner is turned off.

Due to the setup of the pilot with movable open shafts, handling of the hot scrap has proved to be difficult without conditioning of the scrap after treatment. Nitrogen has been used to reduce and homogenize the scrap temperature before lifting the shafts to reduce the risk of self-ignition of the hot scrap due to air being sucked in due to the chimney effect. In an industrial setup the transport of the treated scrap needs to be redesigned.

From analysis of the scrubber fluid significant amounts of Zn have been found. This indicates that the process concept functions as suggested. Zn is being removed from the scrap and collected in the scrubber. The amount of Zn found in the scrubber fluid corresponds to the theoretical amount of $ZnCl_2$ formed from the amount of HCl entering the system.

Visual inspection of the treated material shows that some material have undergone a significant removal of Zn, other show a yellowish discolouring. The discolouring is from the zinc coated sheet material while the road fence material does not show this tendency. This indicates that the removing zinc removal efficiency is depending on the galvanising method.

Extended melting trials in two more campaigns at SSAB EMEA will be carried out during 2013 within the on-going RFCS project.

5. CONCLUSIONS

A process concept, allowing for simultaneous surface cleaning of scrap and preheating has been suggested. Small scale experiments and pilot tests have been used to develop the concept.

The tests supported the thermodynamic and reaction kinetic expectations. The findings from the small scale tests showed chlorine rich gases e.g. exhaust gases from ASR combustion can be a suitable gas for cleaning and preheating scrap. The combustion and generation of chlorine-rich preheating gas needs to be further investigated.

The 1st generation pilot test showed that it is possible to achieve uniform scrap preheating of 650ºC. The zinc removal efficiency is high. The preheating to 650ºC generates a metal loss less than 1%. There is a loose scale on the treated scrap which requires further processing, e.g. vibration or similar treatment.

The process concept including oxyfuel combustion, dedicated gas scrubbing and exhaust gas recirculation has been proved in the 2nd generation pilot trials. Operation principal and operational strategies regarding gas composition and gas temperature have been addressed. Further trials are needed before industrial melting trials can be made.

Results from analysed scrubber fluids show that there are significant amounts of Zn found in the scrubber fluid. Depending on the pH of the scrubber fluid the Zn reports either to the sludge or the water phase.

The use of chlorine (Cl_2 or HCl) can generate dioxins. The amounts indicated by the measurements from the 1st generation setup needs to be taken care of with a dioxin treatment of the exhaust. The trials in the 2nd generation pilot have shown that it is possible to reduce the exhaust gas vented out from the process utilising oxyfuel combustion and exhaust gas recycling. This will enable management of the dioxins.

The process concept shows substantial potential for removing the coatings from scrap, thereby producing a fine material either for use in integrated steel making or scrap-based steel making. Use of surface cleaned scrap will result in less dust formation, and a dust without zinc. This will allow for new possibilities for internal recirculation of the dust. If ASR is used together with oxygen as suggested in the concept, it is possible to decrease the off gas volume to the stack. This will allow for treatment of the gas and the removal of harmful elements in a cost-efficient manner.

6. FURTHER RESEARCH

- Further pilot plant process optimisation to manage the preheating gas conditioning (temperature, analysis) needs to be performed.
- Further industrial melting trials of treated material is needed to verify the industrial benefits needs to be performed.

7. DISSEMINATION AND PUBLICATIONS WITHIN THE CURRENT PROJECT

Conference Non-refereed

S. Ångström, M. Larsson, P. Johansson., Kombinerad förvärmning och ytrening av skrot, Stål2007, 9-10 May 2007, Borlänge (2007).

Conferences Refereed

M. Larsson, S. Ångström., A novel process for simultaneous scrap preheating and surface rinsing, Scanmet 3, Luleå, Sweden, 2008.

M. Larsson, S. Ångström, E. Burström, G. Ye., Preheating and Surface Cleaning of Steel Scrap by ASR, REWAS, Cancun, Mexico, 2008.

M. Larsson, P. Hahlin, S. Ångström., The future of scrap preheating and surface cleaning, Scanmet IV - 4th International Conference on Process Development in Iron and Steelmaking, 10-13 June 2012, Luleå, Sweden.

M. Östman, K. Lundkvist, M. Larsson., System analysis of the steel making route when including scrap preheating and surface cleaning, Scanmet IV - 4th International Conference on Process Development in Iron and Steelmaking, 10-13 June 2012, Luleå, Sweden.

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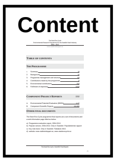

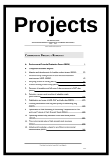

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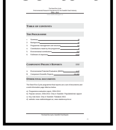

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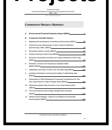

Recovery of vanadium and fully use of slag components in BOF-slag (88031)

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Abstract

The economic and environmental potentials of the annually disposed Swedish BOF-slag are estimated to about 125millions of US$, savings of over 100 000 tons of CO_2-emission and 140 GWh of energy.

A process concept for recovery of vanadium aiming at production of standard ferrovanadium and a useful slag product based on the following process steps has been developed in this project:

- *reduction of hot BOF-slag aiming at a slag product with less than 0.3% V*
- *V-P separation by selective oxidation of the obtained metal from the reduction step aiming at a high vanadium slag with the target ratios of V/P>500 and V/Fe>1, ready for production of standard ferrovanadium products*

A preliminary economic feasibility study of the process including process flowsheets, preliminary investment and operation cost analysis have been carried out and reported to the participating industrial partners. The economic analysis of the proposed processes shows high economic potential.

Results from the extensive laboratory experiments, pilot and industrial test campaigns have showed that the hot slag reduction step is approachable and the vanadium content could be reduced to well below 0.1% which is set as the limit for possible use in cement production. The long term tests of the quenched and ground reduced slag have shown at least equally good hydraulic property as that of the reference cement material. Selective oxidation trials have been carried out in a 150 kg induction furnace. It is shown that the target V/P ratio (>500) in the vanadium slag could be achieved and the V/Fe ratio over one was easily obtained. Basic thermodynamics studies on V-bearing slag systems have been initiated by the industrial partners. This activity is essential for further optimization of the investigated concept.

A process for enrichment of V-concentration in the slag has also been developed. The V-enriched slag is called LUVA-slag and can be sold externally or use as V-bearing feed for the VILD reduction process instead of BOF-slag. The total economy potential will be improved by almost 100% as the vanadium content in the LUVA-slag is about the double of the BOF-slag. The LUVA process is currently in its commercialization stage.

Direct use of the FeV metal obtained from reduction of BOF or LUVA slag without P-removal has also been studied in detail. The laboratory and initial pilot tests have indicated that it is possible to use the obtained FeV metal alloy without the V/P separation step without negative impact on the physical properties of the alloyed steel qualities. A pilot scale experiment is still going on.

1. INTRODUCTION

1.1 Background and potentials

SSAB AB and Finnish Rukki, run their blast furnaces with 100 % LKAB pellets containing 0.2% V_2O_5. Vanadium is reduced to the metal phase in the blast furnace and the V-content in the hot metal is about 0.3%. In the subsequent decarburization step vanadium is oxidized and ends up in the BOF-slag. The Swedish BOF-slag contains about 4-5% V_2O_5 which corresponds to 2.2-2.8%V. The annual production of BOF-slag in Sweden alone is 350-400 000 tons. About 50% of that, the coarser fraction of over 6-7 mm, is recycled to the blast furnace process for fully use of the excess amount of CaO and iron oxide in the slag, see Figure 1. The recycling rate is limited by the tolerance for phosphorous and vanadium accumulation. The fine fraction is disposed and stored. Disintegration of the slag and high vanadium content are the main problems for external use of the slag.

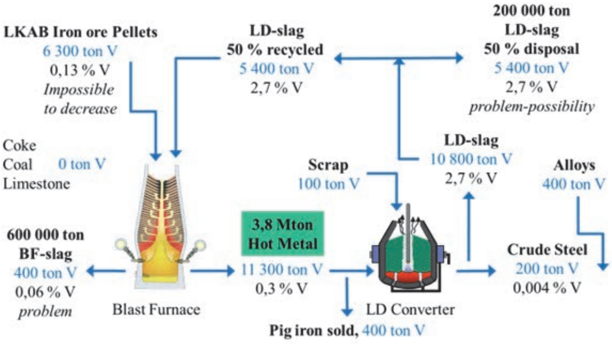


Figure 1 Vanadium flow in the SSAB Steelmaking system

The total vanadium content in the disposed Swedish BOF-slag is about 5 million kilogram. With the current vanadium price of 25 US$/kg, it corresponds to a total value of 125 million US$ which is lost in the slag yards per year.

If vanadium and phosphorus in the BOF slag are reduced the slag could be recycled to BF or used externally. For one ton of BOF-slag back to BF, there is about 300 kg excess amount of burnt lime. This corresponds to a total amount of 56 000 tons of burnt lime. Based on figures for production of burnt lime (CaO) in a LCA study, a fully use of this will provide potential savings of more than 100 000 ton CO_2 emission and about 140 GWh of energy per year. If the final BF slag could be used in cement production, the environmental savings will be even more.

1.2 V-recovery by pre-treatment of hot metal

V-recovery by pre-oxidation of hot metal is a method currently practiced in South Africa, China, Russia and New Zeeland. A slag with 15-30%V_2O_5 is produced and it is used as the main raw material for production for V_2O_5. There are however three major drawbacks of this approach if they are to be used in Sweden:

- The V/Si-ratio in the hot metal should be at least 1 to be able to prepare a usable high vanadium slag for V_2O_5 production
- An extra process step/reactor is needed and is included in the production chain. Risk for a production disturbance is thus high
- The V_2O_5-content in the final BOF-slag will still be too high for external use in Sweden

This concept has also been extensively investigated by SSAB several times since 1970s without leading to any commercialization.

During this on-going VILD-project, a new way to enrich the vanadium in the slag by pretreatment has been tested by the industrial partners and since 2009 this became part of the VILD-project. Both SSAB and Ruukki run plant trials on this.

1.3 V-recovery from BOF-slag

Beside the pre-treatment possibility described in 1.2, a lot of work has also been done over the years on recovery of vanadium from BOF-slag in Sweden which is summarized in the followings methods:

- Direct soda roasting
- Direct acid leaching
- Slag reduction

Over 80% yield of V-recovery of the first two methods has been achieved. However the soda consumption was too high for the first method. The required molar Na/V-ratio was up to 28 as compared to 2-3 for a conventional roasting process. For acid leaching, a large amount of new waste would be created. Internationally, acid leaching has been practiced in Mexico in the past, but with the strict environmental regulations today it will never be possible to apply it in the developed countries.

Slag reduction has been investigated in an ECSC-project during 1995-1998. The fine fraction of BOF-slag was reduced in a DC-furnace for V-recovery and at the same the remaining slag components were composed to a target composition. The slag products obtained include water granulated slag with hydraulic properties, de-S agent and cement clinker material. The obtained metal with about 10% vanadium was further treated for production of V_2O_5 by hot soda oxidation followed by a conventional hydrometallurgical method. An overall vanadium yield of over 90% has been achieved. An improved method has also been suggested based on hot slag reduction using FeSi as reductant.

1.4 The VILD-concept

The VILD project has in the first project phase (2005-2008) focused on slag reduction and V/P separation. In the second phase (2009-2012) the concept has been extended to also include V-enrichment in the slag and direct use of the VILD- and LUVA-metal with 10-20%V without P-removal. The project activities are summarized in Figure 2 and described in the followings:

- LUVA-slag production by two step blowing (1)
- Reduction of cold/hot BOF- and LUVA-slag (2)
- V/P separation by selective oxidation (3 and 4)
- Use of the reduced slag (5)
- Direct use of VILD- and LUVA-metals (6)

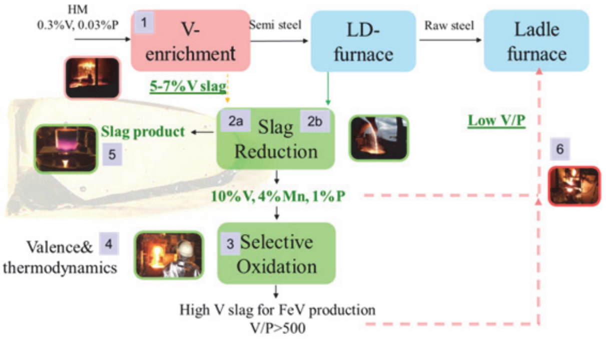


Figure 2 The extended VILD-project

The present research and development work has been focused on the proposed VILD concept (**V**anadium **i**n **LD**-slag) based on experiences from previous vanadium projects. This research approach is also based on slag reduction but differs from the method mentioned above in the steps for further processing of the obtained metal alloy from the reduction for a final vanadium product, see Figure 2. Only pyrometallurgical process will be applied. The possible products are:

- FeV products in form of standard FeV or FeV alloy from the slag reduction
- LUVA slag for external sale
- Reduced slag for use in cement production or road construction

Optimization of VO_x-bearing slag systems is essential for further optimization of the VILD-concept. Basic studies on this subject have therefore been included in this project. Since higher vanadium content in the BOF-slag will lead to significant reduction of the total cost and savings of environment, enrichment of V-concentration in the BOF-slag by mineral technical and metallurgical treatment has also been investigated. Expenses of these activities were covered by the industrial partners.

As mentioned in Chapter 1.2, production of a V-enriched slag became part of the VILD-project. This means reduction test works will also include the V-enriched slag, the LUVA-slag. Using such a slag the reduction cost per kilo vanadium will be reduced by about 40-50%.

2. OBJECTIVES

The main objective of this project is to develop new and reliable methods for metal and mineral recovery of the Swedish and Finnish BOF-slag. Special attention has been paid on vanadium recovery and the use of reduced slag for internal and /or external utilizations. Direct use of the FeV product from the slag reduction without the V/P separation step has also been studied.

Industrially it is expected that a cost efficient method for production of ferrovanadium based Swedish and Finnish BOF-slag will be delivered as a result of the project. This will also enable and facilitate the internal and external uses of the reduced BOF-slag.

3. METHODS

The methods applied for approaching the objectives include theoretic studies on the concerned systems of the concept followed by laboratory experiments, pilot trials and industrial tests.

3.1 Laboratory scale test for slag reduction

Theoretic studies on slag reductions have been performed using FACTSage and HSC Software to evaluate the different approaches of slag reduction including selective reduction and total reduction. Reductions with C, FeSi, Al and CaC_2 have been simulated. Also carbon in combination with FeSi, Al and CaC_2 as reductants has been calculated.

About 30 tests were carried out at Luleå Technical University (LTU) in an induction furnace with a sample amount of about 500 grams. The aim was to see how far the V-content in the BOF-slag could be reduced and to establish the relationship between the amount of added reductants and the reduction degree of the slag under near equilibrium conditions. Mixtures of powdered FeSi or aluminum and BOF-slag were mixed and heated until the desired reaction occurred. After cooling, the reduced slag and the obtained metal were separated and analyzed. The experimental set-up is shown in Figure 3. Both graphite and MgO crucibles were used for the experiments.

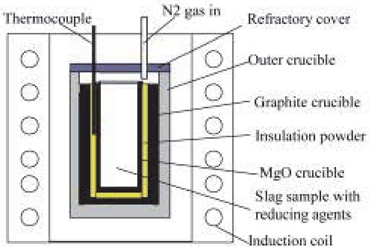


Figure 3 Experimental set-up for reduction test at LTU

3.2 Direct hot slag reduction

A pilot test on hot slag reduction has been carried out at MEFOS in 1999 as illustrated in Figure 4.

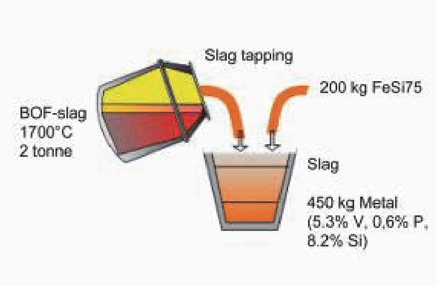


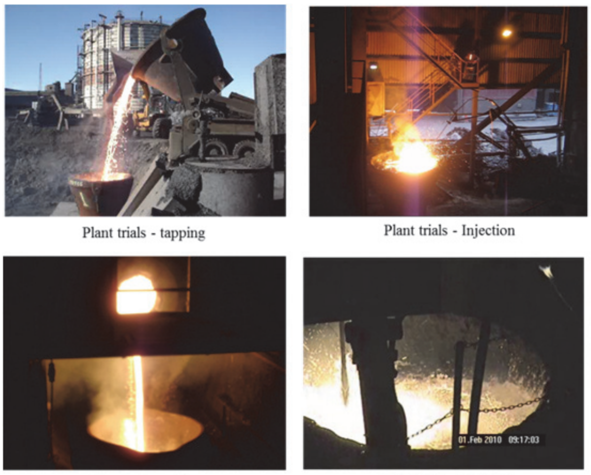
Figure 4 Set-up for the pilot trial at MEFOS

During this project a large number of test campaigns based on this hot slag reduction concept have been further verified. The test set-ups are shown in Figure 5 and these included:

- Initial plant trials in the slag yard at SSAB work in Luleå 2007 where lumpy and granule FeSi and Al were added in the bottom of a slag ladle (the reactor) and during slag tapping. The purpose of these tests was to see if the reduction step could be realised in a safe, simple and reliable way in full scale. When the slag truck from the steel plant arrived the experiment site, a reference slag sample was taken and the slag temperature measured. The hot slag was then tapped from the big slag pot into a MgO-lined slag ladle of about 2 m^3. The reductant was fed into the slag stream at the same time. Both FeSi and aluminum have been tested.
- In order to see if a longer retention time for slag and metal will improve vanadium recovery yield, some tests were performed in the end of

June 2008, using the pilot KALDO furnace at Swerea MEFOS. Two tons of LD-slag was melted in the KALDO converter using an oxy-fuel burner. When the slag was melted, FeSi and Al were added to the furnace. The furnace was kept rotating during the trials. Slag was sampled for analysis. In the end of test, the slag was tapped to a slag ladle. Some additional FeSi/Al was also added during tapping to see if vanadium could be further reduced.

- Pilot and plant trials using injection technique has been tested during 2009-2010 aiming for a better control of vanadium reduction. The test facilities were installed in an indoors test hall making it possible to run the trials independent on the weather conditions. FeSi-powder was injected in the molten slag. It is possible to inject the FeSi-powder into different levels of the slag bath. Pilot trials were made at Swerea MEFOS using the same principle between the plant trials in order to optimize the heat and mas balance condition of the process.

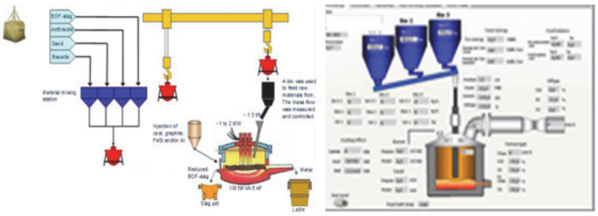


Plant trials - tapping
Plant trials - Injection
Pilot trials - Kaldo
Pilot trials - Injection

Figure 5a Set-up of pilot and plant trials for hot slag reduction at Swerea MEFOS and SSAB Luleå work

3.3 Hot and cold slag reduction using an electric arc furnace

Hot and cold slag reductions were also tested in both AC and DC arc furnaces. The purpose was to see the controllability of the reduction process. By using AC it is also possible to use injection of stronger reducing agent in the end of the process to ensure a high vanadium recovery. See Figure 5b.



AC-furnace DC-furnace

Figure 5b Experiment set-ups for slag reduction using AC and DC arc furnaces at Swerea MEFOS

Several test campaigns using these arc furnaces have performed since 2008. During September 2011, a pilot test campaign on reduction of LUVA- and BOF-slag was performed using the 3 MW DC furnace at Swerea MEFOS.

3.4 Selective oxidation

The initial part of this work includes basic studies of viscosity calculation and laboratory scale tests in a Tamman furnace in order to determine a suitable start-slag composition. The experimental set-up is shown in Figure 6. About 1.2 kg metal samples consisting of 10%V, 4-5%Mn and 1%P simulating the obtained metal from the hot slag reduction were melted in a Al_2O_3-crucible for selective oxidation. The designed slag formers, totally about 0.3 kg, were added on the top of the metal melt and the oxidizing agents O_2 or CO_2 gases were introduced to the metal melt via a Al_2O_3 tube. The temperature is automatically controlled at 1650°C by the power input. The melt was then refined by blowing CO_2 at 4 l/min for 180 minutes. A slag sample was taken once per hour.

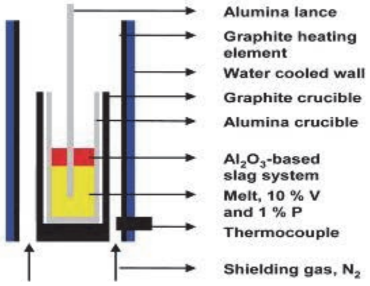


Figure 6 The experimental set-up of the Tamman furnace tests

After the initial tests in the Tamman furnace, more detailed experiments were carried out in two major campaigns in an induction furnace equipped with porous plug in the bottom of the furnace for introduction of the oxidizing gases and N_2. A metal bath of 130 kg with the same composition as described above for the Tamman furnace experiments was made up for the trials. O_2 and CO_2 were used as the oxidizing agents in the first campaign. In the second one, only CO_2 was used as it has shown a more selectivity for control of V/P-ratio and

V/Fe-ratio. Two slag former mixtures (A and B) consisting of CaO, Al_2O_3, SiO_2 and MgO were tested. The metal alloys for the selective oxidation tests were prepared using FeV, FeMn, LCFe, HCFe and FeP. The experimental set-up is shown in Figure 7a.

As the slag phase could not receive the inductive heating, only a fraction of the necessary slag amount (for pickup of all 10 kg vanadium in the metal) was added for a defined blowing time. Each test campaign was therefore divided into a number of heats to bring the vanadium content in the metal from about 8% to 1% and also to test different slag mixes. For each new heat the high V-slag from the previous heat was removed and a fresh slag mix was added for the next heat. The vanadium content thus decreases stepwise heat by heat.

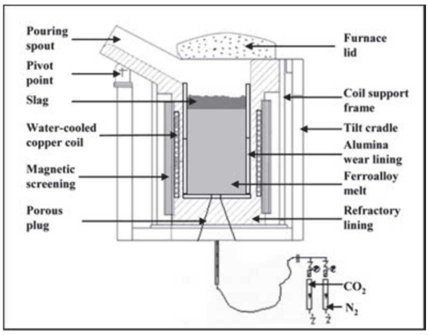


Figure 7a Experiment set-up for selective oxidation in the 150 kg induction furnace at MEFOS

3.5 Slag optimization

To support the development work on the described process concept, an extensive study on vanadium bearing slag systems has been included in the project financed mainly by the industrial partners, SSAB, LKAB, MEROX and Ruukki. The main activities of this subproject include theoretic study of the slag system involved, activity measurement in laboratory scale and valence determination of vanadium using XPS at Umeå University and titration at Beijing General Research Institute of Mining and Metallurgy (BGRIMM). The experimental set-up was described in a seminar and will not be detailed in this report. Both slag samples from activity measurement at KTH and from the induction furnace tests at MEFOS were investigated and compared. The samples were also studied in details by SEM. The research group is currently cooperating with Chalmers University of Technology using their “insitu” XPS for valence determination of vanadium in the slag.

The other important issue concerning the slag optimization is the V-solubility in the slags of interest. Maximizing the V-solubility and at the same keep the slag fluid is essential for a successful V-P separation during the selective oxidation step. Experiment set-up for the V-solubility study (see Figure 7b) has been installed at KTH and extensive experimental work has been carried out during 2009-2010. The oxygen potential is controlled by the gas mixture. It is arranged in such a way that the slag sample could be cooled under the same gas atmosphere. The slag samples with various VO_x-content were melted and equilibrated at certain temperatures under well controlled atmosphere. The slag samples were then quenched for microprobe analysis. If the VO_x-content is higher than the V-solubility, solid VO_x-bearing phase will be observed and identified.

A test furnace of the same kind has now built at Swerea MEFOS. It can be used for both vanadium valence determination studies and vanadium oxide solubility investigations.

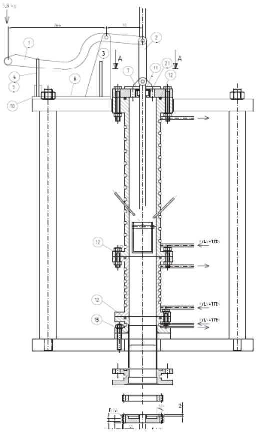


Figure 7b Experiment set-up for V-solubility study

3.6 Enrichment of vanadium in BOF-slag

As the specific energy and reductant consumptions represent up to 70% of the total processing cost of the VILD-concept, a higher V-content in the processed steel slag will significantly reduce the total process cost. A subtask, concentrating vanadium into target mineral phases by SiO_2-additon and control of the cooling rate, was also investigated. The experimental works were carried out at KTH and the mineral phase investigations by XRD and SEM were conducted in China. Another subtask was processing of BOF-slag by Tornado reactor, a cyclone like crushing and drying facility, followed by magnetic separation.

Another V-enrichment method called LUVA, based on metallurgical modification of the existing process has been developed during the second phase of the VILD-project. By this method the V-content in the slag could be increased by 80-100%. Industrial trials have been carried out at SSAB and Ruukki plants.

3.7 Treatment of the reduced LD-slag

The reduced LD-slag has been water granulated. The physical properties of the granulated slag were studied to see if it could be used for cement application. Figure 7C shows the slag granulation process.

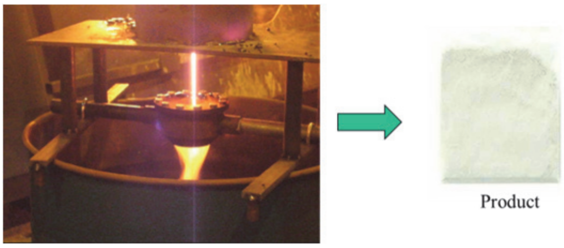


Figure 7C Granulation of the reduced BOF-slag during the trials

3.6 Use of FeV-product with high P-content

As mentioned previously, in the second phase of the VILD project (2009-2012) direct use of the FeV product obtained from the slag reduction without removal of phosphorus became part of the project. The experimental method used included:

- Preparation of metal samples with P-content of 0.005%, 0.015%, 0.025% and 0.033%
- Simulated hot rolling in lab-scale and pilot scale
- Characterization of the tested material using tensile tests, charpy test
- Compression tests for investigation of the susceptibility to hot crack

4. RESULTS AND DISCUSSION

4.1. Slag reduction

The main purpose of this task is to develop a technically feasible method for slag reduction aiming at a high V-recovery degree and increased possibility for external use of the slag. SSAB MEROX has set the V-limit for various external applications, see Table 1. It is shown that for use for road construction the V-level should be reduced to below 0.3%V and for use in cement industry lower than 0.1%V is required.

Table 1 V-limits for various applications of slag

Uses	Comments	V-limit ppm
Back to BF	Use already today, 50% of SSAB BOF-slag	-
Rock wool	No requirement yet	-
Cement		1 000
Road construction	Stable and low leaching properties required	3 000
Fertilizer	Required very low Cr-content	100
Dumping	As inert solid waste according to NFS 2004:10	1 000

4.1.1 Equilibrium and heat and mass balance

Extensive thermodynamic calculations on impact of different parameters on the reduction processes have been carried out in a Master thesis work [4] and by Ye [27]. The parameters considered include CaO/SiO_2-ratio, temperature and reductants like FeSi, Al, C and CaC_2. Results from the equilibrium studies shows that the most important parameter on slag reduction is the reductant/slag ratio. The slag basicity and temperature have only limited impact on the reduction. Table 2 shows calculated reduction degree of five elements of interest, as a function of the amount of added FeSi. The calculations were based on silicothermical reduction of a typical SSAB BOF-slag consisting of 41.9%CaO, 8.5%SiO_2, 25.2%FeO, 0.7%P_2O_5, 5%V_2O_5, 4.1%MnO, 1.3%Al_2O_3, 11.2%MgO and 1.6%TiO_2.

Table 2 Selectivity of FeSi-reduction of SSAB BOF-slag at 1600ºC, wt%

%FeSi*	Fe	P	V	Mn	Ti
6.3	78.62	16.26	5.18	4.37	0.00
7	**85.80**	36.39	8.70	6.45	0.00
7.7	90.68	**82.12**	14.78	8.98	0.00
7.8	91.17	**91.09**	15.83	9.32	0.00
8.4	94.72	99.56	29.22	13.14	0.00
9.9	98.95	99.56	**89.31**	29.71	0.00
11.1	99.96	99.56	99.91	**86.62**	1.34
14.5	99.99	99.56	99.99	98.15	24.94

*In relation to the amount of the BOF-slag, FeSi(75)

It is shown in the table that up to 80% of FeO in the BOF-slag could be pre-reduced without too much reduction of V-oxide. It is however difficult to separate V from P by selective reduction without compromising the V-recovery yield. It is also shown that for fully recovery of vanadium about 110 kg FeSi is needed for reduction of one ton BOF-slag. Similar results for Al-reduction are shown in Table 3.

Calculations on C- and CaC_2 reductions were also made and reported. In addition to that heat and mass balance calculations on the following cases were also performed and detailed in:

- total reduction using FeSi, Al, C and CaC_2
- 50% pre-reduction followed by final reduction by FeSi, Al and CaC_2
- 80% pre-reduction followed by final reduction by FeSi, Al and CaC_2

Table 3 Selectivity of Al-reduction of SSAB BOF-slag at 1600ºC, wt%

%Al*	Fe	P	V	Mn	Ti
5.8	73.07	14.70	5.19	1.99	0.00
6.9	**85.69**	45.68	12.02	3.52	0.00
7.5	89.88	**85.09**	19.76	4.71	0.00
9.4	98.06	99.56	**88.77**	18.05	0.00
10.5	99.93	99.56	99.96	**89.86**	0.92

*In relation to the amount of BOF-slag, Al

For stoichiometric reduction by FeSi a slag product with about 50%CaO, 29%SiO_2 and 13%MgO is expected. Metal obtained from the reduction is quite independent on the reductant use. It will contain about 9-10%V, 5-6%Mn and 1%P. For the experimental works in pilot and plant trials only FeSi and Al were used for practical reason. Both silicothermical and aluminothermical reduction will provide the necessary heat needed for the process. This makes it possible to use simple reduction systems.

4.1.2 Trials in laboratory scale

The most interesting results from the laboratory scale tests using graphite crucible are shown in Figures 8 and 9. It is shown that by addition of about 110g FeSi per kg BOF-slag over 95% of vanadium could be recovered in the metal phase and the residual V_2O_5-content in the slag is reduced to about 0.3% or lower, see Figure 9. With this FeSi/BOF-slag ratio a slag with 51-53%CaO, 28-32%SiO_2 and 11-13%MgO was obtained which was almost identical to the calculated one as shown in Section 4.1.1. The obtained metal contains about 10%V, 6-7%Mn and 0.6%P which is also quite close to the calculated one. These results indicated that the final products from the experiment are close to that expected at equilibrium. For higher FeSi-addition TiO_2 will also be reduced.

Details of all test results are described and discussed in a report [10]. For this project, the most important finding of these tests is that it has confirmed that vanadium in the slag could be reduced to below 0.1% which has been set as limit for use in cement industry.

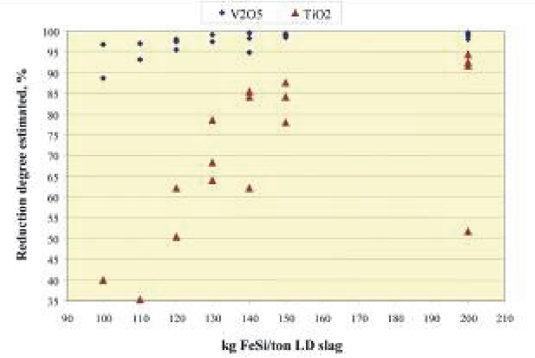


Figure 8 Reduction degree of V_2O_5 and TiO_2 vs. added FeSi(75) per ton BOF-slag, graphite crucible

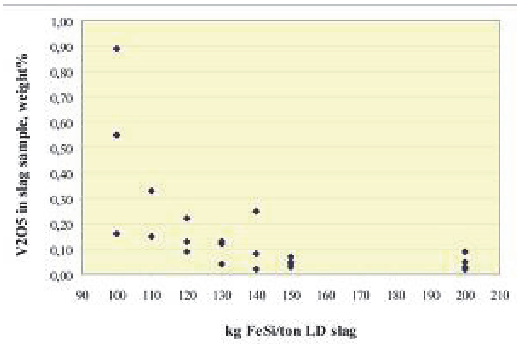


Figure 9 Content of V_2O_5 in the reduced slag vs added FeSi(75) per ton BOF-slag, graphite crucible

4.1.3 Direct hot slag reduction

The experiences from the direct hot slag reduction trials are summarized in Table 4. Generally speaking it could be concluded that it is possible to obtain good reduction results but it is not easy to control the process as you only have one single chance to ensure the success of the trials. Everything has to be correct to get the perfect reduction conditions.

Table 4 Main observations from the direct hot slag reduction trials

	Fe- and P-recovery	V-recovery	Temp control	Comment
Tapping - FeSi	Excellent	Poor	Poor	Ignition important
Tapping - Al	Excellent	Excellent	Poor	Violent reactions
Injection - pilot	Excellent	Moderate	Excellent	Need better V-recovery
Injection - SSAB	Excellent	Moderate	Excellent	Need better V-recovery
Kaldo - pilot	Excellent	Poor	Excellent	Poor slag/metal mixing

For all FeSi-reduction tests it seemed that the reaction occurred but reduction of vanadium oxide was not good enough. In one of the tests with FeSi75 when coolants were excluded and the simultaneous feed of BOF-slag and FeSi were excellent the reduction of vanadium was much improved and the slag basicity was close to the calculated stoichiometric one. The photograph of the produced metal and slag is shown in Figure 10. The observation learnt from the trials is that the ignition of the reaction between FeSi and BOF-slag is extremely important for the success of the process.

Figure 10 Produced metal and slag from one of the industrial trials using FeSi75.

The best results obtained were the test when aluminium was added during tapping. Vanadium in the slag could be reduced to about 0.1% but also significant reduction of SiO_2 occurred. The metal product had also high content of aluminium and vanadium, about 8.5%, phosphorus 1% and manganese 6.5%. All these indicated excellent reduction results. The reaction was however quite violent and hot and thus hard to control the reduction degree. As a result of that, significant amount of SiO_2 was also reduced.

As both silico- and aluminothermical reductions of BOF-slag are exothermical reactions, a large amount of the heat is released when the reactions start. Theoretically, the adiabatic temperature will be higher than 2000°C. In order to control that it was decided to use injection technique to control the reduction process and the temperature. By this approach it was possible to control the bath temperature to more stable level at about 1650-1750°C and the slag basicity. Close to totally reduction of iron and phosphorus could easily be obtained in all trials. No technical problem was encountered, inspection of the slag ladle showed that there was no significant wear on the lining after three completed trials. However, as shown in Table 4, the vanadium recovery was not good enough. By applying larger contact area between slag and metal will essentially further improve the recovery of vanadium and the ferrosilicon efficiency.

The reason for use of a Kaldo furnace to treat hot slag it is that the furnace is relatively simple and for the possibility to control the retention time. It was shown however that the retention time did not improve so much on the recovery degree of vanadium. The main reason is probably due to the high slag volume in relation to the metal volume in the bottom. In general, the slag/metal weight ratio is about 4 to 1, which corresponds to a slag/metal volume ratio of 12 to 1. This means that the reaction interface of slag and metal is too small to get an efficient reaction. A possible way to improve the reaction interface of slag and metal could be by applying a hot heel, thus saving of metals between taps.

4.1.4 Hot and cold slag reduction using arc furnaces

AC arc furnace processing

In order to further improve the controllability of the reduction degree and the process temperature. The hot slag reduction was also simulated in an electric arc furnace. Two test campaigns using the 5 MVA EAF furnace at Swerea MEFOS have been performed during 2009-2010, the schematically experimental setup is shown in Figure 5b. The advantages of using an AC or a DC-furnace compared to a more simple reactor is the possibility to treat cold BOF-slag, use of carbon based reductant (endothermic reaction), improved process control and higher degree of flexibility to compose different slag products. Various process parameters such as reducing agents and slag basicity have been investigated [5].

The BOF-slag, slag additives (silica sand or bauxite) and in some cases anthracite (treatment of cold LD-slag) were feed on a 5 tons metal bath low in carbon via a chute positioned in the middle of the three electrodes. Slag additives were chosen aiming for a liquid slag at a process temperature of 1650°C and for desired slag properties. Final reduction was done by injection of ferrosilicon and/or aluminium powder through the slag door into the molten slag. In an industrial process the most preferable method for the EAF case is to charge hot BOF-slag into the furnace. For the hot case, pre-reduction was instead carried out by injection of carbon based reductants into the molten slag.

Most of the iron, phosphorus and vanadium were successfully recovered in the metal phase. The recovery is 92-99 % for Fe, 96-99 % for P, 70-92 % for Cr, 50-96 % for Mn and up to 99% for V. This demonstrates the high reducing efficiency of this process concept. It was found that the efficiency of ferrosilicon is almost in the same range as of the aluminium and was used in most of the trials. The final V-content in some of the obtained reduced slag is shown in Table 5.

Table 5 Chemical composition of some of the typical slag samples from the AC furnace trials

Slag	%Fe	%V	%CaO	%SiO_2	%MnO	%P_2O_5	%Al_2O_3	%MgO
1	0.08	0.03	41.6	37.4	0.32	0.01	2.9	17.2
2	0.07	0.03	37.6	14.2	0.21	0.01	37.9	11.2
3	0.64	0.04	37.2	23.5	0.34	0.01	27.9	11.9

To summarize, the slag reduction using an AC furnace has shown that high reduction degree could be achieved in a controlled way. Pre-reduction using coal combined with final reduction using stronger reductants such as FeSi or Al seems to be a promising and cost efficient way to achieve high vanadium recovery and to make a good slag product.

DC arc furnace tests

In an ECSC-project a method called IPBM (In-Plant By Product Melting) based on carbothermal reduction of BOF-slag using a DC-furnace with hollow electrode was developed, the concept was tested in several campaigns. The DC-furnace with a hollow electrode was found suitable for the simultaneous treatment of slags and fine-grained products including those with volatile metals such as zinc and lead. By charging slag, slag additives, fine-grained by-products and reductant through the electrode into the DC plasma region the material was found to be efficiently treated. The DC furnace set up for slag reduction is shown in Figure 5b.

This concept was further tested and verified in a recently performed (September 2011) pilot campaign using Swerea MEFOS 3MVA DC-furnace as the basic equipment for co-treatment of steel slags and BF-sludge. The reductants being tested included anthracite and silicon carbide (SiC). Small amount of ferrosilicon and aluminium were added in some of the tests. The purpose was to investigate lowest possible residual V-content that could be achieved in the slag. Slag formers used for slag modification was silica sand and bauxite.

Overall more than 14 tons of BOF-slag and more than 15 tons of LUVA-slag were treated in 16 trials in the campaign. The pilot tests have verified that the DC-furnace is a powerful reduction tool for recovery of vanadium from steel slags. The reduction degree and slag composition were easily controlled by the reductant/slag ratio and the addition of slag additives. Blast furnace sludge (BF-sludge) was also treated in some of the trials for metal recovery and additional carbon source. The main results of the most important parameters obtained from the DC-trials are summarized in Table 5.

Table 5 Summary of the major test results

	V-recovery %	Energy cons MWh/ton slag	Flexibility	Reductants
LD-slag	>90%	1.3	Excellent	C, C+FeSi, C+Al, C+SiC
	>90%	0.9	Excellent	SiC
LUVA-slag	>90%	1.2	Excellent	C, C+FeSi, C+Al
	>90%	0.9	Excellent	SiC

The anthracite/slag rate was about 130 kg/ton slag and the energy consumption at a feeding rate of 1 ton cold BOF-slag per hour was about 1.6 MWh. The heat losses through the furnace wall, tap-hole and roof were 400 kWh. Less slag additives were needed for treating LUVA slag due to lower basicity (~1.6) compared to BOF-slag (~4).

The SiC/slag rate was about 110 kg per ton slag and the energy consumption at a feeding rate of 1 ton BOF-slag/h was about 1.2 MWh/ton. The heat losses through the furnace wall, tap-hole and roof were 370 kWh.

Theoretically, about 220 kg of metal with up to 10 % vanadium could be obtained and about 800-1000 kg clean slag per ton BOF-slag will be formed depending on the target slag composition. If LUVA slag is treated, a metal with up to 15 % vanadium could be obtained instead.

4.1.5 Use of the reduced BOF-slag

Two major slag products have been considered and made during the various slag reduction trials. One is granulated glassy slag for cement use and the second one high Al_2O_3 calcium silicate slag also aiming for cement use. Figure 11 shows one of the obtained high Al_2O_3 calcium silicate slag product. As shown it is white meaning it has been well reduced.

Figure 11 High Al_2O_3 slag product for cement use

Two of the water granulated reduced slag samples aiming for cement used were tested for its hydraulic properties. One is from AC furnace reduction and the other from DC-furnace reduction. The granulated slag samples were crushed, ground and mixed with OPC. The strength of these was measured after 2, 28 and 91 days and compared with a reference sample which was consisted of standard slag product of SSAB MEROX, MERIT5000 mixed with OPC. Table 6 shows the test results as compared with reference mixture. It is clearly shown that the water granulated VILD-slag product has the same hydraulic property as MERIT5000.

Table 6 Physical properties of the obtained ViLD slag products compared with the reference MERIT5000/OPC

	AC-slag sample	DC-slag sample	Merit 5000/OPC
Strength, MPa			
2 days	12.8	15.6	16.5
28 days	43.6	54.4	52.2
91 days	56.7	60.2	61.0
Glass content	73.2	97.3	99
Density, kg/m^3	3018	2961	2924
Blaine, m^2/kg	460	466	505

4.2. Selective oxidation

In order to make it possible for direct production of a standard FeV product based on the proposed concept, vanadium has to be separated from phosphorus. The concept of selective oxidation is to selectively oxidize vanadium in the obtained metal from slag reduction to a high vanadium slag with lowest possible oxidation of P and Fe. The required ratios of V/P>500 and V/Fe>1 in the high vanadium slag has to be satisfied.

4.2.1 Results from Tamman furnace tests

The main purpose of these tests was to identify a suitable slag system as base for selective oxidation. The slag should have a high capacity for vanadium oxides and a low one P_2O_5. The slag should also have a reasonable melting point so that a good metal and slag separation would be possible.

A liquid and glassy slag containing up to 15 % V_2O_5 was obtained. Details of the results are shown in a Master Thesis [3]. Three major phases was found in SEM studies as shown in Figure 12. One slag phase consisting of the charged slag formers with 1-2%V (point 5 to 7) and the other one with about 20-27%V (point 1 to 4).. Whether the two oxide phases have been formed during solidification or due to liquid immiscibility must be further investigated. Metal droplets (point 8 and 9) were also identified. They have a composition as the expected one, about 10%V, 1%P and 5%Mn.

These investigations confirm that good separation of metal and slag is essential to reach the aimed V/Fe- and V/P-ratios.

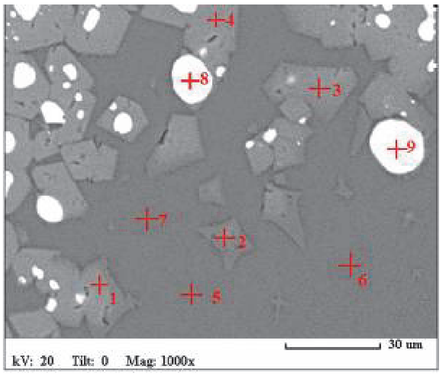


Figure 12 Point analyses of the slag phase (180 minutes)

4.2.2 Results from trials using the 150 kg scale induction furnace

Two test campaigns in the 150 kg induction furnace at MEFOS have been performed. The initial one in 2006 in a Master Thesis work [3] and the other one in 2007 to reproduce some of the good results obtained from 2006 and also to cover the whole range of the selective oxidation process, i.e. to oxidize vanadium in the metal bath from about 10%V to below 1%.

4.2.2.1 Results from Campaign 1, 2006

Test program for campaign 1 is shown in Table 7. All together 10 test heats have been performed in campaign 1. Iron and ferroalloys were melted during 2 to 3 hours in an inert nitrogen atmosphere. Upon attainment of a bath temperature of approximately 1600ºC, slag formers were charged. The melt was then refined by blowing O_2/N_2 or CO_2 via porous plug in the bottom of the furnace. After a certain blowing time, the slag was sampled and skimmed off for the heat and a new slag mix was added for the next heat.

Table 7 Test program for campaign 1, 2006

Heat	Gas [l/min]			Time [min]	Slag formers [kg]	Slag mix [no.]
	O_2	N_2	CO_2			
1			10	30	0.5	A
2			10	30	1.0	A
3			10	30	0.5	B
4			10	30	1.0	B
5			10	30	1.0	A
6			10	30	2.0	B
7			10	30	2.0	A
8*	5	5		30		
9*	5	5		30	2.0	A
10*	5	5		20	2.0	B

*Start with a new melt

Metal analysis during the selective oxidation as a function of blowing time of oxidizing gases (expressed in terms of Heat no.) is shown in Figure 13. As shown the V-content was gradually decreased from 9.45% to 3.16 % (Heat 7) by CO_2-oxidation. For heat 8-10, a new melt was prepared and an O_2/N_2 mixture of 50:50 was used for the oxidation. For both cases, V-decreases and P-content remains more or less constant.

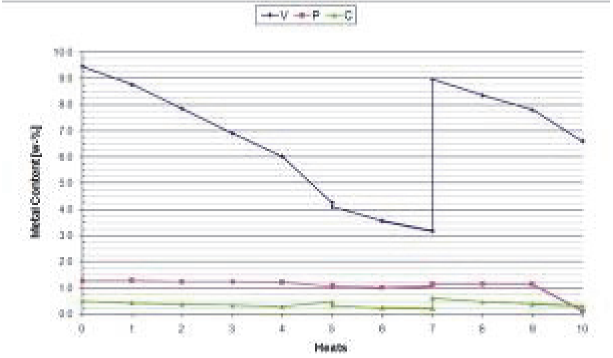


Figure 13 V-, P and C-content in the metal for all 10 heats

As shown in Table 8, a high V-slag could be prepared. The target V/Fe-ratio (>1) could be achieved in four heats and the V/P-ratio (>500) in three heats with CO_2 as the oxidant as shown in Table 9. This confirmed the theory that CO_2 is more selective with regard to the V/Fe- and V/P-ratio. The wear of the porous plug was also substantially increased when oxygen was used. Only three heats were performed with oxygen.

Table 8 Slag analysis, campaign 1, 2006

Heat no.	Al_2O_3	SiO_2	V_2O_5	CaO	MnO	Fe_2O_3	MgO	P_2O_5
1	3.8	2.1	25.5	0.6	1.0	64.9	0.4	0.8
2	7.0	6.4	34.0	2.1	1.7	45.7	1.8	0.3
3	6.9	10.0	47.1	3.3	1.9	29.1	0.8	0.2
4	7.2	17.0	42.6	5.4	2.4	24.4	0.4	<0.1
5	8.8	14.4	43.3	4.7	3.2	23.6	0.7	0.1
6	9.5	20.2	25.4	5.7	2.4	35.1	0.5	0.2
7	17.6	20.9	24.8	7.8	2.5	22.8	2.4	<0.1
8	5.5	1.9	24.7	0.3	1.3	62.4	2.7	0.5
9	14.2	9.1	24.9	3.6	2.2	39.8	5.0	0.3
10	12.8	16.7	18.7	4.9	1.6	41.6	2.7	0.4

Table 9 The obtained V/Fe- and V/P-ratio, campaign 1, 2006

No	1	2	**3**	**4**	**5**	**6**	**7**	8	9	10
V/Fe	0.3	0.6	**1.3**	**1.4**	**1.5**	**0.6**	**0.9**	0.3	0.5	0.4
V/P	41	146	**302**	**1094**	**556**	**163**	**637**	63	107	60

It is shown from this campaign that it is possible to make a high V-slag with good V/P-separation.

4.2.2.2 Results from Campaign 2, 2007

In order to confirm the promising results from some of heats from Campaign 1, it was decided to carry out a second campaign using the same experimental set-up and procedure with focus on CO_2 and slag A. Selectivity at lower V-concentration in the metal phase (< 3 %) was also investigated in this campaign.

Details of the test program were described in a separate report [9], here only the most interesting results will be summarized and discussed. Altogether, 27 test heats were performed covering the V-range from 8.2% to 0.5%. For heats 10-17, special samples were made for thermodynamic investigations. For this purpose, a P-free metal alloy was used, oxygen potential and temperature in the melt was measured for each sampling. Some of the results from thermodynamic studies will be briefed in Section 4.3.

Figure 14 shows the analysis trend of V, P and C in the metal bath as a function of CO_2-blowing time (expressed in terms of heat no.) during selective oxidation. The steady and even decrease of vanadium and an almost constant content of phosphorus indicate that there is a good selectivity of oxidation of vanadium prior to iron and P even at low V-contents.

In purpose to study the equilibrium effect with time only nitrogen gas was used in heat 4, 5, 14, 15 and 18. It can be seen in Figure 14 that the V- and P-content in the metal phase is quite stable even after 20 minutes of N_2-purging. Two minutes of that seem sufficient in the end of each heat for this kind of test.

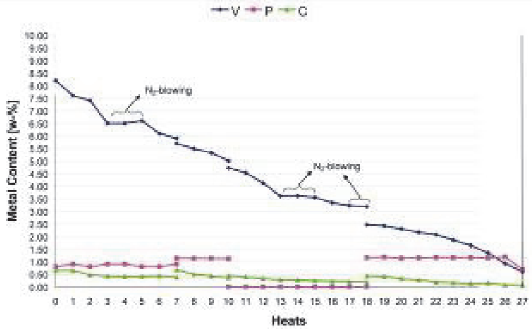


Figure 14 V-, P- and C-content during selective oxidation, campaign 2, 2007

The slag analysis throughout the test campaign is plotted in Figure 15. It is shown that the slag analysis is consistent throughout the test heats.

It is clearly demonstrated by figures 15 and 16 that the V/Fe- and V/P-ratio based on the slag analysis is well beyond the targeted values of 1 and 500 respectively. There is no V/P-figure for heat 10-18 since the melt for those heats was free of phosphorus. The V/Fe-ratio in campaign 2 in general varied between 1.0 up to 2.5.

In most cases, the P_2O_5-content was below the lowest detectable level (0.005 %) and it is not possible to shown in Figure 15. The ratios between CaO, Al_2O_3 and SiO_2 in the final slag were almost identical as the initial ones. This means that the wear of the Al_2O_3 lining was rather limited. The most important results are the targeted ratios of V/P and V/Fe which are shown in Figure 15 and 16.

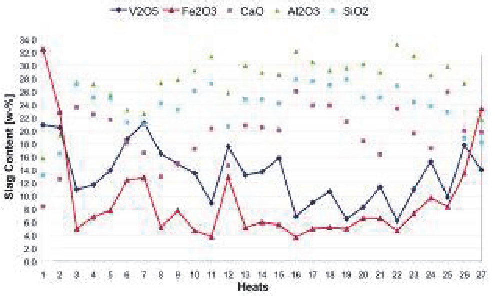
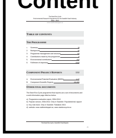
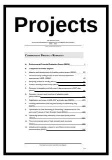


Figure 15 Composition of slag from each heat, campaign 2, 2007





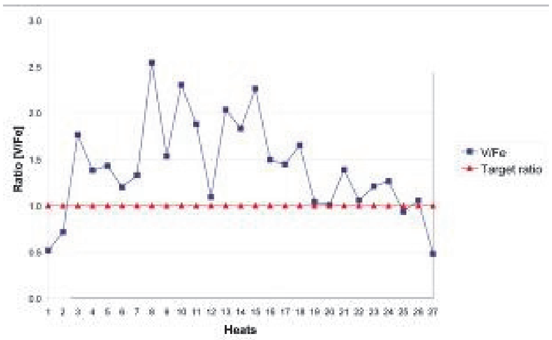


Figure 15 V/Fe ratio in the slag from each heat

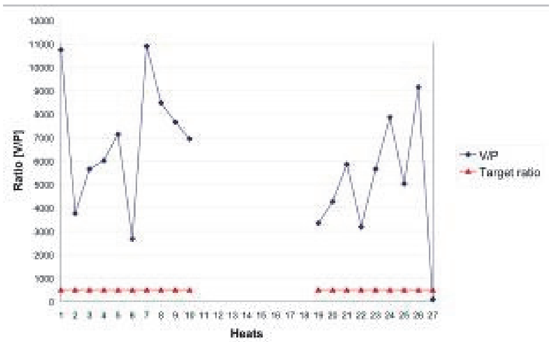


Figure 16 V/P ratio in the slag from each heat

A liquid and glassy slag could be obtained. This is of great importance since a viscous slag will result in a slag with small metal droplets and hence make it difficult to achieve the target V/P-ratio due to the high content of P in the metal. It was observed during the trials and also indirectly confirmed by SEM investigations that there was a clear increase of the slag viscosity when the VO_x-content was approaching 20 %.

It is believed that in pilot and full scale reactors, handling of slag will be much more practical and conditions for metal and slag separation will be much improved.

During 2009-2012, works on the vanadium solubility in the slag system of Al_2O_3-CaO-SiO_2 have carried out. About 40 samples have been prepared and sent to our cooperation laboratory in China for microprobe analysis. The equilibrium composition of the slag and the V-solubility is under investigation. The VOx solubility in the considered slag system is found to be in the range of 10%V_2O_3 as shown in Figure 17.

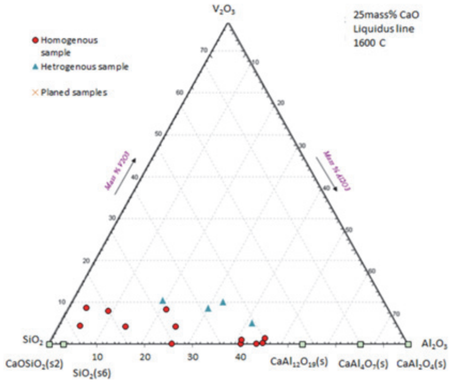


Figure 17 Phase digram of the for the V2O3 solubility study

4.3. Thermodynamics of VOx-bearing slag system

As indicated Section 4.2, it seems that slag viscocity increases with V-content in the slag. In order to understand the mechanism and also be able to estimate the activity of VOx it is essential to know the oxidation state of the vanadium oxides in the slag, the valence of vanadium. Samples from MEFOS induction furnace tests (see 4.2.2) and from KTH laboratory scale tests were used for this study. The valence determination methods considered include:

- titration in oxygen-free atmosphere
- ESR + titration
- Mössbauer + titration
- XPS

It is shown in Figures 18-19 that as the oxidation proceeds, more and more V is selectively oxidized to VOx and V-content in the slag increased with oxidation time. It is also clearly shown that at a lower V-level, the slag is fluid and clean without metal droplets. As the V-content increases, the slag becomes more viscous and hence many metal droplets suspended in the slag.

Valence determination of Slag I by XPS performed in Umeå University, Sweden shows that the ratio of V^{5+}/V^{4+} is 1:1. Titration determination carried out in BGRIMM, China shows following distribution of V of the same slag sample:

- 43.50 % V^{5+}
- 45.32% V^{4+}
- 7.25 % V^{3+}
- 3.93 % V^{2+}

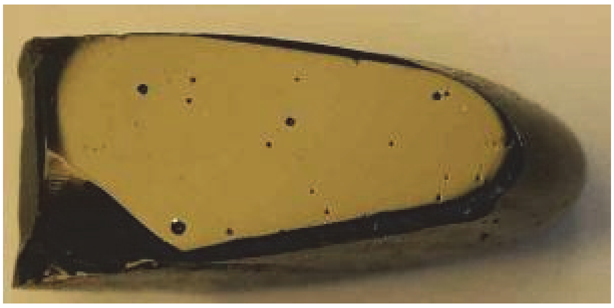


Figure 18 Slag I: 7%V_2O_5, after 12 min oxidation with CO_2, sample from test campaign 2

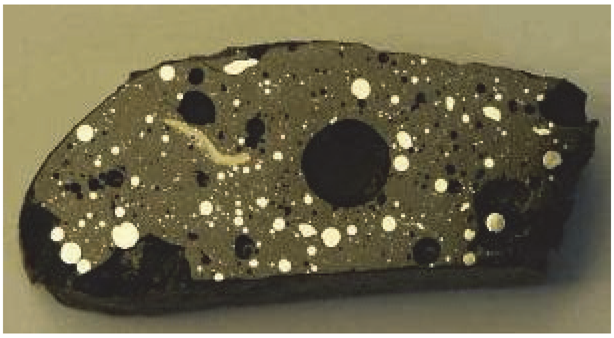


Figure 19 Slag II: 13%V_2O_5, after 55 min oxidation with CO_2, sample from test campaign 2

These results indicate that most of the vanadium in the slag concerned exists almost equally as V^{5+} and V^{4+}. Twenty more samples will be prepared in 2008 and analyzed in the same way. By doing these tests, the validity and reliability of the used methods will be proved and improved. They will also show if XPS is good enough for determination of vanadium valence. Once the vanadium valences in the slag are known it will be possible to provide the necessary thermodynamic data for slag optimization for the selective oxidation step, a fluid slag with high vanadium and low phosphorus content.

During 2009-2010, an experimental furnace for small scale tests with possibility for good atmosphere control has been built at Swerea MEFOS furnace for this purpose. This made it possible to prepare a large number of slag samples necessary for the valence determination. Co-laboration with Chalmers University of Technology on the in-situ XPS analysis has also been intensified during this period. Valence determination using XANES technique has been conducted at Stanford University, USA and compared with the XPS analysis of Chalmers and the analysis based on wet chemical analysis by BGRIMM, China.

4.4. Direct use of the obtained FeV from slag reduction without P-ermoval

This study is performed by Swerea KIMAB. The aim of this subproject is to clarify if the intermediate metal alloy, with about 10% V, 6% Mn and 1% P, obtained from the reduction of LD-slag can be used directly without negative impact on the steel product qualities. This study includes analysis of results of tensile testing, Charpy testing and microstructure studies done on a 150 kg scale with two different P-contents: 0.011% (as reference) and 0.025% in hot-rolled micro-alloyed steel. The results of tensile tests of both the rolling and the transverse direction show no scattering. There is no indication that phosphorous has caused some deterioration. No negative effect has been found on the toughness of the sample with higher phosphorous. A plateau at higher temperature (100ºC) has been observed. Comparison of the hardness of the material with 0.025%P and production materials showed no effect of higher phosphorous. Toughness of the HAZ-simulations for two different cooling rates “$\Delta t_{8/5}$”, 20s and 40s has shown no deterioration in toughness from the increased P content. Scanning Electron Microscopy with EDS/WDS showed no further precipitation of phosphorous and/or vanadium.

Based on the test results obtained so far it is concluded that the P-tolerance in the HSLA steel qualities is actual higher than the normal tolerance levels. The project is still going on and it is highly interesting for the vanadium users.

4.5. Production of LUVA-slag

The LUVA slag making process is initially developed by SSAB Luleå works and laterly further developed in the second phase of the VILD project together with the other participating industrial partners and Swerea MEFOS. It is a two-step blowing process similar to the Japanese MURC process. Instead of P-slag, a V-slag is produced in the LUVA process as shown in Figure 20. The process concept has also been successfully demonstrated at Ruukki Raahe plant.

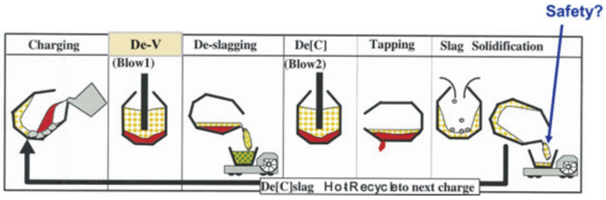


Figure 20 LUVA slag concept

The advantages of the LUVA process include:

- LUVA slag can be sold externally
- LUVA slag can be used as V-feed in the VILD process and will make the VILD process much cheaper
- V is enriched in a spinel phase which is P-free and which might be possible to be separated from the slag

The LUVA-slag making is already in its industrialization stage and the technology will be implemented during 2012-2013.

4.6. V-concentrating and enrichment

As indicated in Section 3.4, the process cost will decrease almost proportionally with increased V-content in the BOF-slag. Attempts have been made in this project to enrich vanadium content in a certain fraction or special target mineral phases. Treatment by the Tornado process has been tested at MEFOS with subsequent mineral processing tests in Finland, however without great success.

Metallurgical manipulation to concentrate vanadium into targeted phases has also been studied in this project. Figure 21 shows results from a test where vanadium was concentrated into the solid solution of the $3CaO{\cdot}V_2O_5$-$3CaO{\cdot}P_2O_5$-$2CaO{\cdot}SiO_2$ system.

The grey colored phases remarked by 9 and 10 in Figure 19 have a V-content of up to 30-33%. The main challenge for this method is the cooling control of the slag in the industrial scale. Also the mineral separation method on such fine grains of the V-concentrated phases has to be developed to make it interesting.

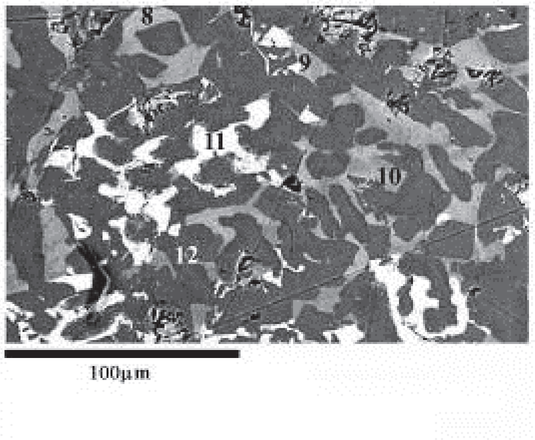


Figure 21 Modified BOF-slag and the V-concentrated phases

V-enrichment has also been studied by concentrating V into a spinel phase. Figure 22 shows that a stable spinel with high content of vanadium could be formed and grain size of the V-rich spinel phase could be enlarged by controlled slow cooling. The preliminary mineral separation studies have shown however that it is so far not feasible to clearly separate the spinel phase from the other minerals in the slag as the vanadium spinel occurs mostly as mixed grains, not as free particles, even in the very fine particle size.

V-enrichment by minor modification of the steelmaking process has also been investigated with promising results.

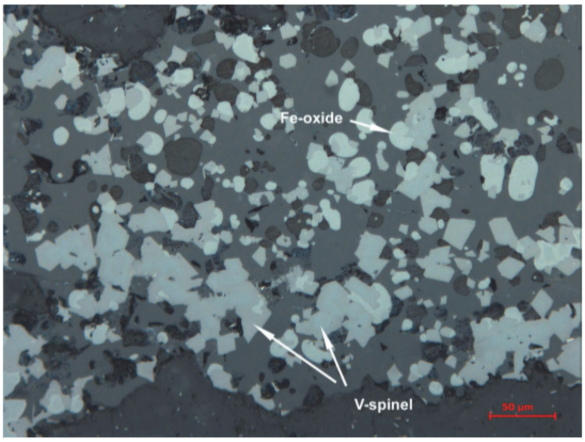


Figure 22 SEM picture showing the stable V-enriched spinel phase

5. SUMMARY AND CONCLUSIONS

The VILD project has been a big part of the success of the MISTRA financed Eco-Steel Cycle Program. The project has been awarded the Inspiration Price 2011 of the Swedish Recycling Industries (ÅI). The major outcomes of the project are summarized in the followings:

- LUVA-slag: by minor modification of the existing iron- and steelmaking cycle, the V-content in the steel slag could be doubled. The V-enriched slag could be sold as feedstock for V_2O_5 production or as a high value raw material for the slag reduction process
- Commercialzation of the LUVA-slag process is ongoing and the first commercial LUVA-slag delievery is expected in the end of 2013
- Efficient slag reduction for high vanadium recovery has been achieved. Both BOF-slag and LUVA-slag have been tested with promising results.
- Detailed CAPEX and OPEX analysis based on the most suitable reactor has been shown very high profitability of the process
- High quality slag product with vanadium content below 0.1% could be obtained after reduction and this has been confirmed in all test campaigns using DC and AC furnace
- V-enrichment in the BOF-slag by concentrating vanadium in a target phase C_2S is possible but not practical.
- Two different phosphorus removal concepts for selective oxidation of vanadium from a Fe-V-P melt is under investigation, the results so far is promising but more work is needed
- Investigation of possibility to direct use the FeV product with some P has so far indicated that the tolerance of P in the V-alloyed steel qualities is much higher than the normal restrictions. This will open new opportunities to use the "less" clean but good enough and much cheaper V-source as alloying material

The industrial significances of this project are demonstrated by dedicated industrial PhD students and the strong financing supports from LKAB, SSAB, MEROX and Ruukki to the basic studies on slag optimization and industrial trials.

In addition to the main activities mentioned above SSAB and PRISMA (Research Centre for Process Integration) at Swerea MEFOS has also made an analysis on consequences of the existing steelmaking processes if the VILD-concept is implemented in the industry.

6. FURTHER UTILIZATION

The technical results and know-how obtained from the VILD-project will be utilized as described in the followings:

- **LUVA-slag operation**: Industrial implementation of the LUVA-slag process is going on and it is expected that commercial production of the slag will be started next year.
- **Slag reduction concept (VILD-process):** The concept of slag reduction of LD- and LUVA-slag for production of commercial vanadium product, pig iron and clean slag products will further used for evaluation for further smelter.
- **Selective oxidation**: The knowledge obtained from the PhD studies on vanadium valence and vanadium oxide solubility in the CaO-SiO$_2$-Al$_2$O$_3$-VO$_x$ system will used for optimization of the existing steelmaking process, the LUVA-process (under implementation) and the investigated slag reduction process (VILD-process)
- **Direct use of high P FeV:** The promising results from this project activity will be used for preparing a technical and scientific document for marketing and selling the Fe-alloy (10-15%V and 1%P) obtained from the VILD-slag reduction process in the future.
- **Technical properties of the reduced LD-slag**: The technical properties of the reduced slag have been investigated carefully in details by SSAB MEROX and shown excellent results. The results will be utilized in a future VILD-slag reduction smelter for selling of the clean slag product

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7. DISSEMINATION AND PUBLICATIONS WITHIN THE CURRENT PROJECT

Refereed publications

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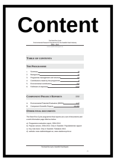

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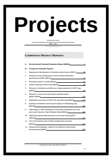

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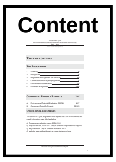

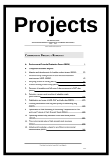

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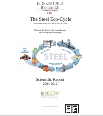

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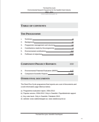

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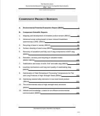

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2004 – 2012
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RETENTION, RECOVERY AND RECYCLING OF VALUABLE METALS (88032+88034)

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**Research and Development (R&D), Uddeholms AB

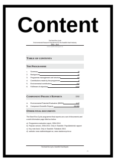
Abstract

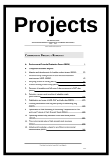
The project work was carried out in two parallel directions, fundamental and applied studies. In the applied part, three different aspects, viz. Retention of metal values in the steel bath, Recovery of metal values lost in the slas phase and dust and Recycling of the recovered metals as well as the residual slag were investigated.

In the **fundamental studies** part: thermodynamic studies have been carried in with respect to Fe-Cr-C, as well as Fe-Cr-C-N alloys by solid electrolyte galvanic cell method using CaF_2 solid electrolyte. The results were confirmed by ab initio calculations. The valence state and thermodynamic activities of the oxides of Cr and V in steel slags were carried out by slag-gas equilibration studies. A mathematical correlation was established for estimating the ratio of $Cr^{2+/}Cr^{3+}$ as a function of temperature, partial pressure of oxygen and slag basicity based on the results in the present group obtained by X-ray Absorption Near Edge Structure, (XANES) method and High temperature Knudsen Cell Mass spectrometry. This has clarified the uncertainties in earlier works regarding the valence states of stainless steel slags. XANES method was also adopted to determine the oxidation states of vanadium in the CaO-MgO-Al_2O_3-SiO_2-VO_x slag system. The results indicate that, x in VO_x increases with increase of slag basicity, indicating that higher basicities stabilize higher vanadium oxidation state. On the other hand, higher temperatures stabilize lower vanadium oxidation state.

In the **Retention part,** decarburization of steel melts under controlled oxygen partial pressure was carried out theoretically and experimentally. Theoretical studies showed that it could be advantageous to use CO_2 both as an oxygen supplier as well as a diluents instead of Ar. By using CO_2 in the decarburizing gas mixture, minimization of Cr losses to the slag could be noticed. A generic model was been developed to describe the reactions between liquid metal and gas bubbles. The potential of the model is illustrated by its application in predicting the evolution of Cr and C contents in a Fe-C-Cr melt during injection of different O_2-$_-CO_2$ mixtures. The model can also be advantageously used in conjunction with mixing models or models based on CFD to simulate larger systems. The experimental results obtained from experiments conducted in a 1 kg scale induction furnace experiments indicate that the predictions of the model could be validated by the experimental results. These experiments indicate that the Cr-losses can be significantly lowered by replacing the oxygen with CO_2 in the injected gas, specifically for Fe-Cr-C melts with carbon levels higher than about 0.8 mass%.

Within the **Retention part** of the project, a new procedure was invented for Mo addition in EAF furnace in the making of tool steel grades. Theoretical assessment of Mo-additions and plant trials were carried out. Design of Mo precursors from MoO_3 concentrates and mill scale was carried out. The evaporation rate of pure MoO_3 was studied by TGA and compared with the evaporation rates from mixtures of MoO_3 with CaO, $CaCO_3$, MgO. It was found that MoO_3 can be stabilized by mixing with CaO, MgO or $CaCO_3$ and heating the mixtures to form the appropriate molybdates. The results were confirmed by high temperature XRD. The Mo yield by use of three different Mo alloying mixtures (MoO_3+C; MoO_3+C+FeO_x; and MoO_3+C+CaO) was tested both in laboratory and industrial experiments. During laboratory experiment, both in 16- and 500-g-scale trials, Fe_2MoO_4





precursor mixture (MoO_3+C+FeO_x), showed the Mo yield is up to 98 %, which can be explained by the absence of molybdenium evaporation from this substance. During industrial trials it was found that for the Fe_2MoO_4 precursor mixture (MoO_3 + C + FeO_x), the Mo yield in 5 ton induction furnace reached 98 % and in the 60 ton EAF the yield was reached to 99.5%. This is a significant achievement in the process optimization in the case of Uddeholms AB.

In ***the Recovery part*** *of the project, the salt extraction of valuable metals from slags was investigated for the extraction of Cr and Mo using suitable fluxe.The electrochemical behavior of different metal ions, Cr(III), Cr(II), Cu(II), Fe(III), Mg(II) and Mn(II) was studied by using cyclic voltammetry at 827^{o}C in ($CaCl_2$-NaCl-KCl) system. The deposition process of Cr(III) species was found to consist of two electrochemical steps, Cr(III)/Cr(II) and Cr(II)/Cr(0) exchanges. A new salt system based on NaCl-KCl-LiCl ternary system has been studied to lower the molten salt process temperature. A modified electrolysis cell design was developed to produce the $AlCl_3$ in situ and recycle the Cl_2 gas in the process cell. The present results show that the molten salt extraction process offers a promising route towards the recovery of metal values from slags, low grade ores and rare metals from recycled electronic materials. Successful electrodeposition of ferrochrome from the salt bath after salt extraction has been demonstrated. Even non-ferrous industries like Stena Metall AB and INCO Nickel, Canada have shown strong interest in the salt process.*

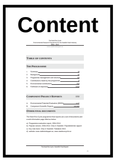
In the ***Recovery part****, process developments towards the recovery of Fe and Mn from steel slags by oxidation-electromagnetic separation route were carried out. Oxidation of FeO and MnO in the ternary FeO-CaO-SiO_2 and quaternary FeO-CaO-SiO_2-MnO slag systems respectively were investigated. The mechanism of oxidation of FeO in molten slags was analyzed by combining advantages of Confocal Scanning Laser Microscopy and Thermogravimetric technique. The TGA experiments showed that, during 10-15 min, 70-90% of oxidation could be achieved. Increase of temperature was found to cause an increase in the rate of the reaction. Kinetics of the crystal precipitation from the liquid FeO-CaO-SiO_2 and FeO-CaO-SiO_2-MnO slags has been investigated by Confocal Scanning Laser Microscopy. Successive CSLM images showed the crystal formation during oxidation. Nanocrystalline manganese ferrates (ca 25 nm) could be synthesized by tailoring the process parameters suitably.*

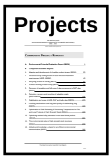
It was also demonstrated that the slag residue both in the case of salt extraction as well as oxidation routes would have heavy metal concentrations well below the tolerance limits and thus, could be ***recycled*** *even in non-metallurgical applications.*

1. INTRODUCTION

The present day steel industry is under extreme strain due to world-wide competition as well as stringent environmental constraints due to global warming. It is realized that drastic changes in steel processes towards environmental improvements cannot be easily accommodated. Modifications of existing processes and design of new process steps can only be enabled using process fundamentals which would lead to a win-win situation due to environmental as well as economic advantages.

It is common knowledge that alloying elements like Cr and V form stable oxides and that the recovery of these





metals in the elemental form is energy-intensive. A simple mass-balance consideration reveals that:

1. it would be useful if these elements can be retained in the steel, minimizing the loss of the same to the slag or dust, referred to in this project as **“Retention”,**
2. recovery of the elements from the slag and dust phases in a suitable form needs to be enabled so that these valuable metals can be reused in the steelmaking cycle, referred to in this project as **“Recovery”**, and
3. the recovered metals, as well as the rest products (slag and the dust), could be recycled, referred to in this project as **“Recycling”**.

With the industrial expansion of progressing countries like China and India, and a consequent increase in the prices of the alloying elements, there is a strong economic motivation for the recovery of metal values from slags and dust. For example, in the production of high alloy steel of 1 ton at Uddeholms AB, Hagfors, Sweden [1], the amount of Mo per ton of steel is about 13 kg. The slag contains 0.4 kg Mo and the dust about 1 kg. Apart from the fact that there is a strong economic value, about SEK 1500 for Mo per ton steel produced which is lost in the slag and the dust, this amount of Mo ends up in the environment. The situation is similar even in the case of Cr, Ni, Ta, Nb and V. Design of suitable process steps towards retention, recovery and recycling of these metal values is the primary motivation of the present project.

2. OBJECTIVES

A general solution towards retention, recovery and recycling is a diffuse target. On the other hand, in the present work, specific project steps are being looked into, with reference to plant practice of Uddeholms AB in Hagfors, Sweden. Solutions towards the loss of metal values in the EAF practice at Uddeholms AB are critically analyzed from process fundamentals, and solutions are offered. The intentions are that the solutions can be suitably adopted for other steel plants in Sweden, i.e. Sandvik, Avesta and Hofors, with appropriate modifications as mentioned in the project task in the initial project application [2]. New generation technologies have been initiated, and the results are being disseminated and implemented.

3. METHODS (STRATEGY)

The strategy adopted in the present project has been tailored primarily to the EAF practice of Uddeholms AB. The present project approach consists of five essential components, *viz.*

i) Thermodynamic studies of Fe-Cr-C and Fe-Cr-C-N alloys, as well as Cr- and V- bearing slags (at low concentrations of these elements)

Providing fundamental data to the other participating groups is a very important part of the present research (as mentioned by the project reviewers). The thermodynamic studies of the alloy systems are essential in designing the new approach to decarburization of alloy steel. The slag properties that are needed are the thermo-chemical and thermo-physical property data that are missing, especially for the systems relevant to high alloy steel-making. The present research group has built up excellent measurement facilities for such studies. The division has also developed the following commercial software for thermodynamic studies for steelmaking:

- the “Thermosteel” software for activity calculations[3]
- the “Thermoslag” software for the computation of thermodynamic activities, sulphide capacities, densities and viscosities[4]

ii) Retention of Cr in the steel melt using oxygen partial pressure control

In the case of the decarburization of alloy steels, especially stainless steels, the oxidation of carbon is carried out by blowing O_2-Ar mixture (AOD process). While at the initial stages, carbon is preferentially oxidized, at later stages, as the oxygen potential of the bath increases, elements with strong affinity to oxygen (as for example Cr) will be oxidized and will be lost to the slag phase. In order to minimize this loss, it was proposed in the present work, to use O_2-CO_2(-Ar) gas mixtures with high CO_2 contents at the beginning of blowing and increasing the oxygen content in the gas in the later stages.

iii) *Minimization of metal loses in dusts by process modification*

In the addition of alloying elements, losses are encountered, especially in slag and dust. Minimization of the loss of these metals from dust is very important from environmental, as well as economic view points, as dust processing requires additional process steps. Once again, the EAF practice in Uddeholms AB has been taken up for investigation.

iv) Extraction of metal values by using a salt extraction process

Despite the precautions taken in process optimization, in view of the thermodynamic and kinetic constraints, valuable metals are always lost in the slag. Chromium in stainless steel making slag can be usually 2-4 %, according to information from Outokumpu in Avesta, Sweden[5], and it could go up to as high as 8 %. During the EAF process at Uddeholms AB, 2.5% of the Mo added to steel is lost to the slag[1]. The presence of such metals, apart from the economic losses, poses a serious challenge to the disposal of the slags. The present group has been devoted to developing a new process concept in this regard.

v) Recovery of iron and manganese values from the liquid slags by oxidation and subsequent electromagnetic separation

FeO in EAF and BOF steel making slags can be usually 20-30 %. During the EAF process at Uddeholms AB the FeO content in slag could be 40% for some steel grades [1]. The present group has proposed a way of iron recovery from the liquid slags [6]. The concept was based on transformation of non-magnetic wustite (FeO) to magnetic magnetite (Fe_3O_4) using an oxidation atmosphere. Experiments on the ternary CaO-FeO-SiO_2 and quaternary CaO-FeO-SiO_2–MnO systems, followed by thermodynamic and kinetic modelling, showed the feasibility magnetite/manganese ferrite production with further separation potential [6]. The produced ferrites could be in the form of nano particles with optimized magnetic properties [6]

3.1. Thermodynamic studies of Cr- and V- bearing slags

3.1.1. Thermodynamic studies of Fe-Cr-C and Fe-Cr-C-N systems [7,8, 9, 10]

In order to study the thermodynamic stabilities of Cr in Fe-Cr-C, as well as Fe-Cr-C-N alloys, a solid state galvanic cell method with CaF_2 as the solid electrolyte were designed. The total cell reaction is given in Appendix A together with the cell arrangement (see Figure 1). Extreme care was taken to purify the argon gas atmosphere in the cell compartment so that the oxygen partial pressure in the gas was less than 10^{-24} bar. This is illustrated by the phase stability diagram presented in Figure 2 in Appendix A.

3.1.2. Thermodynamic studies of Cr- and V- bearing slags

The objective of the present investigation is to measure the thermodynamic activity of chromium and vanadium oxides in CaO-SiO_2-MgO-Al_2O_3-CrO_X(VO_x) molten slags by using the gas equilibrium technique. The P_{O2} was controlled by the mixture of CO-CO_2-Ar. The present division has the necessary instrumentation as well as experience in such measurements [11]. The valence state of Cr and V were studied by using both the High temperature mass spectrometry method and X-ray Absorption Near Edge Structure (XANES) method.

3.1.2.1 Gas-slag equilibration method - principle of the method:

The principle of the method is to equilibrate the slag sample kept in a Pt crucible with a gas mixture consisting of CO-CO_2-Ar, so that the oxygen partial pressure in the gas was predetermined. Based on knowledge of the thermodynamic activity of Cr in Cr-Pt alloy, as well as the oxygen partial pressure in the gas stream, it is possible to calculate the thermodynamic activity of chromium oxide in the slag. A similar procedure is applicable for vanadium. The thermodynamic background is presented in Appendix A. The oxygen pressures used were 10^{-8}, 10^{-9} and 10^{-10} bar, and the experiments were carried out at 1823,1873 and 1923K.

The materials used are presented in Table 1 in Appendix A. The experimental apparatus and the gas-cleaning train used are presented in Figure 3 and 4 respectively in Appendix A. By preliminary experiments, it was found that the attainment of equilibrium could be attained after soaking for 14 h or more (Figure 5 in Appendix A); consequently, all the equilibrations were carried out at a safe limit of 20 h. After the equilibration, the slags were quenched in argon atmosphere and analyzed. The slag compositions investigated are presented in Table 2 and 3 of Appendix A.

3.1.2.2 High temperature mass spectrometry method to measure the valence state of Cr and V in slags[12]:

Using mass spectrometric experiment, the conventional information of the Knudsen methods i.e. the vaporization rate of the substance as a function of temperature, as well as the ion mass number and specific for mass spectrometry were recorded by the value of the ion current resulting from ionizing of the corresponding i-component of the gas phase(I_{ij}) yielding a j-ion. The reactions with respect to pure Cr_2O_3 occurring that would lead to the formation of the vapor species Cr, CrO and CrO_2 are

$$Cr_2O_3\ (s) = 2Cr\ (g) + 3O\ (g) \qquad (1)$$

$$Cr_2O_3\ (s) = 2CrO\ (g) + O\ (g) \qquad (2)$$

$$Cr_2O_3\ (s) = CrO_2\ (g) + CrO\ (g) \qquad (3)$$

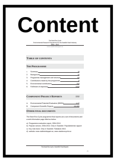
The slag samples were evaporated from two tungsten effusion cells with the ratio between the effusion and evaporation areas being 1:100. One effusion cell was kept for the slag sample while the other was for the reference oxide.

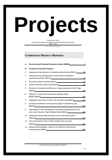
Knudsen effusion mass spectrometric method was also used to study vaporization processes and thermodynamic properties of pure V_2O_3 and fourteen samples of the vanadium-containing slags in the CaO-MgO-Al_2O_3-SiO_2 system in the temperature range 1875-2625 K. Temperature dependencies of the partial pressures of these vapour species were obtained over V_2O_3 and the slags studied. The ion current comparison method was used for the determination of the V_2O_3 activities in slags as a function of temperature with V_2O_3 solid as a reference state.

3.1.2.3 XANES method to measure the valence state of Cr and V in slags[13]:

Wet chemical method was commonly used for analyzing the contents for different chromium species wherein, the slag samples were dissolved in acidic medium and subjected to re-dox titration. In view of the possible errors arising due to the oxidation of Cr^{2+} to Cr^{3+}, this method was not resorted to in the present work. Instead, the samples were sent to Rutger University, USA for the valence state analysis of chromium in the slags by X-ray Absorption Near Edge Structure (XANES) method. The absorption peaks of XANES spectra were determined by multiple scattering resonances of the photoelectrons excited at the atomic absorption site and scattered by neighboring atoms. The near-edge structure is characteristic of the environment and valence state.

The valance state of vanadium in CaO-MgO-Al_2O_3-SiO_2-VO_x slag system was determined by XANES method. The oxidation states of vanadium were investigated with the initial V_2O_5 content varying from 1 to 10 mole





fraction, in the temperature range, 1823 to 1923K (1550-1650℃), and partial pressure of oxygen, $P_{O2}=10^{-5}-10^{3}$ Pa, with the basicity ranging from 0.85 to 2.20. The present results are useful in the quantification of V^{3+}/V^{4+} and V^{4+}/V^{5+} ratios for a given slag as functions of basicity, temperature and oxygen partial pressure.

3.2. Retention of Cr in steel melt using oxygen partial pressure control [13]

Thermodynamic calculations were carried out in order to examine the possibilities of the effect of decarburization using CO_2.

Experiment series 1

In this series, a steel melt containing pre-determined amounts of Cr and C was decarburized with oxygen and CO_2 blowing respectively. The melting was carried out in an induction furnace at KIMAB, Stockholm, Sweden. Sampling of the melts was carried out periodically and subjected to chemical analysis.

Experiment series 2

In this series, steel melts were exposed to gas mixtures with different oxygen partial pressures; viz. pure O_2, 75 vol. % O_2-25 vol. % CO_2, 50 vol. % O_2-50 vol. % CO_2, 25 vol. % O_2-75 vol. % CO_2 and pure CO_2. The samples were withdrawn at different time intervals and the C, as well as Cr, contents were analyzed. The amounts of Cr and C in the melt, as well as the temperature, were varied. The aim of these experiments was to determine the mass transfer effects of reducing the oxygen partial pressure during decarburization.

Experimental series 3

In this series, experiments are planned to examine the effect of reducing the oxygen partial pressure in the plant practice. The experiments will be carried out at Uddeholm Tooling AB. Dr. Mselly Nzotta from Uddeholms AB will supervise this work. The time for conducting the experiments has not yet been finalized.

Model development

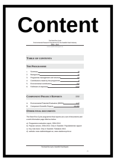
If the oxygen partial pressure is to be continuously decreased during the decarburization process, it is essential that a mathematical model is developed that could predict the decarburization and the Cr-loss by oxidation. Such a model has been development and is currently being tested.

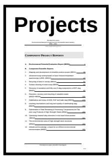
3.3 Minimization of Mo metal loses in dusts by process modification [14]

From the analysis of the dust samples at Uddeholms AB (60 ton EAF), it was revealed that the total amount of Mo lost during the EAF practice amounts to 72.64 kg/heat, 60.94 ton/year, 3.2 millon EUR/year. Similar is the situation with respect to Cr dust losses. The total amount of Cr lost is similarly 207.9 kg/heat, 140.54 ton/year, 0.2 millon EUR/year. This part of the present work was focused on Mo losses in the dust. Plant data collection shows that the main problem for the direct molybdenum trioxide addition in EAF at Uddeholms AB is the evaporation of MoO_3, which has a high vapor pressure at steelmaking temperatures. In the case of the EAF practice at Uddeholms AB, the losses of molybdenum to the furnace exhaust dust can reach up to 7 % [1].This will create not only valuable element loss, but also ecological problems as Mo is a heavy metal which is very capable for leakage to the environment. One of the solutions to this problem can be the conversion of MoO_3 into more stable molybdates like $CaMoO_4$, $MgMoO_4$ or Fe_2MoO_4. The sequence of investigation, all the methods used and material tested are shown in the **Figure 1.**

3.3.1 Thermodynamic calculation to find out the stable molybdates

Thermodynamic calculations were conducted to find out the cheap alternative source for steel alloying with Mo. Three main criteria were considered during the thermodynamic analysis: 1) the vapor pressure of MoO_3 as a





function of temperature; 2) the thermodynamic stability of the substance and 3) the compound could be formed *in situ* and could dissolve readily in the steel melt. After choosing the most suitable molybdates as candidates for Mo sources, more detailed lab-scale studies were performed on the molybdates thermal stability to confirm the results of thermodynamic analysis.

3.3.2 Lab-scale studies of molybdates stability

Investigations in lab-scale were carried out in order to find out suitable Mo compound, formed from commercial ingredients as an economically viable alternative for Mo addition to steel melts in the EAF. The thermal stabilities of different molybdates, *viz*. Fe_2MoO_4, $CaMoO_4$ and $MgMoO_4$, were studied using thermogravimetric analysis (TGA). The possibilities for *in-situ* formation of Fe_2MoO_4 and $CaMoO_4$ from their precursor mixtures were studied with the aid of high-temperature X-ray diffraction (XRD) and TGA analysis.

3.3.3 *In-situ* formation of molybdates

It was interesting to achieve *in-situ* formation of Fe_2MoO_4 and other perspective molybdates when mixing initial components and heating them together during scrap melting. It was also attractive in a view of cost lowering, as it can simplify the process of alloying material production and combine it together with EAF practice. To study the possibilities for *in-situ* formation of $CaMoO_4$, $MgMoO_4$ and Fe_2MoO_4 from their precursor mixtures, a number of methods were used, such as thermogravimetry (TGA), evolvedgas analysis by gas chromatograph (GC), high-temperature X-ray diffraction (HT-XRD) and laboratory trials on steel alloying.

3.3.3 Lab- and industrial-scale studies of Mo yield

Lab scale experiments and industrial trials on steel alloying with Mo were conducted using different molybdates as well as precursor mixtures as sources of Mo. The industrial trials were conducted in a 5 ton induction furnace at Uddeholms AB. It was found that the mixture, which contains FeO_x, MoO_3 and C (Fe_2MoO_4 precursor), can provide the Mo yield up to 98 % at all the experiment scale levels.

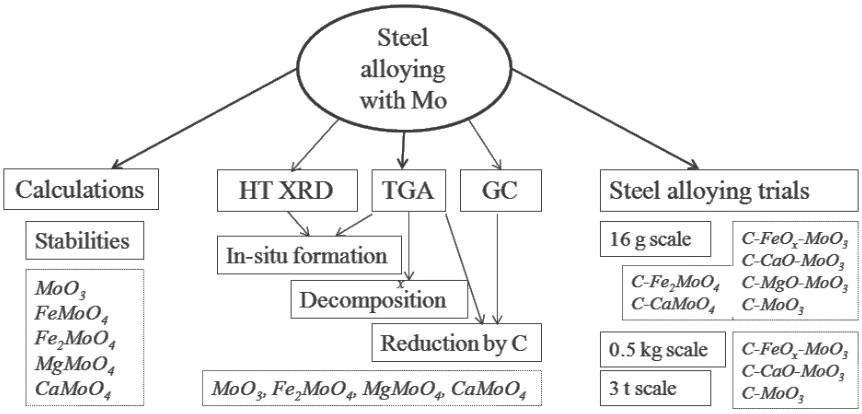


Figure 1 Research plan and instruments for a new Mo source development

3.3.4 Full industrial-scale test in 75ton EAF at Uddeholms AB

Industrial testing of Mo alloying in 75 ton EAF has been done for 2 steel grade in 8 heats and results are very positive. The Mo yield is increased from 90% to 99%. Uddeholms AB is very satisfied with the results. Outokumpu (Avesta) is interested with the results from Mo alloying technique and they are doing some test work in their 150 ton EAF furnace.

3.4 Extraction of metal values by using a salt extraction process [15, 16]

For the extraction of valuable metals in steelmaking slags, a salt extraction process has been designed by the present group. In this, the slag is treated with a salt melt of suitable composition, and fluxes are added in order to extract the metals into the salt phase. The salt phase can be electrolyzed, or if necessary, leached to extract the valuable metals in the aqueous phase. Alternately, the vapours of volatile chlorides, as for example $MoCl_5$ can be fractionallycondensed from the vapour phase. The results have been encouraging and a patent application has been approved. The process parameters have also been examined for process optimization.

3.4.1 The principle of the salt extraction process

This new process is based on the principle of "extraction of the metal values" from the materials covering slags, low grade ores and oxidic refractory waste materials using molten salts at temperature above 600^oC. The process can be divided into two steps: In the first step, the slag or the ore containing metal values of interest, such as Cr is dissolved into the molten salt phase at a suitable temperature. This extraction step is enabled by the choice of a suitable fluxing agent. Earlier work in the present laboratory has shown $AlCl_3$, which has now been protected by a patent application, is a powerful fluxing agent in this regard. In the second step, the salt phase is subjected to electrolysis in order to recover the metal of interest as a cathode deposit. The schematic diagram of this process is shown in Figure 2. It is interesting to note that the salt melt used for extraction can be recycled. The metals can be selectively electrodeposited from the salt melt. The process can be designed to be continuous by combining the two steps. There is also the option of aqueous processing of the salt phase containing the metal values. The residue after processing, which consists essentially of CaO, Al_2O_3 and SiO_2, can safely be used for landfill, building construction or as a raw material for the refractory industry.

Investigations were carried out in order to optimize the process parameters for dissolution of slag/chromite in the eutectic salt mixtures of NaCl-KCl and/or NaCl-KCl-LiCl containing the patented flux, $AlCl_3$. Based on the optimized conditions, lab-scale investigations of electrolysis were carried out applying a cell voltage of 2.8V. Ferrochrome was recovered as the cathode deposit.

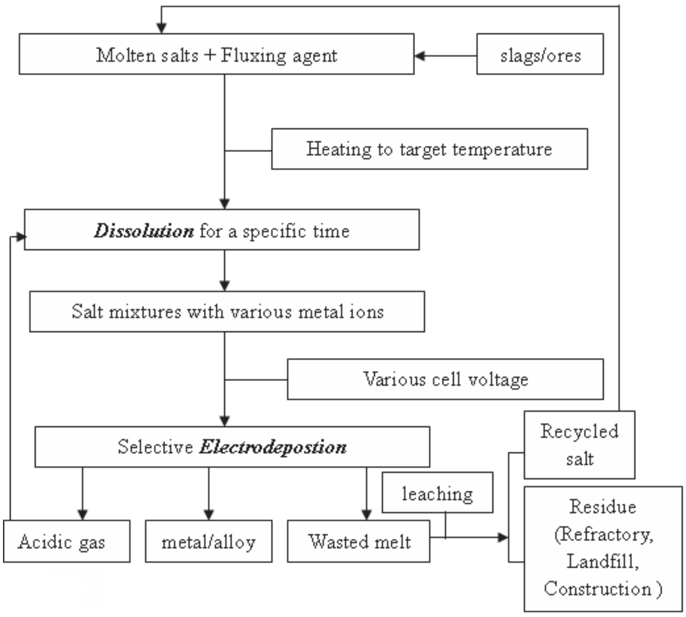


Figure 2 Schematic diagram of Salt Extraction Process [15]

4. RESULTS AND DISCUSSION

The results obtained so far are summarized in the following section. Details are presented in the appendices.

4.1. Thermodynamic studies

As part of the present project, thermodynamic studies of Fe-Cr-C and Fe-Cr-C-N alloys were conducted in order to investigate the effect of nitrogen on decarburization. The valence state of Cr and V in the metallurgical slags are studied by high temperature mass spectrometry and XANES methods. Thermodynamic measurements of the Cr- and V-containing slags by gas-slag equilibration method were also carried out.

4.1.1. Thermodynamic studies of Fe-Cr-C and Fe-Cr-C-N systems [7, 8, 9, 10]

The results of the EMF measurements indicate clearly that addition of nitrogen to Fe-Cr-C slags significantly decreases the thermodynamic activity of Cr. This is shown in the case of the two alloy compositions presented in Figure 3. This effect could be confirmed using atomistic simulations [8].

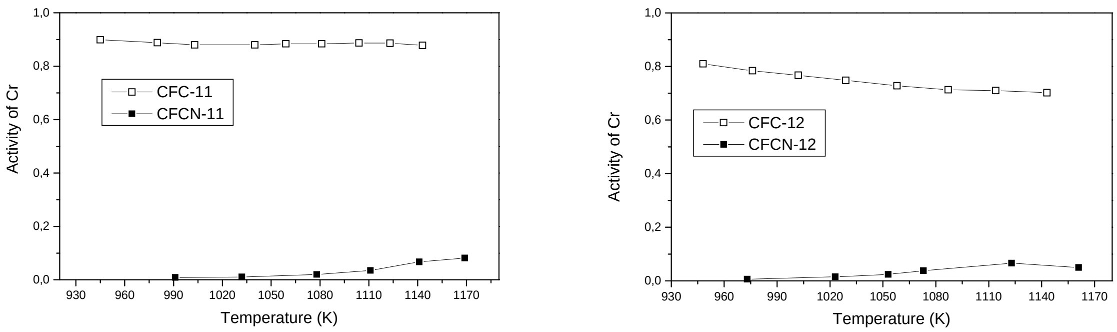


Figure 3. Effect of addition of nitrogen to Fe-Cr-C alloys.

4.1.2 Thermodynamic studies of Cr- and V- bearing slags

4.1.2.1 Cr valence studies

The distributions of CrO and $CrO_{1.5}$ in the $CaO\text{-}SiO_2\text{-}CrO_x$ and CaO-MgO-(FeO-) $Al_2O_3\text{-}SiO_2\text{-}CrO_x$ slag systems were measured in the present study by gas-slag equilibrium method and by high-temperature Knudsen cell-mass spectrometry, respectively

High temperature mass spectrometry

Ten slag samples of $CaO\text{-}MgO\text{-}FeO\text{-}Al_2O_3\text{-}SiO_2\text{-}CrO_x$ slags were prepared based on the relevancy to the high alloy steel producers in Sweden. A typical vapor species recorded during vaporization is shown in Figure 4. It can be seen that three kinds of chromium species, i.e. Cr, CrO and CrO_2 were detected in the temperature range of 1950K-2050K and the ratio of the partial pressures p(CrO)/p(CrO_2) in the gaseous phase over these samples was always much greater than that corresponding to pure chromium oxide at the constant temperature. In the case of the present slags, the partial pressure of CrO is attributed to two species in the condensed phase, *viz.* $CrO_{1.5}$ and CrO; while the partial pressure of CrO_2 is solely generated by $CrO_{1.5}$.

$$(\mathrm{CrO})_{\mathrm{slag}} \Rightarrow \mathrm{Cr}_{(g)}, \mathrm{CrO}_{(g)} \qquad (4)$$

$$(\mathrm{CrO}_{1.5})_{\mathrm{slag}} \Rightarrow \mathrm{Cr}_{(g)}, \mathrm{CrO}_{(g)}, \mathrm{CrO}_{2(g)} \qquad (5)$$

According to the ratio of the partial pressure of CrO_2, CrO in pure Cr_2O_3, the part of the partial pressure of CrO contributed by Cr_2O_3 in condense phase can be obtained from reaction (4) and (5) as $2p_{CrO2}$. Thus,

$$\frac{X(\mathrm{CrO})_{\mathrm{slag}}}{X(\mathrm{CrO}_{1.5})_{\mathrm{slag}}} = \frac{p_{CrO} - 2p_{CrO2}}{2p_{CrO2}} \qquad (6)$$

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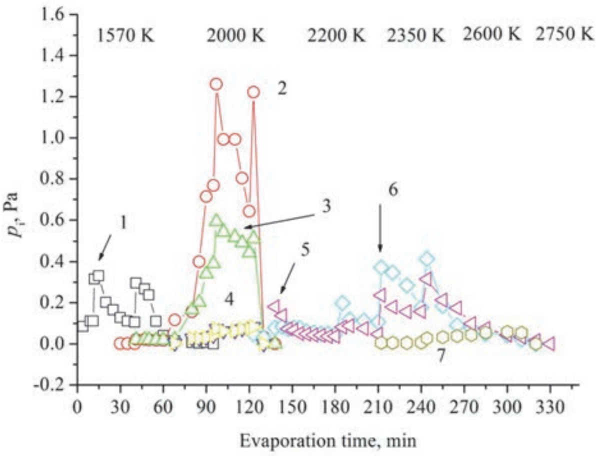
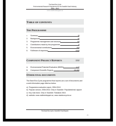
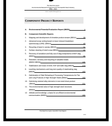


Figure 4 Partial pressures of molecular species above sample N 17
as functions of temperature and time of vaporization [12]:
1 – Fe, 2 – Cr, 3 – CrO×10, 4 – CrO_2×10, 5 – SiO×10, 6 – Ca, 7 – Al×10.

XANES method

In order to quantify the contents of CrO and $CrO_{1.5}$ in quenched samples of $CaO\text{-}SiO_2\text{-}CrO_x$, further analysis was made on the basis of XANES spectra. Two standard spectra regarding to the Cr (II) and Cr (III) were established

according to the largest and lowest amount of Cr (II) in the present samples. Other measured XANES spectra can be fitted as a mixture of the standards (end members). The results were summarized in Table 1, along with the experimental conditions.

Table 1 Experimental conditions and results in the present study

No.	Experimental condition			$X_{CrO}/X_{CrO1.5}$
	T(K)	P_{O2}(Pa)	Basicity	
08D	1873	2.83×10^{-3}	1.0	1.38
10B	1873	1.79×10^{-4}	0.7	5.25
10C	1873	1.79×10^{-4}	0.5	9.00
12A	1873	2.83×10^{-5}	1.16	1.56
12D	1873	2.83×10^{-5}	1.0	4.26
21A	1823	6.63×10^{-5}	1.16	1.50
21B	1823	6.63×10^{-5}	0.7	3.76
21C	1823	6.63×10^{-5}	0.5	4.26
21D	1823	6.63×10^{-5}	1.0	1.78

Factors influencing chromium valence states

A mathematical formula was established for estimating the effects of slag basicity, temperature and oxygen partial pressure on the distribution of Cr in slags. Based on the present results and the selected literature data, a correlation between ratio of $\log_{10}X_{CrO}/X_{CrO1.5}$ and three factors, viz. temperature, oxygen partial pressure and basicity was arrived at. The results indicate that ratio $X_{CrO}/X_{CrO1.5}$ increases with the increasing temperature, decreasing oxygen partial pressure and slag basicity. Combining the results obtained in present study and selected literature values, a mathematical expression of $X_{CrO}/X_{CrO1.5}$ ratio described as functions of temperature, oxygen partial pressure and slag basicity was built up. This correlation equation is presented in (7).

$$\log\left(\frac{X_{CrO}}{X_{CrO1.5}}\right) = -\frac{11534}{T} - 0.25\cdot\log\left(p_{O_2}\right) - 0.203\cdot\log\left(B\right) + 5.74 \qquad (7)$$

where T is temperature in K, P_{O2} is oxygen partial pressure in Pa and B refers to basicty defined as (%CaO+%MgO)/(%Al_2O_3+%SiO_2). The correlation is compared with the experimental results from the present as well as earlier works in Figure 5. It is seen that the correlation is satisfactory.

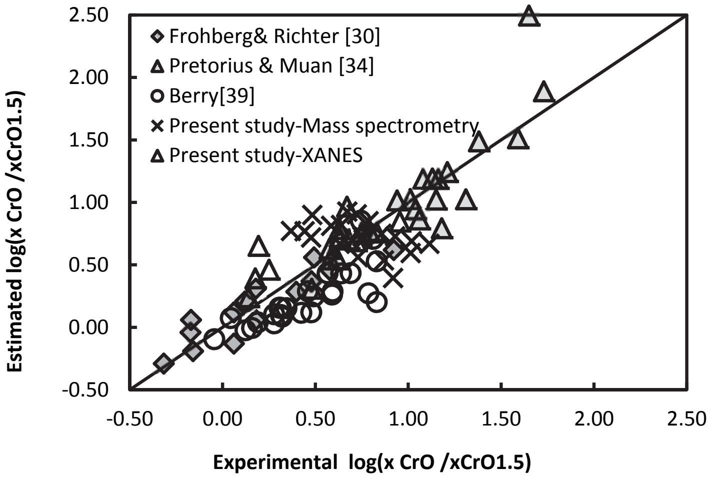


Figure 5 Comparisons between experimental and estimated $X_{CrO}/X_{CrO1.5}$ [12]

Equation (7) can be utilized in estimating the chromium oxidation level in slags in industrial practice. With a knowledge of basicity, oxygen partial pressure prevailing as well as temperature of the process, the extent of Cr (III) in the slag can be estimated. This information is considered to be useful in process control.

4.1.2.2 Vanadium valence studies

XANES method

A quantitative analysis of oxidation state of vanadium can be obtained by comparing near-edge peaks obtained with standard materials. If the three vanadium ions V^{3+}, V^{4+}, V^{5+} are assumed to coexist at high temperature, the moles of vanadium and oxygen n_V and n_O in a given slag have the following relationship[13]:

$$n_V = n_{V^{3+}} + n_{V^{4+}} + n_{V^{5+}} \tag{8}$$

$$n_O = 1.5 n_{V^{3+}} + 2.0 n_{V^{4+}} + 2.5 n_{V^{5+}} \tag{9}$$

Then x in VO_x is

$$x = \frac{n_O}{n_V} = \frac{1.5\frac{V^{3+}}{V^{5+}} + 2.0\frac{V^{4+}}{V^{5+}} + 2.5}{\frac{V^{3+}}{V^{5+}} + \frac{V^{4+}}{V^{5+}} + 1.0} \tag{10}$$

Based on the analysis above, x in VO_x can be obtained by analyzing near-edge information in XANES. The x in VO_x was measured changing the initial V_2O_5 content from 1 to 10% mole fraction, in the basicity range 0.85 - 2.20, the temperature range 1823-1923K (1550-1650℃) and partial pressure of oxygen, $P_{O2}=10^{-5}$-10^{3} Pa. The results indicated that, at given P_{O2} and basicity, x increases slightly with initial V_2O_5 content. It was also found that x increases with increase of basicity, indicating that higher basicities stabilize higher vanadium oxidation state, as shown in Figure 6. The intensity of pre-edge peaks linearly decreases with increase of T and the plot of log of the redox couple ratio vs.1/T also gives a straight line. Higher temperature stabilizes lower vanadium oxidation state. For a given value of basicity, the value of x was found to increase with the increase of oxygen partial pressure. From the present results, the V^{3+}/V^{4+} and V^{4+}/V^{5+} ratios can be estimated under different conditions.

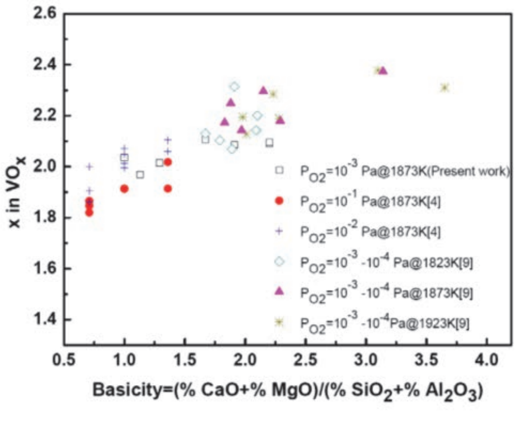


Figure 6 Vanadium oxidation state as a function of basicity of slag [13]

Mass spectrometric method

Using the Knudsen effusion mass spectrometric method, the vaporization processes of fourteen vanadium-containing slags were followed by the transition to the gaseous phase of the individual oxides available in the samples studied in the temperature ranges 1880-2625 K [13]. Temperature dependences of the V_2O_3 activities as well as the VO_2, VO and O_2 partial pressures over the samples in the $CaO\text{-}MgO\text{-}Al_2O_3\text{-}V_2O_3\text{-}SiO_2$ system were obtained. Fig. 7 illustrates the changes of the V_2O_3 activities as a function of basicity of samples of slags in the $CaO\text{-}MgO\text{-}Al_2O_3\text{-}V_2O_3\text{-}SiO_2$ system at the temperature 2100 K. It was shown that the V_2O_3 activities as a function of the slag basicity decreased at the temperatures 1900 K, 2000 K. The activity was practically constant in the slag melts at 2100 K.

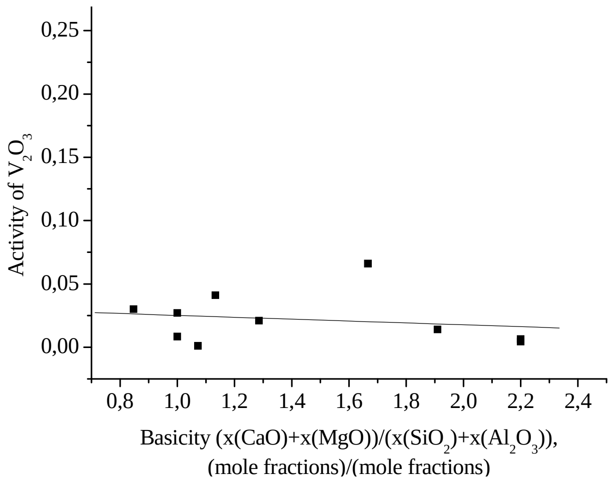


Figure 7 Dependences of the V_2O_3 activities as a function of the slag basicity $(x_{CaO} + x_{MgO})/(x_{SiO_2} + x_{Al_2O_3})$ expressed in mole fractions found in the samples of slags in the $CaO\text{-}MgO\text{-}Al_2O_3\text{-}V_2O_3\text{-}SiO_2$ system at 2100 K (c). ■ – presented the experimental data corresponding to the liquid phase (melt) and ● - presented the experimental data corresponding to the solid phase.

4.1.2.3 Thermodynamic activity of CrO in slags [14]

20 different slag compositions with varying amounts of slags have been investigated in the present work. The slag compositions are presented in Table 2 in Appendix A. The work has been restricted to low Cr-contents, and the slag consisted of CaO, MgO, Al_2O_3 and SiO_2 apart from CrO_x. The Pt-crucibles were analyzed after the experiment and the Cr-content of the alloy in equilibrium with the slag was determined (see Figure 6 in Appendix A). The amount of chromium oxide retained by the slag was fund to be strongly dependent on the slag chemistry, above all, the basicity. The effect of the basicity on the final chromium oxide content of the slag is presented in Figure 7 in Appendix A. The thermodynamic activity of chromium oxide was calculated utilizing the thermodynamic information on the Pt-Cr system reported by literature. The activity of Cr in Pt-Cr alloys in the temperature range 108 - 1923 K is presented in Figure 9 in Appendix A.

It is well known that Cr exists as Cr^{2+} and Cr^{3+} in slags. In the present work, the amount of chromium oxide is very low. Further, the slag is in equilibrium with a Pt-Cr alloy as well as a gas a phase with a low oxygen partial pressure. Hence, all Cr in the slag was assumed to be in the divalent state. This is supported by the measurements of Forssbacka and Holappa[15]. The relationship between the chromium oxide content for the slag compositions investigated in the present work, and the thermodynamic activity of CrO, is presented in Figure 8.

As can be seen, the activity of CrO shows a positive deviation from Raoults law in agreement with the results reported earlier and the activity increase. The values at slightly higher Cr contents could be affected by a slight increase in the Cr^{3+} contents of the slags. The corresponding figure for the activity of $CrO_{1.5}$, assuming that all the Cr in the slag is in the trivalent state, is presented in Figure 8 in Appendix A. It is seen in this figure that the activity is invariant with respect to temperature.

From the present results, an expression for the amount of Cr in the slag as a function of the oxygen partial pressure as well as the basicity was worked out and is given below:

$$\log(\%Cr)_{slag} = 4.488 + \frac{16907.82}{T} + 2.555 \times \log[Cr]_{alloy} + 1.589 \times \log(P_{O2}) - 8.483 \times \log B \qquad (11)$$

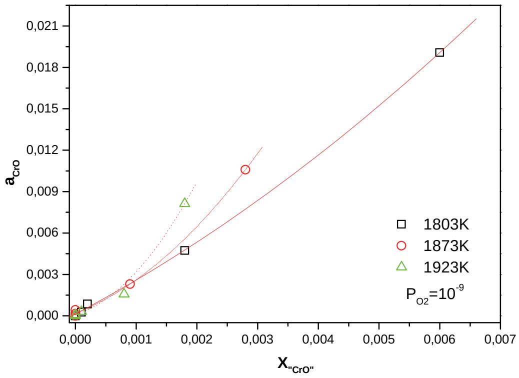


Figure 8. The thermodynamic activity of CrO as a function of the content of CrO_x in the slag. The experimental temperatures were 1803, 1873, 1923 K respectively and $P_{O2} = 10^{-9}$) [14]

Where 'B' is the basicity defined as:

$$B = \frac{wt\%CaO + wt\%MgO}{wt\%SiO_2 + wt\%Al_2O_3} \qquad (12)$$

This expression can be valuable in assessing the amount of Cr lost in the slag under given basicity and oxygen partial pressure if the activity of Cr in steel is known.

4.1.2.4 Thermodynamic activity of $VO_{1.5}$ in slags

18 different slag compositions were studied as part of the present work. The slag compositions are presented in Table 3 in Appendix A. The activity of V in Pt-V alloys from the work of Pretorius and Muan[14] is presented in Figure 10 in Appendix A. The vanadium oxide content in the slags was kept below 1.5 wt %. Hence, all vanadium was considered to be in the trivalent state. The activity of $VO_{1.5}$ in the slags investigated in the present work, as a function of the total vanadium oxide concentration, is presented in Figure 9.

An expression relating the activity of V in the metal phase, the oxygen partial pressure and the basicity of the slag was worked out from the present results. This expression is:

$$\log(\%V)_{slag} = -2.968 + \frac{11070.41}{T} + 0.47 \times \log[V]_{alloy} + 0.467 \times \log(P_{O2}) + 2.63 \times \log B \qquad (13)$$

This expression will be useful in estimating the vanadium losses in the slag under defined slag chemistry and oxygen potential prevailing. This expression was found to describe the present experimental results adequately, as shown in Figure 11 in Appendix A. From the present results, even the vanadium partition between the slag and the metal phases was evaluated. This is shown in Figure 12 in Appendix A. Experiments have been carried out by steel-slag equilibration technique in order to confirm the results obtained by the gas-slag reactions.

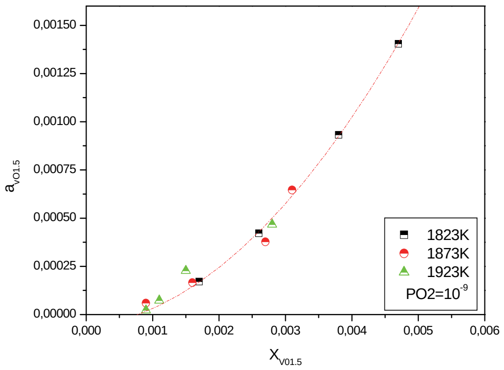


Figure 9. Thermodynamic activity of vanadium (III) oxide as a function of the vanadium (III) oxide content in the slag [14]

4.2 Retention of Cr in steel melt using oxygen partial pressure control [13]

Retention of reactive metals like Cr requires lower oxygen partial pressures, higher temperatures and /or higher thermodynamic activities of the oxide in the slag. During decarburization, the competition between carbon and the reactive metals is an important factor in determining the loss of these metals to the slag. This is shown in the form of an Ellingham-type diagram in Figure 1 in Appendix B. Above the “cross point”, Tc, carbon monoxide will be stable. Figure 10 illustrates the variation of T_c with respect to Cr and C contents. From this figure, it can be seen clearly that T_c increases with the increasing of Cr content when C content is a constant. Further, T_c decreases with the increasing of C content when Cr content is stable. Thus, if the temperature of the melt is kept constant, Cr-loss will increase with progress of decarburization.

Calculations were made with respect to a typical steel containing 18 wt % Cr, 11 wt % Ni, 2 wt % Mo and 0.35 wt % C. An increase of the carbon content decreases the Tc as shown in Figure 2 in Appendix B. The Cr content in the melt, however, increases the Tc as shown in Figure 2 in Appendix B. Kinetic calculations were carried out as part of the present work. When a gas bubble containing Ar and O_2 gas species reacts with the carbon dissolved in steel, the chemical reaction rate would correspond to the following reaction:

$$[C] + \frac{1}{2} O_2 = CO \qquad (14)$$

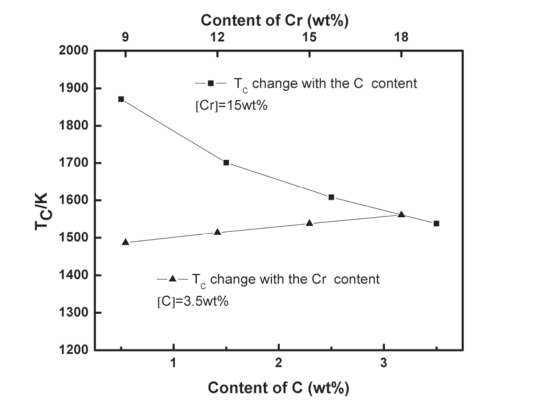


Figure 10 The effect of C and Cr contents on T_c

The critical carbon content would be 0.2 to 0.6 wt %. Considering the lower equilibrium oxygen partial pressure for CO_2 gas, and the reactions of decarburization including the Boudouard reaction, preliminary rate calculations with chemical reaction as the rate-controlling step were carried out. The results are presented in Figure 3 in Appendix B. The calculations were extended to the C transfer in molten steel as the rate-controlling step. The results are presented in Figure 11.

It is seen that the duration for decarburization is about 30 min which is approximately the normal time in the plant practice. It is to be noted that replacement of O_2 by CO_2 in decarburization leads to the endothermicity of the chemical reaction and corresponding lowering of the temperature. Further, the oxygen in the gas bubble would initially react with Fe abundant in the melt, and further reactions should take place by mass transfer in the steel bath. A mathematical model has been developed taking into account the mass transfer aspects. The model takes into account the reaction between the gas bubble and the steel melt. Wetting and interfacial reactions are also considered in the model development. The model is designed to suit the EAF practice of Uddeholms AB.

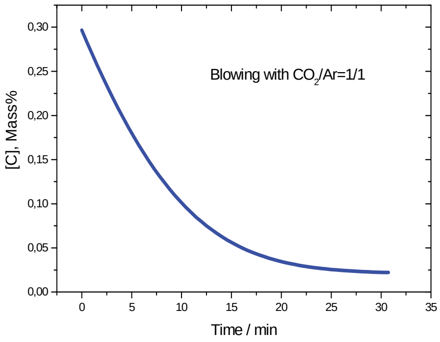


Figure 11. Rate of decarburization with mass transfer of C in steel as the rate-controlling step (18t AOD, T=1873K, Flow rate 1200 Nm^3/h)

4.2.1 Modeling studies of CO_2 decarburizaiton [13]

A theoretical generic model describing the mass transfer phenomena between rising gas bubbles and a metal bath has been developed to predict the composition change in the melt as a consequence of blowing different oxidant gases. When a gas is injected into a bath of liquid metal, bubbles formed will rise through the bath.

During bubbles ascent, chemical reaction takes place at the gas-liquid interface, accompanied by mass transfer of reactant species from the bulk gas and liquid phases to the interface and *vice versa* for product species. Significant volume fraction of gas is present in the plume, and the resultant buoyancy-driven flow gives rise to good mixing in the liquid. In order to simplify the reaction, a single bubble rising through a column of liquid steel was considered. It is quite reasonable to assume equilibrium at the gas-liquid interface since the temperatures for steel processes are quite high. Therefore, the reactions are limited by transfer of species from the bulk gas and liquid phases to the interface or *vice versa*.

For the case of a bubble containing O_2, CO_2 and CO gas mixture (CO_2 could function as an oxidant as well as a diluent and can be replaced by Ar according to process requirements), rising through a carbon-containing liquid steel bath (temperature around 1873 K), it can be modelled through the following steps:

1) Transfer of C from the bulk liquid steel to the gas-liquid interface.

2) Transfer of O_2, CO_2 from the gas phase to gas-liquid interface and transfer of CO from the interface to bulk gas phase.

CO, CO_2 and O_2 are considered to be in equilibrium with the dissolved C at the interface. This is illustrated schematically in Figure 12.

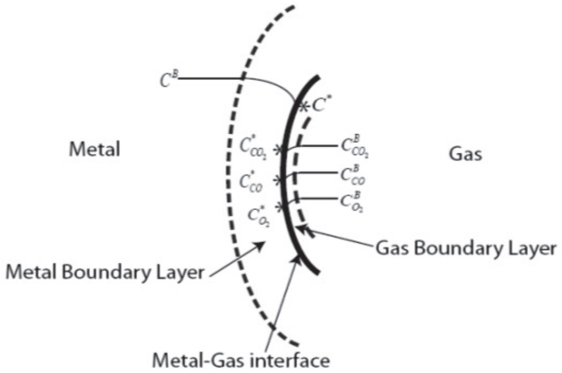


Figure 12 Schematic of equilibrium at the gas-liquid interface

Mathematically, this can be written as,

$$\dot{n}_C = \frac{A_b\, k_m^C\, \rho_m}{100\, M_C} (wt\%C^B - wt\%C^*) \tag{15}$$

$$\dot{n}_{CO} = A_b\, k_g^{CO}\, (C_{CO}^B - C_{CO}^*) \tag{16}$$

$$\dot{n}_{CO_2} = A_b\, k_g^{CO_2}\, (C_{CO_2}^B - C_{CO_2}^*) \tag{17}$$

$$\dot{n}_{O_2} = A_b\, k_g^{O_2}\, (C_{O_2}^B - C_{O_2}^*) \tag{18}$$

Where, '$\dot{n}_i$' is the rate of transfer of species i; 'A_b' is the surface area of the bubble; 'k' is the mass transfer coefficient; 'ρ_m' is density of liquid steel; subscripts 'm' and 'g' refer to metal and gaseous phases respectively; 'C_i' is the concentration in gas phase and superscripts 'B' and '*' refer to bulk and gas-liquid interfaces respectively.

This model can be extended for oxidation of other solutes like Cr, Mn, Ni, *etc*. For example, consider Cr in liquid steel in addition to carbon. One needs to consider an equation representing the mass transfer of Cr from the bulk metal to the interface and an additional equation for equilibrium which is as follows:

$$\dot{n}_{Cr} = \frac{A_b\, k_m^{Cr}\, \rho_m}{100\, M_{Cr}} (wt\%Cr^B - wt\%Cr^*) \tag{19}$$

$$K_3 = \frac{a^*_{Cr_2O_3}}{(wt\%Cr^* \cdot f_{Cr})^2 \cdot (p^*_{O_2})^{\frac{3}{2}}} \qquad (20)$$

Here, K_3 is the equilibrium constant for the reaction

$$2\underline{Cr} \;+\; \frac{3}{2}O_2(g) \rightarrow \; Cr_2O_3(s) \qquad (21)$$

In the present case, the product of oxidation of Cr dissolved in Fe has been considered to be pure solid Cr_2O_3 since as per thermodynamic calculations, the product of oxidation in Fe-Cr melts will be solid Cr_2O_3 down to Cr content of approximately 3 wt%. Thus, its activity can be taken as 1. In more complicated cases as in complex slags, the appropriate activity value can be inserted in the model.

4.2.2 Modeling results

Simulations were carried out with an objective of understanding the effect of a systematic replacement of O_2 with CO_2 in the gas injected into liquid steel containing C and Cr. For this purpose, simulations for a steel melt containing 22wt% Cr and 1.2wt% carbon were carried out. This composition is typical of the melt with the composition during EAF stainless steelmaking. Simulations were implemented for three injection gas compositions, i.e., 100%O_2, 50%O_2-50%CO_2 and 100%CO_2 (Table 2). Gas flow rate of 1360 Nml/min was employed for all 3 cases.

Table 2 Three cases considered for simulation to understand the effect of replacement of O_2 with CO_2 in the gas injected into Fe-C-Cr melt

Case	Wt % C	Wt % Cr	Composition of gas being injected
1	1.2	22	100 % O_2
2	1.2	22	O_2:CO_2= 50:50
3	1.2	22	100% CO_2

Simultaneous oxidation of C and Cr in the melt can be best understood by plotting the evolving C against the Cr content in the melt for cases 1, 2 and 3 (see Table 2). Please note that for all the three cases, the starting C and Cr contents in the melt are 1.2wt% and 22 wt% respectively. Further, the C and Cr amounts in the steel bath progressively diminish with blowing time. In order aid the discussions, C and Cr contents in the melt in equilibrium with carbon monoxide at one atmospheric pressure and solid Cr_2O_3 respectively are also depicted in Figure 13. Based on this equilibrium consideration, one can clearly see from the figure that Cr can be protected without being oxidized till the carbon content in the melt reduces to 0.77 wt%. However, in the actual oxidation process, oxidation of Cr starts much above this carbon content of 0.77 wt %. It should be noted that as per the present model, the equilibrium prevails at the gas-melt interface. Therefore, the C and Cr concentrations in the bulk are much above the equilibrium values because of mass transfer resistances.

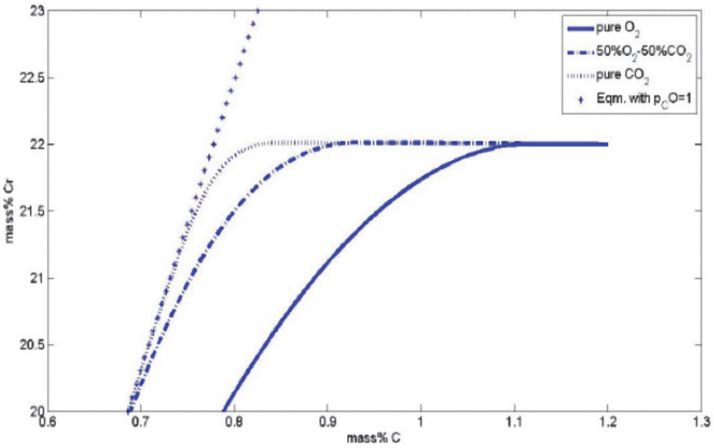


Figure 13 Carbon and chromium composition evolution in a Fe-1.20C-22Cr melt injected with gases containing $100\%O_2$, $50\%O_2$-$50\%CO_2$ and $100\%CO_2$ separately(Case 1, 2 and 3 in Table 2)

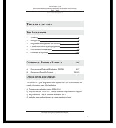
It can be clearly seen from Figure 13 that the increase in CO_2 content in the injected gas leads to bulk metal compositions moving closer to the equilibrium line. In other words, with increasing CO_2 content in the injected gas, higher amount of Cr is protected from oxidation. This clearly demonstrates that the loss of chromium by oxidation can be lowered by injecting CO_2 especially during the initial stages of blowing where in the carbon contents are high.

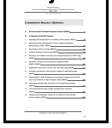
In order to verify the model predictions, a series of experiments involving reactions between Fe-Cr-C melts and different O_2-CO_2 gas mixtures were carried out. The results showed that the decarburization deviates significantly from thermodynamic paths predicted on the basis of bulk compositions and that the model was able to make reasonably reliable predictions of the changes of chromium and carbon contents in the melt as a function of time. According to the model, the compositions in the vicinity of the injection point as well as at the gas-melt interface in the bubble are likely to be far from that in the bulk. The results of the present set of experiments showed, with CO_2 injection, the utilization of *the available oxygen for decarburization* was higher as compared to O_2 injection in the case of melts containing higher carbon levels (>1mass%), as shown in Figure 14. Reverse is the case in low carbon melts. The results also indicate relatively less Cr-losses from the metal bath when CO_2 is used as the oxidant. As the model predictions are found to be reasonably reliable, the model predictions are extended to predict the impact of the variation of different process parameters. Figure 15 shows a clear picture of effect of CO_2 in Cr retention.

Preliminary laboratory experiments at 500 g scale using an induction furnace were carried out with Fe-C melts, blowing O_2 and CO_2 respectively. Samples were taken periodically in order to analyze the C and Cr contents. The loss of Cr was found to be much less in the case of CO_2 decarburization as shown in Figure 15, where the Y-axis is the relative loss of Cr from the melt.

Experiments have been conducted in order to study the mass transfer rate under static conditions in a horizontal furnace with different gas mixtures flowing over the steel melt. The effects of the alloy composition, the gas composition and the temperature were also studied.

Plant trials at Uddeholm Tooling AB will be carried out, and the model predictions will be compared with the plant operations. At present no specific time has been scheduled for the plant trials.





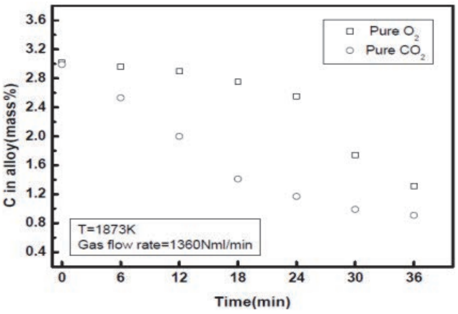


Figure 14 The variation of carbon content with time in low carbon alloys employing gases of different compositions. Injection rate =900Nml/min [13]

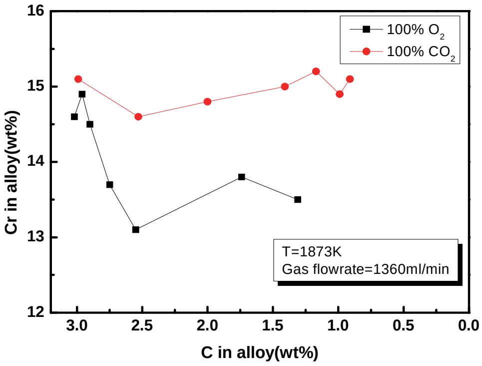


Figure 15 The Cr loss with decarburization in induction furnace at 1873K [13]

4.3 Minimization of Mo metal loses in dust s by process modification

Plant trials were conducted in the EAF practice at Uddeholms AB in collaboration with Dr. Nzotta[1], in order to investigate the Mo-losses in the slag as well as in the dust. The raw data from these experiments are presented in Table 1 and 2 in Appendix C. A mass balance for Mo have based on this been worked, and the results is shown Figure 16 below.

The addition of Mo is in the form of two different types of oxides. The compositions of these at the time of trial, given by the supplier, are given below:

1. C= 0.02, P= 0.01, S= 0.05, Mo= 64.66, Cu= 0.46, Pb= 0.01, Fe= 2.46, O= 32.33
2. Si= 3, P= 0.5, S= 0.3, Mo= 30.92, W= 6.91, Cu= 0.05, Fe= 42.86, O= 15.46

An analysis of the raw materials reveals that a significant part of the Mo in the system exists as MoO_3. From the Gibbs energies of formation of MoO_3 and Fe_2MoO_4 (see Figure 1 in Appendix C), it can be seen that the latter is more stable and thus addition in this form will reduce the vapour losses.
The division has developed the process for the production of Fe_2MoO_4 from these raw materials, as well as from mill scale. Laboratory trials have been performed, and industrial trials are in progress in order to monitor the Mo losses during successive additions of produced Fe_2MoO_4.

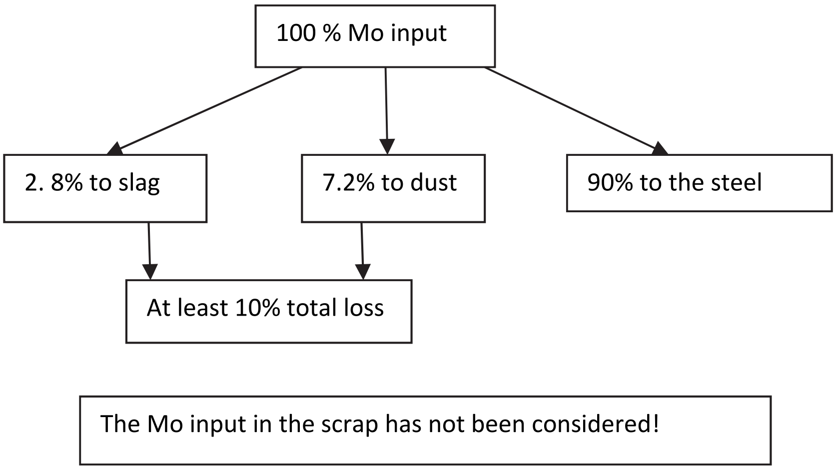


Figure 16 The Mo mass balance in the 60 ton EAF for one steel grade at Uddeholms AB

The evaporation rate of pure MoO_3 was studied by TGA and compared with the evaporation rates from mixtures of MoO_3 with CaO, $CaCO_3$, MgO. It was found that MoO_3 can be stabilized by mixing with CaO, MgO or $CaCO_3$ and heating the mixtures which would result in the formation of appropriate molybdates. The formation of $CaMoO_4$ from the mixtures of MoO_3 with CaO or $CaCO_3$ starts after 773 K (as confirmed by high temperature X-ray diffraction studies) and is completed around 973 K.

The Mo yield by use of three different Mo alloying mixtures (MoO_3+C; MoO_3+C+FeO_x; and MoO_3+C+CaO) was tested both in laboratory and industrial experiments. During laboratory experiment, both in 16- and 500-g-scale trials, Fe_2MoO_4 precursor mixture (MoO_3+C+FeO_x), showed the Mo yield is up to 98 %, which can be explained by the absence of molybdenum evaporation from this substance.

4.3.1. The development of new precursor for steel alloying with Mo [16]

4.3.1.1 $CaMoO_4$, $MgMoO_4$ and Fe_2MoO_4 stabilities with respect to evaporation and oxidation

Fe_2MoO_4 stability by TGA. Pure iron molybdate (Fe_2MoO_4) was tested both in argon and air as gas atmosphere while heating up to 1573 K with 10 K per minute rate. The results are shown in **Figure 17**. During heating in air, Fe_2MoO_4 is subjected to oxidation, which starts after 573-673 K and results in the mass increase followed by decrease. The peak of mass increase, compared to initial mass of Fe_2MoO_4, is around 12 % which can be explained by the oxidation of Fe_2MoO_4 into MoO_3 and Fe_2O_3 mixture according to the equation:

$$Fe_2MoO_4 + O_2 = Fe_2O_3 + MoO_3 \qquad (22)$$

According to stoichiometry, the process should lead to the 11.8 % of mass increase. After reaching of 1173 K, the mass of mixture starts to decrease, probably due to the subsequent MoO_3 evaporation from the mixture. By the end of the experiment, the total mass change indicates the evaporation of approximately 43 % of MoO_3, formed as a result of iron molybdate oxidation by air.

It should be noted that there is no mass change for Fe_2MoO_4 during the same heat treatment in the argon atmosphere, and this substance seems to be very stable source of molybdenum in the absence of oxygen (**Figure 17**).

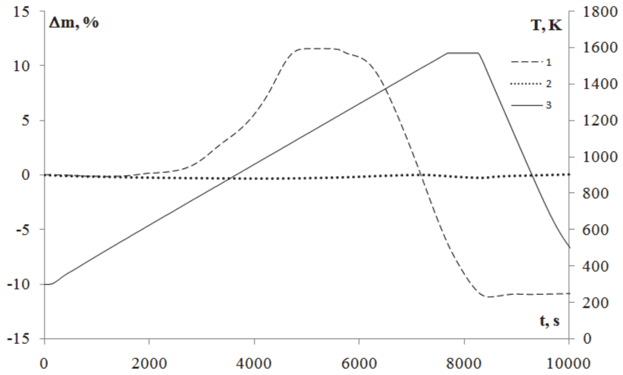


Figure 17 The mass change of Fe_2MoO_4 during heating in different atmosphere: 1 – Fe_2MoO_4 in air atmosphere; 2 – Fe_2MoO_4 in argon atmosphere; 3 – temperature profile [16]

4.3.1.2 The *in-situ* formation of $CaMoO_4$, $MgMoO_4$ and Fe_2MoO_4 from industrial grade materials

TGA studies of Fe_2MoO_4 formation. TGA studies of the binary mixtures showed that in the case of MoO_3+C mixture two steps of mass change were observed (ca 900 and 1250 K respectively, line 3, **Figure 18**), which can be explained by intermediate MoO_2 formation and agrees both with mass balance calculation and other investigations. The reaction is fast and almost completed within 10 min of holding at 1373 K. The mass decrease for the Fe_2O_3+C mixture starts after 900 K (line 2, **Figure 18**) and goes without noticeable intermediate steps. The reaction rate is much less than that for (MoO_3+C) mixture and the reduction is not complete within 10 min of holding time at 1373 K. In the case of Fe_2MoO_4 synthesis, the mass change profile has 2 steps (line 1, **Figure 18**).

The final mass decrease was 11.45 % while the theoretical value should be 11.65 % corresponding to the reduction of Fe_2O_3 and MoO_3 in the mixture by carbon to FeO and MoO_2 respectively with CO formation. The reduction is reasonably fast and, as it was found from the mass change profile that the reactions were complete within 6 min after reaching the temperature of 1373 K at a heating rate of 10 K per minute.

The first step of approximately 2.8 % of mass decrease after 900 K can be mostly attributed to the reduction of Fe(III) to Fe(II) in the mixture, which should lead to 3.1 % decrease in mass if the mixture composition and reaction stochiometry were considered. The second phase of 8.65 % mass decrease after 1200 K can be linked mostly to the formation of Mo(IV) compounds from Mo(VI), which should lead to 8.3 % decrease. It can be expected, that first, Fe_2O_3 is reduced by carbon to FeO, followed by the reduction of MoO_3 to MoO_2 and finally, Fe_2MoO_4 would be formed. MoO_3 melts above 1068 K and can form a eutectic with MoO_2 having even a lower melting temperature. However, the second step of the reduction of Mo(VI) to Mo(IV) takes place at higher temperatures than for the binary C+MoO_3 mixture. The reaction sequence with respect to the formation of Fe_2MoO_4 from the precursor mixture can thus be described by the following equations:

$Fe_2O_3 + C = 2FeO + CO$ (above 773-973 K) (23)

$MoO_3 + C = MoO_2 + CO$ (above 1173 K) (24)

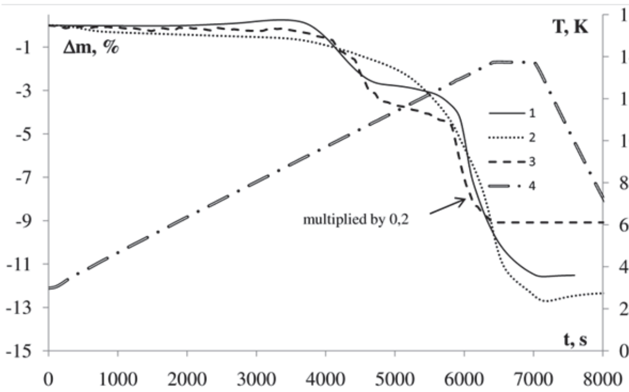


Figure 18 The mass changes for different mixtures observed by TGA studies: 1- mixture for Fe_2MoO_4 synthesis; 2- Fe_2O_3+C; 3- MoO_3+C (Δm multiplied by 0.2); 4- temperature profile [16]

High temperature XRD studies on Fe_2MoO_4 formation from precursor mixture. There are no serious differences between XRD peaks at room temperature and 773 K. However, some small changes in XRD peaks are observed at 873 K as compared to room temperature, probably due to the chemical reactions getting started. The major phase, found after reaching 973 K was MoO_2. The peaks of the samples were almost the same at 973 and 1073 K, and MoO_2 seems to be the major component of the Fe_2MoO_4 precursors mixture treatment, together with the small amounts of iron oxides FeO, Fe_3O_4 and $Fe_2Mo_3O_8$ (**Figure 19**). This means that the reduction of MoO_3 started around 873 K and the formation of MoO_2 is finished before reaching 973 K. On the other hand, there was no fast reaction between MoO_2 and FeO at 1073 K as there were no XRD peaks corresponding to Fe_2MoO_4 found at such temperatures after 10 min holding. These results are in conformity with the TGA results. Thus, it can be concluded that the reaction of MoO_3 reduction by carbon includes at least 2 steps. First one is a fast reaction resulting in the formation of MoO_2 before 973 K, while the second stage of MoO_2 reaction with FeO proceeds much slower and requires more than 10 min holding time at 1273-1473 K.

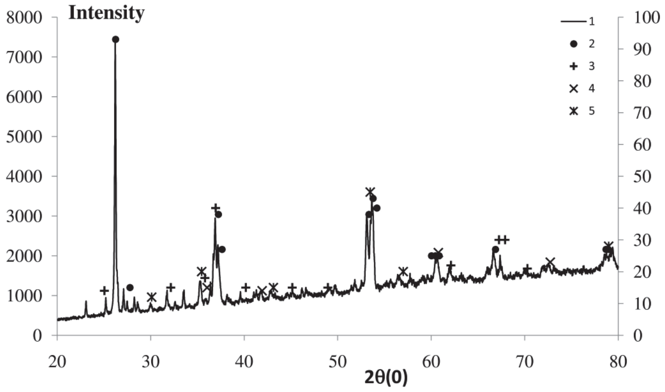


Figure 19 XRD patterns for the mixture for Fe_2MoO_4 precursor at 1073 K: 1-patterns, 2-MoO_2 markers, 3-$Fe_2Mo_3O_8$ markers, 4-FeO markers, 5-Fe_3O_4 markers) [16]

Gas chromatograph (GC) studies. Gas chromatograph studies were carried out for Fe_2MoO_4 precursor mixture. The results of composition changes of gas, passed through the heated mixture are shown in **Figure 20** as a function of furnace temperature.

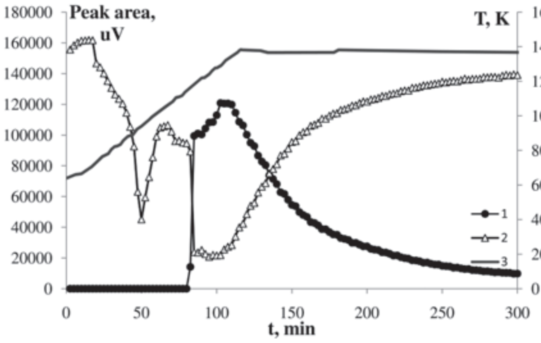


Figure 20 The gas composition changes as a function of mixture temperature: 1 – CO peak intensity; 2 – Ar peak intensity; 3 –temperature profile [16]

It can be seen in the **Figure 20** that argon concentration starts to decrease just above 800 K, probably due to the dilution of gas mixture with CO_2 formed by carbon oxidation (this could not be detected by GC) during the experiment. After 1110 K, a sharp increase in CO concentration is observed. The evolution of CO reaches its maximum at approximately 1300 K and then starts to decrease. The decrease lasts for the whole experiment, probably due to the large volume of the reactor tube and small gas flow rate.

4.3.2 Laboratory trials on steel alloying from 16-g- to 500-g-scale experiments

16-g-scale laboratory experiments. During the 16-g-scale experiments, most of the steel samples showed the concentration of Mo around 2 % after the trials. There was no noticeable crucible contamination as well as metal loses in any form. To compare the results from different heats, molybdenum yield was estimated from each sample analysis. Analysis from different parts of the sample showed similar Mo contents, confirming thereby that the Mo distribution in the sample was uniform. The molybdenum yield could be calculated as the ratio of molybdenum mass in the metal sample to the mass of molybdenum in the initial mixture:

$$\eta_{Mo} = \frac{[\%Mo]_{met} \cdot m_{met}}{[\%Mo]_{mix} \cdot m_{mix}} \cdot 100\% \qquad (25)$$

where $[\%Mo]_{met}$ – molybdenum content in a metal sample, m_{met} – metal sample mass, $[\%Mo]_{mix}$ – molybdenum content in alloying mixture, m_{mix} – alloying mixture mass.

Table 3 The average values of molybdenum yield, obtained from the different molybdenum sources in 16-g-scale test

Mixture	Molybdenum precursor	Number of reliable experiments	Average value of the yield, %
ST-1	$CaMoO_4$+C	3	93.0
ST-3	MoO_3+C	4	93.3
ST-4	CaO+MoO_3+C	3	92.0
ST-5	MgO+MoO_3+C	4	6.6
ST-6	Fe_2MoO_4+C	2	98.2
ST-7	MoO_2+C	3[a]	93.2
ST-8	Fe_2MoO_4 precursor+C	1	95.4
ST-8	Fe_2MoO_4 precursor +C	3[a]	96.2

[a]-experiments with spinel crucibles

The experiments showed that, after 4-5 min after reaching 1923 K, the steel samples were homogeneous, the mixture was completely consumed and the yield of Mo reached the values up to 98 %. This indicated that the dissolution of molybdenum in liquid iron is fast enough and nearly completed during the melting of the iron tablets. The comparison of average values of molybdenum yield for different molybdenum precursor, tested in present work is shown in the **Table 3**. The results showed that both prepared Fe_2MoO_4 and Fe_2MoO_4 precursor mixture provided the highest yield during laboratory steel trials, which can be explained by the absence of molybdenum evaporation from this alloying material in argon atmosphere. These results are in agreement with thermogravimetric studies, described in previous chapter.

500-g-scale laboratory experiments. The 500-g-scale experiments were carried out as the second stage of the process development. Post-experiment observations revealed that the metal had completely melted without any appreciable evidences of crucibles contaminations. The results of the Mo yield calculations after the samples analysis are shown in **Table 4**. The results showed that M1 (Fe_2MoO_4 precursor + C) mixture provides the highest yield, which is in agreement with the smaller scale experiments. The yield from MoO_3 + C mixture is approximately the same as for 16-g-scale trials, while for $CaMoO_4$ + C mixture the yield is considerably lower. The poor yield and scattering of the results during 500-g-scale trials for the M3 mixture may be attributed to incomplete reaction between the components of the mixture and steel.

Table 4 The values of molybdenum yield, obtained during 500-g-scale experiment

Mixture N	Components and their content	Mo yield, %	
		1st series	2nd series
M1	C-12.5 %; Fe_2MoO_4–precursor-87.5 %	97.7	98.2
M2	C-20.0 %; MoO_3-80.0 %	93.0	89.7[a]
M3	C-15.3 %; MoO_3-61.0 %; CaO-23.7 %	76.6	86.7

[a] -There was a leakage of steel from this crucible and the Mo yield obtained is not reliable.

4.3.3 Industrial trials on steel alloying in 3 ton induction furnace

In the case of plant trials at 3 ton scale, the steel samples were taken after complete scrap melting (after ferrosilicon addition). After the chemical analysis of the samples, the yield of Mo was calculated for each heat using the formula (25). The results of steel samples analysis and molybdenum yield together with other parameters calculations are presented in **Table 5**.

In the case of this $FeMoO_4$+C mixture, 3 heats were performed with the same charging mixture and the Mo yields were quite scattered depending on the mixture preparation. For the heats H1(M1) and H2(M1) Mo yield was 89.2 % and 91.5 % respectively. For these heats, large initial pieces of iron oxide were used. Some of the pieces were more that 10 cm in size. Since it was presumed that larger pieces of iron oxide would result in incomplete formation of iron molybdate in the mixture due to the low surface area to volume ratio, for the heat H6(M1) mainly small pieces (below 2 cm in diameter) were taken during mixture preparation. The yield of Mo for heat H6(M1) reached 97.8 %.

Table 5 The results of steel samples analysis and molybdenum yield calculations

Heat No.	Mix No.	Metal composition, %				Calculated parameters		
		Mo	C	Mn	Si	Liquid steel, kg	Slag mass, kg	Mo yield, %
H1	M1	0.9	0.065	0.17	0.13	2936	63.9	89.2
H2	M1	0.91	0.077	0.39	0.29	2917	52.4	91.5
H3	M2	0.94	0.083	0.2	0.15	2894	54.3	92.8
H4	M2	0.93	0.05	0.14	0.015	2891	65.3	92.6
H5	M3	0.93	0.046	0.14	0.002	2884	82.8	92.4
H6	M1	0.992	0.079	0.21	0.26	2922	60.8	97.8

4.3.3 Industrial trials on Mo alloying in 60 ton EAF

The Mo alloying mixture was tested during production of Mo-containing steel in 75 ton EAF at Uddeholms AB, as shown in Figure 21. The amounts of MoO_3 for each heat were the same as for previous practice for pure MoO_3 addition. The experimental results showed higher and more stable concentrations of Mo after scrap melting if compared with traditional technology.

Figure 21 Test of Mo alloying by using $FeMoO_4$+C mixtures in 60 ton EAF at Uddeholms AB

The test results clearly shown that the Mo content after scrap melting (average is 1.54) is higher than that of the existing practice with the addition of the same amount of MoO_3 (average is 1.47). Also the content of Mo seems to be more stable, which is another advantage of the new process of steel alloying. The carbon content is in the acceptable range, which shows that there are no considerable carbon pick-up from mixture. The Mo yield for this tested steel grade is close to 99.5%. Uddeholms AB is very positive with the results and more trials for other Mo steel grades will be conducted. Full Industrial testing of Mo alloying in 75 ton EAF has been done for 2 steel grades (Mo=1.4% and Mo=2.4%) and results are very positive. Uddeholms AB is very satisfied with the results. Outokumpu (Avesta) is interested with the results from Mo alloying technique and they are doing some test work in their 150 ton EAF furnace.

4.3.4 *In-Situ* Chromium Alloying in EAF Operation

As an extention work of Mo direct alloying in EAF, *in-stiu* chromium alloying in EAF has been started in the current project. By using cheap pulverous chromite ore, Carbon, and FeOx/iron scraps as the charge mix for Cr alloying in EAF operation, it is expected Cr can “instantly” be alloyed in the steel, energy be saved, carbon contents in the steel well be controlled, Cr2O3 in slags decreased, and finally production price be reduced and environmental index improved.

The preliminary laboratory investigation of the proposal discussed above has showed very good results. The Thermogravimetric Analysis results showed that the present of metallic iron in the alloying mixture (iron chromite + Carbon+ iron) is kinetically favorable for the reduction process, since during the reduction process, reduced Cr can *in-stiu* be adsorbed by iron and thus reduce the activity of Cr, which can further stimulate more and faster reduction. The best results of induction furnace experiments, by using (chromite ore + charcoal + iron) as mixture, showed that the Cr yield can reach as high as 92%, and the left part of chromite was found to be dissolved in the slags that added in the mixture. The Further step of induction furnace experiments will separate the process of alloying mixture addition and slags addition, i.e., slags will be added after the completely reduction of chromite, by which a Cr yield of more than 95% can be expected. The induction furnace experiments by using (iron chromite + Carbon+ mill scale) as charge mix is being done, and mill scale is expected to be more effective than iron, since mill scale will be reduced first to produce iron, which is more active than the added iron. Mass balance, energy balance and production efficiency calculation, as well as the plant trial works will be done to justify the effectiveness of present work in the real production process

4.4 Extraction of metal values by using a salt extraction process [17]

A salt extraction process was designed in order to extract the metal values from slag rests. Attention was mainly focused on the Cr in the slag. The flow sheet for the extraction part of Cr from the slag is presented in Figure 1 in Appendix D. Experiments were conducted with Cr-slags from Uddeholm Tooling AB by extracting the Cr-values by NaCl-KCl melts at 1023 K at different time intervals. The results are shown in Figure 2 in Appendix D. The fundamental aspects of salt extraction were also investigated. The Pourboux-type of diagram for Cr-extraction by molten salt is presented in Figure 3 in Appendix D. The experiments conducted under acidic dissolution conditions showed up to 80 % Cr recovery (see Figure 4 in Appendix D). Experiments with a typical slag from Uddeholm Tooling AB containing 0.17 wt % “MoO” showed that the “MoO” in the slag after the salt extraction was 0.04 under typical experimental conditions

It is demonstrated that it is possible to recover various metal values from slags from alloy steel production, low-grade ores and even spent refractory linings. The process consists of a salt extraction step and an electrolytic deposition step.

4.4.1 Dissolution of slag/chromite

Figure 22 shows the standard Gibbs energy changes of metal oxides with the flux $AlCl_3$. This figure indicates that SiO_2 is very difficult to be dissolved in the salt melt. Thus, the oxides Al_2O_3 and SiO_2 can be separated as the residue after leaching the salt and slag phases in water at the end of the process. Two typical EAF slags, No.S1 and S2 with a high content of FeO and Cr_2O_3, respectively, as shown in Table 6**,** were investigated. Four factors, holding temperature, holding time, flux content (mole ratio to NaCl-KCl mixture) and flux/slag(weight ratio) were investigated.

Table 6 Composition of EAF slags from Uddeholm Tooling AB and Vietnamese chromite

No.	Stages	CaO	MgO	Al_2O_3	SiO_2	FeO	MnO	Cr_2O_3	MoO
No.S1	After tapping	41.4	7.91	3.29	10.44	23.06	4.98	3.25	0.17
No.S2	Before blowing O_2	29	12.4	3.6	18.4	11.2	2.5	21.1	0.02
No.C1	original	0.12	8.88	11.94	12.73	22.31	0.08	41.40	-

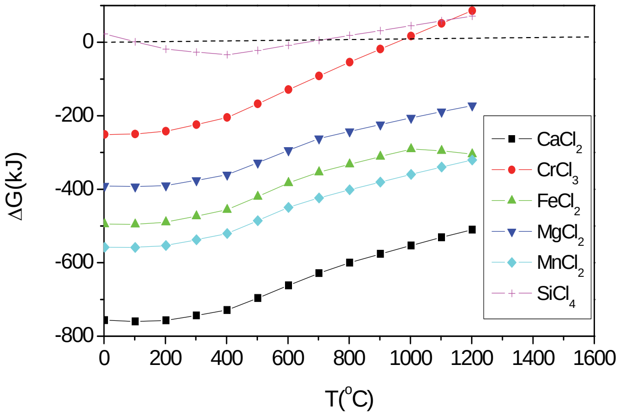


Figure 22 The standard Gibbs energy change of different metal oxides versus temperature

For slag No. S1, an orthogonal experimental design was employed. The yields of the extracted metal are shown in Table 7. In this table, the solubility ratio is defined as the ratio of dissolved oxide in the salt to the amount of corresponding oxide in the starting slag. In the present work, two methods were used to estimate the amount of dissolved oxide. First, the residue after dissolution was filtered and subjected to the chemical analysis, then the dissolved oxide can be estimated from the difference between the starting slag and the residue. Alternatively, the filtrate was diluted and subjected to Inductively Coupled Plasma Atomic-Emission Spectrometry(ICP-AES), then the contents of different metal ions in the solution can be converted to the amounts of different oxides in the salt phase. From Table 7, one can see that most of CaO, MnO and FeO can dissolve into the salt phase, while half or more Cr_2O_3 can be dissolved, and the dissolution is in the order of '$CaO>MnO>FeO>MgO/Cr_2O_3$'. Some results from ICP-AES analysis are also listed in Table 7, which are in good agreement with the ones from chemical analysis.

Table 7 Solubility ratio of metal oxides in NaCl-KCl system

No.	Solubility of metal oxides*					Conditions			
	CaO	MgO	FeO	MnO	Cr_2O_3	Temp.(^oC)	Time(h)	Flux	Flux/Slag
1	97,92%	7,23%	68,10%	93,84%	36,92%	850	6	20%	1.0:1
2	100%	31,88%	88,35%	98,18%	55,52%	850	8	25%	1.2:1
3	99,73%	35,59%	82,37%	94,68%	56,92%	850	10	30%	1.5:1
3I	98.81%	33.48%	78.36%	95.16%	55.79%	850	10	30%	1.5:1
4	100%	79,80%	83,83%	92,08%	58,37%	900	6	25%	1.5:1
4I	99.21%	70.36%	79.25%	91.88%	57.39%	900	6	25%	1.5:1
5	99,82%	17,39%	71,66%	90,76%	48,23%	900	8	30%	1.0:1
6	100%	31,86%	91,40%	97,26%	55,27%	900	10	20%	1.2:1
7	100%	46,89%	84,97%	91,24%	55,97%	950	6	30%	1.2:1
8	98,83%	80,88%	82,29%	89,28%	68,16%	950	8	20%	1.5:1
8I	99.25%	74.55%	78.86%	90.35%	66.20%	950	8	20%	1.5:1
9	90,61%	13,14%	83,36%	96,59%	48,24%	950	10	25%	1.0:1

$$* \quad \frac{W\_MOx(slag) - W\_MOx(residue)}{W\_MOx(slag)} * 100\%$$

4.4.2 Electrolytic Recovery

The dissolution test proves that the metal oxides in EAF slag/chromite can be extracted into the salt phase. The corresponding ionic states for the cations are likely to be Fe^{2+}, Cr^{3+}, Mn^{2+}, Mg^{2+} and Ca^{2+} together with Na^+, K^+. The schematic diagram of the selective electrolysis method is shown in Fig.23. Under different cell potentials, the various metals or alloy can be deposited on the cathode surface. The theoretical decomposition voltage plotted in Fig.24, can give the deposition trend as $CrCl_3>FeCl_2>MnCl_2>AlCl_3>MgCl_2>NaCl>CaCl_2>KCl$. It shows that Fe and Cr will deposit first. Taking account of the higher cell voltage requirement and the lower content of Mn^{2+} and Mg^{2+} in salt phase, under a cell voltage of 2.8V, ferrochromium alloy is likely to be the main product. It should be noted that, the electrodeposition of metals can be affected by a number of factors even in pure molten salt systems, as for example, over voltage, current density, current efficiency, electro-bath conductivity, the nature and surface of the cathode material and distance between electrodes, etc. In the present work, several electrolysis tests on EAF slag/chromite were carried out with promising results.

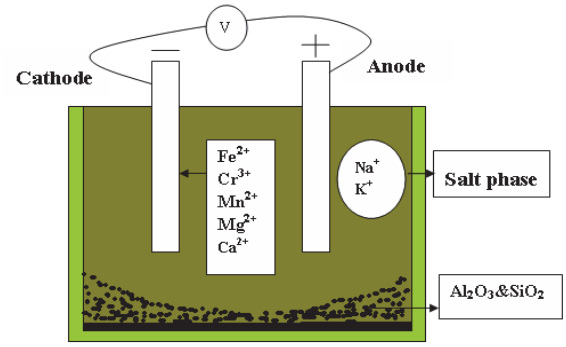


Figure 23 The schematic diagram of the selective electrolysis method

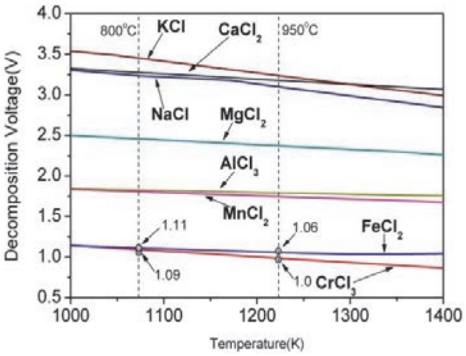


Figure 24 The theoretical decomposition voltage of different metal chlorides

A typical photo of the cathode product after electrolysis of the slag is shown in Figure 25 (left). The deposit consists of FeCr-rich alloy with a low amount of oxygen and salt mixtures with some undissolved slag. The present experiments show clearly that ferrochrome can be recovered from the slag by the combined extraction-electrolysis process. XRD results of the adhered substances on the cathode confirm the formation of Fe-Cr, as shown in Fig.25 (right). The cathode products consist mainly of Fe-Cr, inclusions of NaCl and KCl from the electrolyte apart minor levels of other impurities.

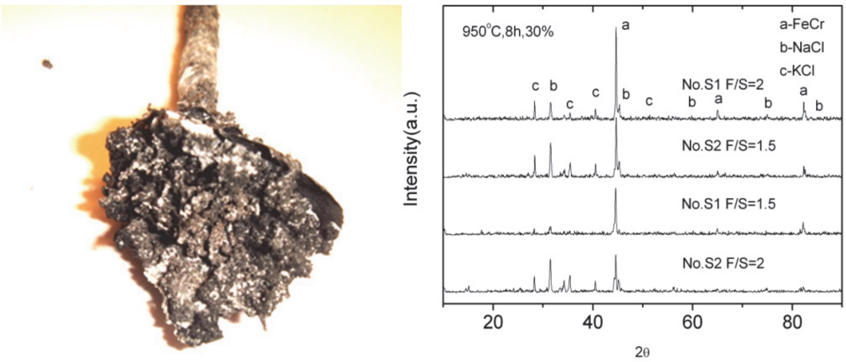


Figure 25 (left): A typical photo of the cathode product after electrolysis; (right): XRD patterns of the cathode products of slag electrolysis

4.4.3 New improvement

The present results show that the molten salt extraction route offers a promising route towards the recovery of metal values from slags, low grade ores and rare metals from recycled electronic materials. The electrolysis of the extract to get Fe-Cr has also been demonstrated. A new salt system based on NaCl-KCl-LiCl ternary system has been studied to lower the molten salt process temperature [18]. In our previous studies on this process the extraction of metallic values were carried out through utilization of aluminium chloride ($AlCl_3$) which acts as flux in the process. This however leads to high consumption of $AlCl_3$. Now the focus of this work is based on our new electrolysis system in which the required $AlCl_3$ is produced *in-situ* by the modification of the electrode reactions. This has the added advantage of eliminating chlorine evolution during electrolysis. This is done by replacing $AlCl_3$ with metallic aluminium which is used as the anode material.

For this, electrolysis experiments were carried out on mixture of iron and chromium oxides for the recovery of chromium and iron. SEM/EDS analysis of the cathode deposit confirmed the deposition of CrFe alloy on the cathode by the modified technique. Besides, electrochemical behaviour of iron and chromium in the LiCl+KCl+NaCl (the supporting electrolyte) has been studied by performing cyclic voltammetry and chronoamperometry experiments. These experiments were performed at NTNU, Trondheim, Norway.

A three kilogram upscaling experiment of Cr salt extraction process from slag will be carried out in the new constructed big scale equipment, as shown in Figure 26.

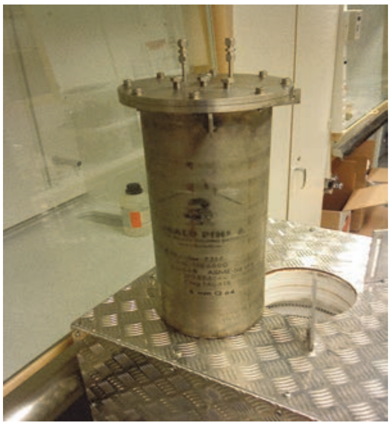


Figure 26 The photo of the big scale unit with slag treatment capacity of 3 kg

4.4.4 Recovery of Nd from Na-Fe-B magnets by MSE

The molten salt extract method has been extended to the recovery of neodymium from spent Nd-Fe-B magnets ($Nd_2Fe_{14}B$). The salt bath consisted of a mixture of NaCl-KCl-LiCl eutectic composition. Liquid aluminium with a graphite lead was used as the anode and a graphite rod dipped in the salt bath formed the cathode. In this method, $AlCl_3$ was formed *in situ* during the process by reaction between liquid Al anode and chlorine gas liberated by the electrolysis of the chlorides, which functioned as a flux. The voltage for the electrolysis was chosen on the basis of the decomposition potential of $NdCl_3$.The reaction sequence can be described as:

$$Al + 3/2\ Cl_2 = AlCl_3$$

$$AlCl_3 + Nd = NdCl_3 + Al$$

$$NdCl_3 = Nd + 3/2\ Cl_2$$

The schematic diagram of this process is shown in the figure 27.

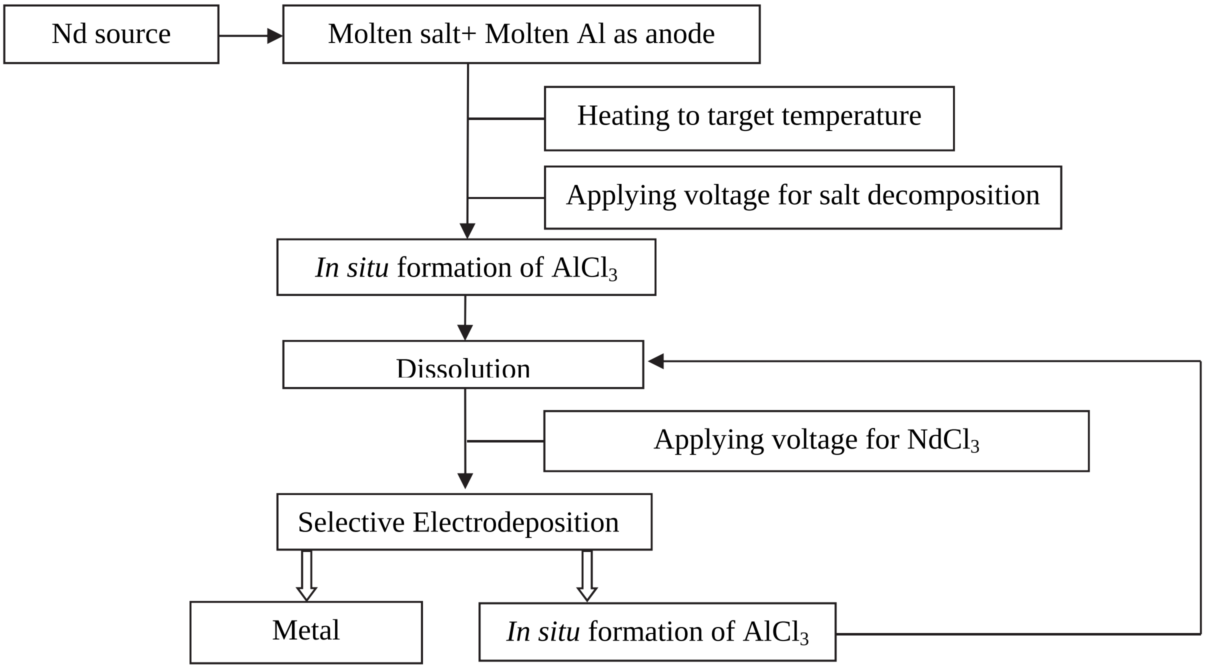


Figure 27 Schematic diagram of the salt extraction process using molten aluminium as anode

Iron-free neodymium deposition could be carried out successfully. In view of the proximity of the electrode potentials, the co-deposition of the aluminum occurred along with Nd at the cathode, as revealed by EDS analysis of the electrodeposit. The SEM image from the cathode deposition is shown in Figure 8. Metal and oxide phases are shown in the figure. The process shows that this method is well-suited for recovering rare earth metals from scrap containing these metals as also oxide raw materials.

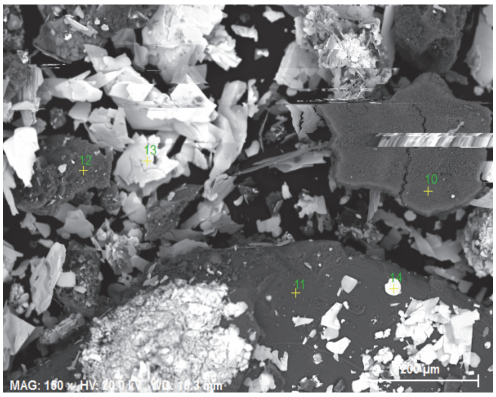


Figure 28 SEM image of cathode deposition after electrolysis of Nd-Fe-B magnet using Al as anode . Electrolysis was done at V=1.8 (V) and T=1073 K during 6 hours. A is the metalic phase (Nd), B and C are oxide phase (Al_2O_3, Al-Nd-O respectlively).

4.5 *Fe and Mn recovery from electromagnetic separation by oxidation route [6]*

The oxidation of FeO in synthetic slags was investigated by thermogravimetric analysis (TGA) using SETARAM TAG 24 (France). Typical experimental curves for the isothermal weight gain during oxidation at different temperatures are presented in Figure 29. In this figure, the horizontal lines indicate the theoretical levels corresponding to complete oxidation of FeO in the slag to magnetite and into hematite. The characteristics of the curves demonstrate that during 10-15 min of the experiment, the oxidation level of 80-90% was reached.

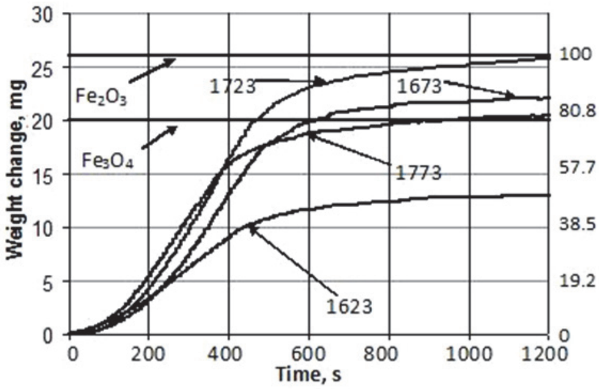


Figure 29 The isothermal weight changes curves for the composition: 25% FeO; 37,5% CaO; 37,5% SiO_2 for different temperatures K

It can be seen in Figure 27 that an increase of temperature in the range 1623-1723 K is followed with the progressive weight gain caused by oxidation. The maximum oxidation level achieved also increases for all the slags studied with rise in temperature. However, at the temperature 1773 K, the oxidation behaviour is somewhat different; oxidation proceeds rapidly in the early stage but slows down at the later stage. The final weight gain (i.e. oxidation level achieved) is below the corresponding levels at 1673 K and 1723 K. The divergence of the oxidation behaviour at 1773 K from the lower temperature experiments can be explained with formation of a liquid with the produced magnetite. For the quaternary system the final product after oxidation was found to be magnetite and manganese ferrite.

The oxidation mechanism at temperatures below 1773 K was described with the mathematical model. Considering the oxidation of the liquid slag in air, the “FeO” in the slag would be oxidized to magnetite or hematite. The oxidation process may consist of three distinct steps, *viz.* nucleation of magnetite from the slag, followed by a chemical reaction-controlled stage and later, the diffusion of oxygen through the product layer.

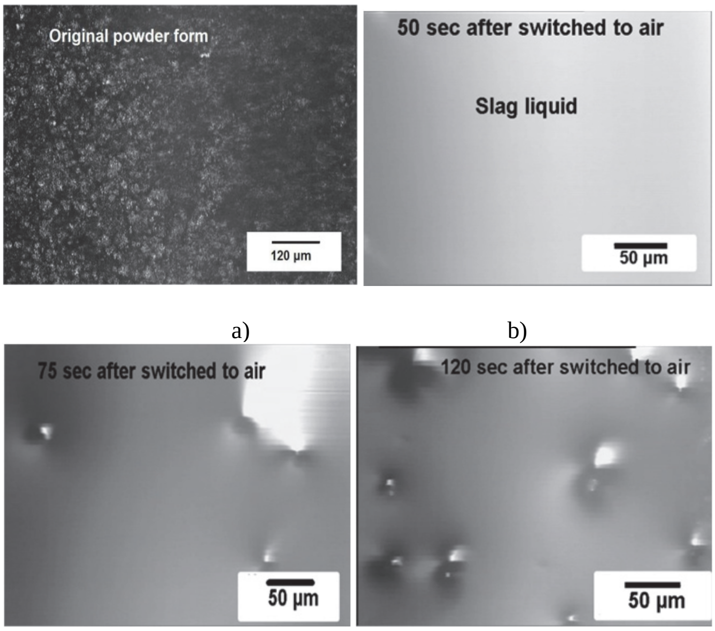
The chemical reaction can be represented as

$$3(\mathrm{FeO})_{\mathrm{slag}} + 1/2\mathrm{O}_2 = (\mathrm{Fe}_3\mathrm{O}_4)_{\mathrm{solid}} \qquad (26)$$

$$2(\mathrm{FeO})_{\mathrm{slag}} + 1/2\mathrm{O}_2 = (\mathrm{Fe}_2\mathrm{O}_3)_{\mathrm{solid}} \qquad (27)$$

$$2(\mathrm{FeO})_{\mathrm{slag}} + (\mathrm{MnO})_{\mathrm{slag}} + 1/2\mathrm{O}_2 = (\mathrm{MnFe}_2\mathrm{O}_4)_{\mathrm{solid}} \qquad (28)$$

As the oxidant gas is let in, the thermograms show an incubation period, which is likely to correspond to the nucleation of the first particles of magnetite on the slag surface. This was confirmed by confocal microscopic studies of the oxidation phenomenon carried out in collaboration with Professor Sridhar Seetharaman at Carnegie Mellon University, USA. A typical CSLM image is presented in Figure 30.



a) b)

c) d)

Figure 30 Typical crystals observed by the CSLM for sample of ternary slag system at 1623K: a) sample as original powder form at room temperature; b) molten sample; c) crystal formation; d) crystal growth [6].

A cold model studies were performed to study the potential way of the magnetite particles separation from liquid slags. The effect of current density, magnetic field, radius, and the shape of the particle on the particle velocity were analysed. With increasing applied current density, magnetic field and radius of the particle, velocity of the particle was increased. Theoretical application of the obtained data on the real magnetite particle/liquid slag system showed that the magnetite will have a subcritical behaviour, and will move with approximate velocity of 0.1-2.5 mm/min.

In the case of slags containing FeO and MnO, it was shown that by suitable tailoring the process parameters, it was possible to precipitate out nano-sized manganese ferrites with optimized properties. A Swedish patent has been applied for by Jernkontoret on this process.

5 CONCLUSIONS

The present part of the MISTRA project, i.e. the “Retention, Recovery and Recycling” part, has been divided into five parts in our work plan.

5.1 Thermodynamic measurements of Fe-Cr-C and Fe-Cr-C-N alloys by EMF measurements, as well as the valence state and activities of chromium and vanadium oxides in slags by gas-slag equilibration method, were conducted. The results show in the case of the alloy systems that N has decreases the activity of Cr in the alloys drastically. This was verified by *ab initio* calculations.

The oxidation states of chromium in slags as well as sulphide capacity of CrO_x-containing slag have been studied. In the studies of oxidation state of chromium in slags, gas/slag equilibrium technique was used for CaO-SiO_2-CrO_x system and the ratio of Cr^{2+}/Cr^{3+} in multicomponent slags was measured by X-ray absorption near edge spectra (XANES). High-temperature mass spectrometry method was also used to obtain the distribution of chromium oxides in CaO-MgO(-FeO)-Al_2O_3.SiO_2.CrO_x system.

A mathematical correlation was established for estimating the ratio of Cr^{2+}/Cr^{3+} as a function of temperature, partial pressure of oxygen and slag basicity. The comparison between experimental valence ratio values and estimated ones presents a satisfactory agreement.

XANES method was adopted to determine the oxidation states of vanadium in the CaO-MgO-Al_2O_3-SiO_2-VO_x slag system. The results indicate that, x in VO_x increases with increase of slag basicity, indicating that higher basicities stabilize higher vanadium oxidation state. On the other hand, higher temperature stabilizes lower vanadium oxidation state. For a given value of basicity, the value of x was found to increase with the increase of oxygen partial pressure. From the present results, the V^{3+}/V^{4+} and V^{4+}/V^{5+}ratios can be estimated under different conditions.

5.2 In the Retention part, decarburization under controlled oxygen partial pressure, was dealt with both theoretically and experimentally. Theoretical studies showed that it could be advantageous to use CO_2 as an oxygen supplier. Minimization of Cr losses to the slag could be noticed. A generic model has been developed to describe the reactions between liquid metal and gas bubbles. The potential of the model is illustrated by its application in predicting the evolution of Cr and C contents in a Fe-C-Cr melt during injection of different $O_{2-}CO_2$ mixtures. The model can also be advantageously used in conjunction with mixing models or models based on CFD to simulate larger systems. The experimental results obtained by induction furnace indicate that the predictions of the model are in good agreement with the experimental results. The present work indicates that the process cannot be fully described by thermodynamic analysis applied to the bulk composition, since the compositions at the reaction site can be significantly different due to mass transfer constraints. The induction furnace experimental results also indicate that the Cr-losses can be significantly lowered by replacing the oxygen with CO_2 in the injected gas, specifically for Fe-Cr-C melts with carbon levels higher than about 0.8 mass%.

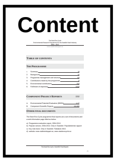
The kinetics of oxidation of Fe-Cr melt and Fe-Cr-C melts can be considered to consist of three distinct steps, *viz.* the chemical reaction and diffusion as rate-controlling steps with a transition region between them. In the initial stages of oxidation, the oxidation rate is controlled by the chemical reaction and can be described by the relationship $\frac{dm}{dt} = \Lambda C_{Cr}^{0.23} C_{CO_2}^{0.41} \exp(\frac{-E_a}{RT})$ at the Cr range of 11-21 mass% in Fe-Cr melt.

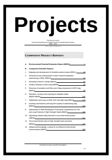
5.3 Further in the Retention part of the project, process modifications with a view to optimize Mo retention, theoretical assessment of Mo-additions and plant trials were carried out. Synthesis of stable Mo-compounds from low-grade Mo-sources and mill scale were carried out. The evaporation rate of pure MoO_3 was studied by TGA and compared with the evaporation rates from mixtures of MoO_3 with CaO, $CaCO_3$, MgO. It was found that MoO_3 can be stabilized by mixing with CaO, MgO or $CaCO_3$ and heating the mixtures as the result of appropriate molybdates formation.

The Mo yield by use of three different Mo alloying mixtures (MoO_3+C; MoO_3+C+FeO_x; and MoO_3+C+CaO) was tested both in laboratory and industrial experiments. During laboratory experiment, both in 16- and 500-g-scale trials, Fe_2MoO_4 precursor mixture (MoO_3+C+FeO_x), showed the Mo yield is up to 98 %, which can be explained by the absence of molybdenium evaporation from this substance.

During industrial trials, it was found that for the Fe_2MoO_4 precursor mixture (MoO_3 + C + FeO_x), the Mo yield in 5 ton induction furnace was reached 98 % and in the 75 ton EAF the yield was reached to 99.5%. Uddeholms AB has applied for a patent for the process. This work has been extended to the in-situ Cr alloying in EAF.

5.4 In the Recovery part of the project, , successful extraction of Cr and Mo from slags using suitable fluxes have been carried out by the salt extraction method. The electrochemical behavior of different metal ions, Cr(III), Cr(II), Cu(II), Fe(III), Mg(II) and Mn(II) was studied by using cyclic voltammetry at 827°C in ($CaCl_2$-





NaCl-KCl) system with a tungsten or glassy carbon electrode. The deposition process of Cr(III) species consisted of two electrochemical steps, Cr(III)/Cr(II) and Cr(II)/Cr(0) exchanges. Other complexes, including Cr(II), Fe(III), Cu(II), Mg(II) and Mn(II) are can all be deposited through one single electrochemical step. All the electrochemical processes related to these metal ions can be regarded as reversible processes, and were proved to be controlled by diffusion as deduced from the linear relationship between the cathodic peak current and the square root of the sweep rate.

The deposition potentials of the electroactive species were confirmed from the voltammograms, and these values are found to follow the order: $CuCl_2<FeCl_3<CrCl_3<MnCl_2<MgCl_2$. The electrodeposition of chromium by using a two-electrode cell under constant voltage was carried out, and pure dendrite and nodular-like crystals of chromium was obtained. The present study provides a good understanding of the electrochemical behavior of several metal ions, and is thus helpful in optimizing the salt process for the recovery of metal values from slags or low grade ores.

A new salt system based on NaCl-KCl-LiCl ternary system has been studied to lower the molten salt process temperature. A modified electrolysis cell design was developed. The present results show that the molten salt extraction route offers a promising route towards the recovery of metal values from slags, low grade ores and rare metals from recycled electronic materials. The electrolysis of the extract to get Fe-Cr has also been demonstrated. Recovery of Nd from Na-Fe-B magnets by molten salt extraction and electrolysis process has also been tested and approved.

5.5 Further, in the recovery part, the oxidation of FeO and MnO in silicate slags followed by electromagnetic separation for the recovery of Fe and Mn was successfully carried out. For the experiments, synthetic slags of the ternary $FeO\text{-}CaO\text{-}SiO_2$ and quaternary $FeO\text{-}CaO\text{-}SiO_2\text{-}MnO$ systems were chosen. The mechanism of oxidation of FeO in molten slags was analyzed by combining advantages of Confocal Scanning Laser Microscopy and Thermogravimetric technique. The TGA experiments showed that, during 10-15 min, 70-90% of oxidation was achieved. Increase of temperature was found to cause an increase in the rate of the reaction. Kinetics of the crystal precipitation from the liquid $FeO\text{-}CaO\text{-}SiO_2$ and $FeO\text{-}CaO\text{-}SiO_2\text{-}MnO$ slags has been investigated by Confocal Scanning Laser Microscopy. Successive CSLM images showed the crystal formation during oxidation. With time, the crystals grew and agglomerated, reaching, in some cases, 50 µm in length. The SEM-EDS results showed the presence of calcium silicate and spinel containing manganese ferrite and magnetite. The phase characterization of the spinel formed at different temperatures was explained on the basis of thermodynamic calculations. Nano manganese ferrites with optimized magnetic properties could be precipitated out of the slags by oxidation.

6 FURTHER UTILIZATION

The future utilization work will be pursued along the tracks previously established as successful.

1. With respect to thermodynamic measurements, the results will be incorporated in the *Thermoslag software* developed in the division. *ThermoSlag software* is a useful tool for the steel industry and research institute to calculate the slag/metal thermodynamic reactions, viscosities and sulphide capacities of slags.

2. With respect to the decarburization studies under controlled P_{O2}, the mathematical model developed will be

extended to other Swedish steel plants for high alloy steel production.

3. With respect to retention of Mo during the EAF practice in Uddeholms AB, the 75ton EAF plant trials have been conducted in full scale and the results are very successful. Development of a standardization method for preparation of Mo alloying mixture has been started by Uddeholms AB by making briquette. Implementation and extension of Mo alloying mixture to other steel plants (such as Outokompu Avesta) will be conducted. The Mo alloying mixture purchase can be used by all the steel plants. Cr alloying by use of chromite ore in EAF will be conducted following the similar technology as Mo alloying by MoO_3.
4. With respect to the salt extraction process, successful results with Uddeholms AB slags have led to upscaling prospects. Off-shoots from the present project with respect to environmentally friendly route to copper production, nickel production, utilization of low grade ores, processing of waste process ceramics, recovery of rare earth metals are underway for parallel investigations.

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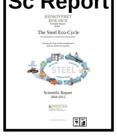

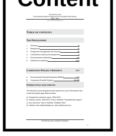

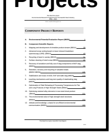

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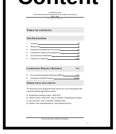

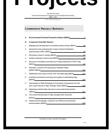

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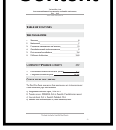
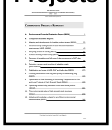

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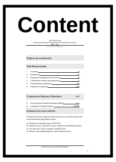

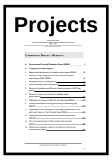

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8.4 Patent

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2. Anna Semykina, S. Seetharaman, V. Shatokha, ‘Nanoferrite combining oxidation and electromagnetic separation –Jernkontorets patent application, 2010.
3. Lidong Teng, Mselly Nzotta, S. Seetharaman, Andrei Chychko, Jan-Olof Andersson, “Process for making a steel melt containing carbide forming elements from iron based raw materials and a mineral containing the carbide forming element, an alloy mixture and use of a mineral containing carbide forming elements for alloying a steel melt in electrical arc furnace (EAF)’’. The Swedish Application No. 1050721-8, June 30, 2010.
4. Lidong Teng, S.Seetharaman, Katsunori Yamaguchi, Yukari Izumi, “Recovery of Lead from glass containing PbO, primarily from Electronic Waste Material”, Applied in Sept. 2011, Sweden.
5. S.Seetharaman, Lidong Teng, S. Sridhar, “A Process for Recovering Metals (Molten aluminium electrode), applied in Sept. 2011, Sweden.
6. S. Seetharaman, Lidong Teng, S. Sridhar, M. Barati, “Recovery of Rare Earth Metals”, patent applied for in June 2012, Sweden.
7. S. Seetharaman, Lidong Teng, S. Sridhar, P. Scheller, “A method for the extraction of vanadium pentoxide from a source containing V_2O_5”, patent applied for in June 2012, Sweden

APPENDIX A

The galvanic cell used can be represented as:

(-)Pt, N_2+CrN + CrF_2 // CaF_2 // CrF_2 + CaF_2 + <u>Cr</u>-alloy+N_2, Pt(+)

$CrF_2 + 0.5\ N_2 + 2e^- = CrN + 2F-$ (left)

Cell reaction : <u>Cr</u>-Alloy + $2F^- = CrF_2 + 2e^-$ (right)

<u>Cr</u>-alloy + $0.5\ N_2$ = CrN (overall)

Activity Calc: $\Delta_f G_{(CrN)} - 2EF = RT \ln a_{Cr\text{-}alloy}$

The galvanic cell used for activity measurements in Fe-Cr-C and Fe-Cr-C-N alloys

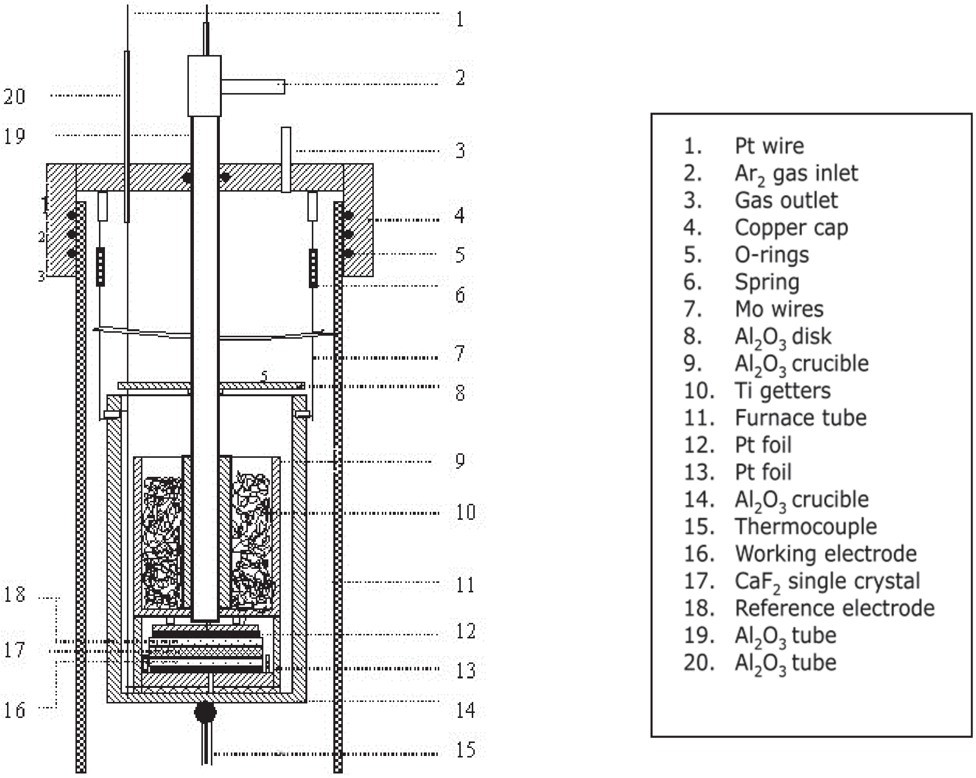


Fig. 1 Schematic diagram of galvanic cell apparatus

The Cr-O-N phase stability diagram at 1273 K is presented in Fig. 2.

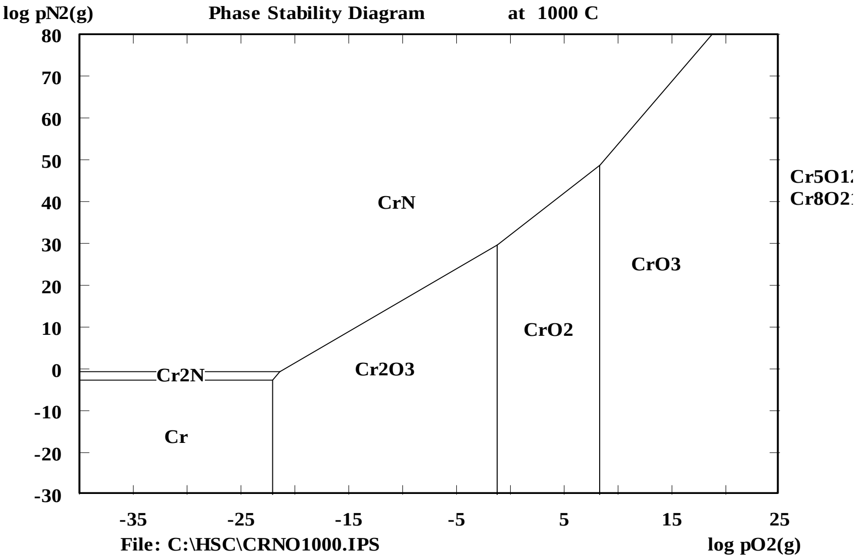


Fig. 2. Cr-O-N phase stability diagram

Principle of the method:

It has been well-known that the measurement of thermodynamic activities of chromium and vanadium oxides in slags is extremely complicated especially due to the high stabilities of these oxides. The traditional EMF method with ZrO_2-CaO electrolyte in the temperature range 1500-1650°C may not give reliable results in view of the contribution of electronic conduction to the cell voltage at the oxygen pressures involved. Consistent results could not be obtained using Knudsen effusion method. In view of this, the gas-slag equilibration method was chosen.

In this experiment the reference states were selected as follow:

Cr—pure solid, CrO—pure liquid, $CrO_{1.5}$—pure liquid

When the slag, kept in Pt-crucible is equilibrated with a gas mixture of known oxygen pressure, a part of the chromium oxide can be reduced and Cr-metal can dissolve in the Pt-crucible. From a knowledge of the thermodynamics of the Pt-Cr alloys, the activity of chromium oxide in the melt can be calculated.

For equilibrium between Pt-Cr alloy, the divalent and trivalent chromium oxides are assumed stable state in melt under the present experiment condition. Relative equations apply:

$$Cr_{(s)} + \frac{3}{4}O_2 = CrO_{1.5(melt)} \text{ ……………..(1)}$$

$$K_1 = \frac{a_{CrO_{1.5}}}{a_{Cr} \cdot (P_{O_2})^{3/4}} = \exp\left(\frac{-G_1^o}{RT}\right)$$

$$Cr_{(s)} + \frac{1}{2}O_2 = CrO_{(l)} \text{ ………………….(2)}$$

$$K_2 = \frac{a_{CrO}}{a_{Cr} \cdot (P_{O_2})^{1/2}} = \exp\left(\frac{-G_2^o}{RT}\right)$$

$$2Cr_{(s)} + \frac{3}{2}O_2 = Cr_2O_{3(s)} \text{ ………………..(3)}$$

$$Cr_2O_{3(s)} \rightarrow Cr_2O_{3(l)}$$

$$(\Delta G_3^o = -1092383 + 237.93T(J).\ \Delta H_{fus}^o = 129690 J/mol, T_m = 2603K)$$

$$\Delta G_1^o = \frac{1}{2}(\Delta G_3^o + \Delta H_{fus}^o - \frac{T\Delta H_{fus}^o}{2603}) \text{ (assuming } \Delta C_P \text{ is negligible).}$$

$$\Delta G_2^o = -334218 + 63.81T(J)$$

$$a_{CrO_{1.5}} = a_{Cr} \cdot P_{O_2}^{3/4} \cdot \exp(-\frac{\Delta G_1^o}{RT})$$

$$a_{CrO} = a_{Cr} \cdot P_{O_2}^{1/2} \cdot \exp(-\frac{\Delta G_2^o}{RT})$$

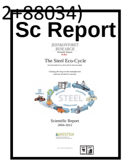
Where *a* are the activities of the various species, K are equilibrium constants and ΔG_i^o is the standard free energy of reaction *i*. The value of K_1 was calculated from fabrication free energy of $Cr_2O_{3(s)}$ and fusion enthalpy of $Cr_2O_{3(s)}$ at 2603K. Based on the thermodynamic data available [JANAF Tables, ThermoCalc] and the relationship of $\log r_{Cr}$ and a_{Cr} from relative literature, and by knowing P_{O2} and temperature, the activity of chromium oxide can be calculated.

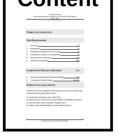
Materials and Slag compositions investigated:

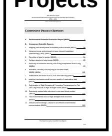
Table 1. Material and gases used in the present work

material	purity	supplier
Calcium Oxide(CaO)	Reagent plus,99.9%	Alfa Aesar, Germany
Silicon Oxide(SiO2)	Pro analyse grade,99.5%	Alfa Aesar, Germany
Aluminium Oxide(Al2O3)	99.7%	Sigma Aldrich, Germany
Magnesium Oxide(MgO)	Pro analyse grade	Sigma Aldrich, Germany
Chromium Oxide(Cr2O3)	99.9%	Sigma Aldrich, Germany
Vanadium Oxide(V2O3)	99.99%	Sigma Aldrich, Germany
Platinum foil(Pt)	0.127mm,99.99%	Alfa Aesar, Germany
Argon gas (Ar)	Grade plus	AGA Gas, Stockholm
Carbon Monoxide(CO)	Grade plus	AGA Gas, Stockholm
Carbon Dioxide(CO2)	Grade plus	AGA Gas, Stockholm
Silica gel	Grade 0.3	Sigma Aldrich, Germany
Magnesium perchlorate(Mg(ClO4)2)	Anhydrous ACS	Alfa Aesar, Germany
Ascarite II		Sigma Aldrich, Germany
Copper turnings	99+%	Alfa Aesar, Germany
Magnesium turnings	99.5%	Sigma Aldrich, Germany
Magnesium Oxide crucible Dense sintered	98%+ (2%Y2O3)	Keranova AB, stockholm
Combustion Alumina Ship	99.7%	Keranova AB, stockholm

Sample Number	Slag composition (*wt*%)					B2	Temperature/T	P_{O2}	X_{Cr}	a_{Cr}--F	a_{CrO}	$a_{CrO1.5}$
	CaO	SiO_2	Al_2O_3	MgO	Cr_2O_3			(atm)	(×10^{-}	(×10^{-}	(×10^{-}	(×10^{-}
CSAMC1	45.1	35.5	4.5	14.0	0.01	1.48	1803	10^{-9}	3.71	0.037	0.026	0.071
CSAMC2	45.9	33.8	4.5	15.2	0.02	1.60	1803	10^{-9}	6.34	0.119	0.085	0.23







CSAMC3	45.3	34.9	4.5	14.5	0.18	1.52	1803	10^{-9}	11.27	0.664	0.473	1.286
CSAMC4	45	34.3	4.5	14.1	1.60	1.52	1803	10^{-9}	16.08	2.68	1.908	5.184
CSAMC5	46.6	34.2	4.4	13.8	<0.01	1.56	1873	10^{-9}	4.3	0.049	0.015	0.03
CSAMC6	48.4	33.2	4.2	13.6	<0.01	1.66	1873	10^{-9}	6.73	0.138	0.043	0.081
CSAMC7	46.5	34.6	4.3	13.9	0.09	1.55	1873	10^{-9}	11.62	0.740	0.23	0.431
CSAMC8	45.8	34.5	4.7	14.2	0.28	1.53	1873	10^{-9}	17.0	3.42	1.059	1.994
CSAMC9	46.4	36.1	4.2	12.3	<0.01	1.46	1923	10^{-9}	4.20	0.047	0.008	0.012
CSAMC10	46.5	35.3	4.5	12.6	0.01	1.48	1923	10^{-9}	7.31	0.173	0.031	0.045
CSAMC11	46.3	35.5	4.5	12.8	0.08	1.48	1923	10^{-9}	12.2	0.884	0.157	0.231
CSAMC12	46.6	34.6	4.5	13.3	0.18	1.53	1923	10^{-9}	18.13	4.59	0.813	1.108
CSAMC13	45.5	27.8	15.1	5.4	5.3	1.19	1873	10^{-8}	3.30	0.029	0.029	0.096
CSAMC14	43.2	34.0	4.5	13.9	3.7	1.49	1873	10^{-8}	3.52	0.033	0.032	0.108
CSAMC15	38.1	38.9	9.6	9.2	3.6	0.98	1873	10^{-8}	2.97	0.024	0.024	0.079
CSAMC16	29.5	49.3	0	18.2	2.4	0.97	1873	10^{-8}	3.0	0.025	0.024	0.081
CSAMC17	49.4	30.3	14.9	5.0	0.18	1.20	1873	10^{-10}	16.5	3.0	0,293	0,311
CSAMC18	44.3	36.6	5.2	13.6	<0. 1	1.39	1873	10^{-10}	16.64	3,11	0,305	0,322
CSAMC19	39.4	40.4	10	9.9	0.15	0.98	1873	10^{-10}	15.24	2,13	0,208	0,221
CSAMC20	29.6	50.7	0	19.4	<0. 1	0.97	1873	10^{-10}	15.99	2,61	0,256	0,271

Table 2. The compositions of the Cr-slags studied and the experimental parameters.

Sample Number	Slag composition (*wt*%)					B2	P_{O2} (atm)	Temperature/T	X_V ($\times 10^{-2}$)	a_V ($\times 10^{-7}$)	a_{VO} ($\times 10^{-5}$)	$a_{VO1.5}$ ($\times 10^{-3}$)	$\gamma_{VO1.5}$	a_{VO2} ($\times 10^{-5}$)
	CaO	SiO_2	Al_2O_3	MgO	V_2O_3									
CSAMV1	55,3	15	24,7	4,5	0,17	1,51	10^{-9}	1823	1,41	0,047	0,635	0,171	7,56	0,653
CSAMV2	54,6	14,8	25,7	4,3	0,26	1,45	10^{-9}	1823	2,37	0,116	1,559	0,421	12,14	1,604
CSAMV3	56,3	14,4	23,9	4,7	0,38	1,59	10^{-9}	1823	3,45	0,258	3,453	0,932	18,40	3,553
CSAMV4	58,1	14	23,1	4,0	0,47	1,67	10^{-9}	1823	4,08	0,388	5,200	1,404	22,40	5,350
CSAMV5	53,6	14,2	27,6	4,3	0,09	1,39	10^{-9}	1873	1,41	0,047	0,313	0,059	4,96	0,215
CSAMV6	56,9	13,8	24,7	4,1	0,16	1,58	10^{-9}	1873	2,52	0,131	0,866	0,165	7,72	0,595
CSAMV7	59,7	13,6	22,4	3,8	0,27	1,76	10^{-9}	1873	3,68	0,300	1,983	0,377	10,48	1,361
CSAMV8	55,3	14,8	24,9	4,4	0,31	1,50	10^{-9}	1873	4,54	0,514	3,396	0,646	15,63	2,331
CSAMV9	55,5	15,8	24,5	3,8	0,09	1,47	10^{-9}	1923	1,42	0,048	0,162	0,022	1,84	0,076
CSAMV10	58,2	14,9	23,2	3,3	0,11	1,61	10^{-9}	1923	2,77	0,159	0,537	0,073	4,99	0,251
CSAMV11	55,1	16,4	24,7	3,5	0,15	1,43	10^{-9}	1923	4,47	0,493	1,665	0,227	11,36	0,779
CSAMV12	54,9	15,2	24,8	4,2	0,28	1,48	10^{-9}	1923	5,73	1,015	3,424	0,467	12,52	1,602
CSAMV13	49,8	29,4	14,3	5,4	0,59	1,26	10^{-8}	1873	1,76	0,068	1,419	0,480	6,10	3,079
CSAMV14	45,2	35,1	4,7	13,9	0,7	1,48	10^{-8}	1873	0,90	0,025	0,515	0,174	1,87	1,118
CSAMV15	40,5	39,9	9,1	9,8	0,18	1,03	10^{-8}	1873	2,58	0,138	2,871	0,971	40,46	6,232
CSAMV16	30,7	49,8	0	19	0,11	1,00	10^{-8}	1873	2,64	0,144	3,007	1,017	69,36	6,528
CSAMV17	45,1	36,6	4,7	12,8	<0,1	1,40	10^{-10}	1873	4,60	0,533	1,113	0,119	99,23	0,242
CSAMV18	49,6	30,5	14,8	4,4	<0,1	1,19	10^{-10}	1873	5,44	0,865	1,805	0,193	160,90	0,392

Table 3. The compositions of the V-slags studied and the experimental parameters

The experimental arrangement:

The furnace arrangement used for gas-slag equilibration studies is presented below:

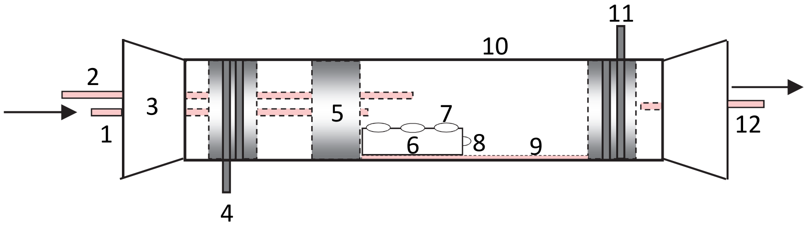


Figure 3: The sketch diagram of the experimental equipment

(1-gas inlet; 2-thermocoulple; 3-silicon rubber stopper; 4-cooling water inlet; 5-refractory; 6-pure aluminum holder; 7- hole on the aluminum holder; 8-ceramic ring for puling; 9- alumina runners; 10-reaction tube; 11-cooling water outlet; 12-gas outlet)

The gases used for the equilibration studies were purified extensively. The gas purification steps adopted represented in Figure 4.

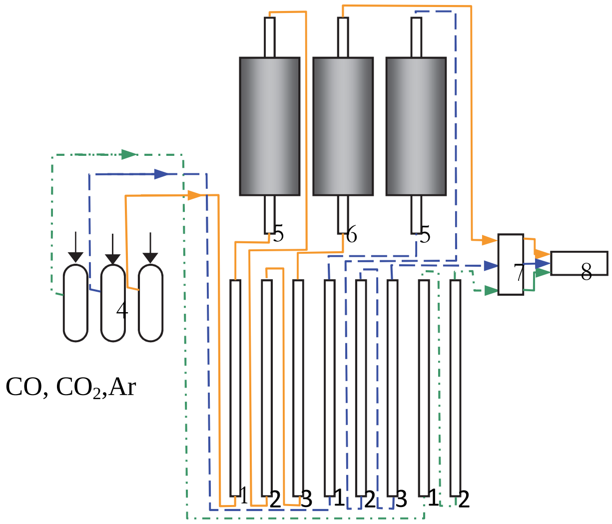


Figure 4: the gas cleaning system(1-silica gel; 2-ascarite; 3- magnesium perchlorate**; 4-bubber** 5-copper turnings<823K>; 6-magnesium chips<773K>; 7-flow controller 8-gas mixture chamber)

The slag and gas phase and the crucible attained equilibrium in about 14 h. The experiments were conducted with an equilibration time of 20 h.

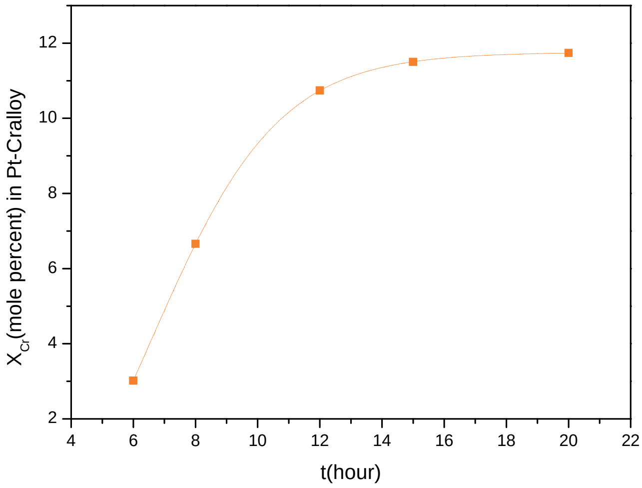


Figure 5: Mol percent of Cr in Pt-Cr alloys as a function of equilibration time

In order to ensure that the Pt-crucible had homogeneous composition with respect to Cr-dissolution, the cross section of the crucible was examined by SEM-EDS analysis. The results are presented in Figure 6

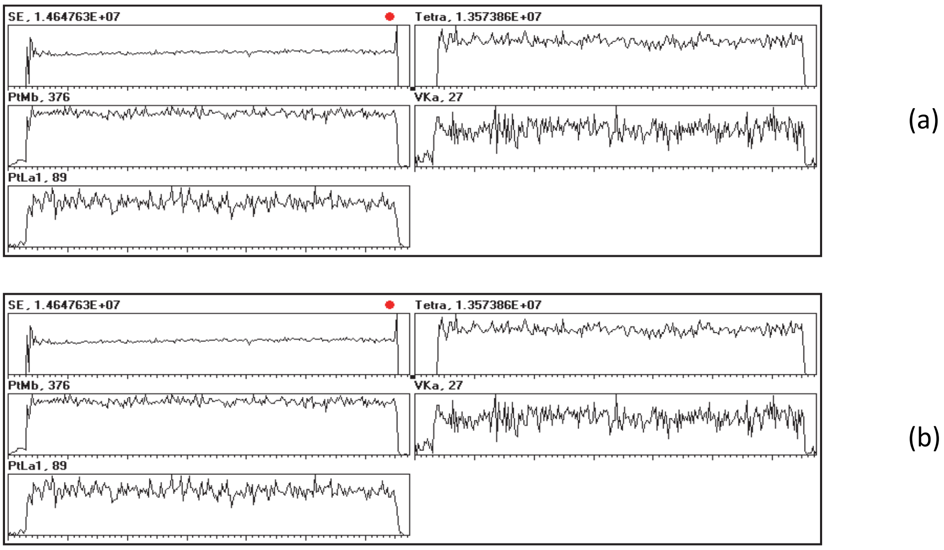


Figure 6: Line analysis of cross section of Cr(V)-Pt alloy

((a) is from the Cr-Pt alloy and (b) the V-Pt alloy)

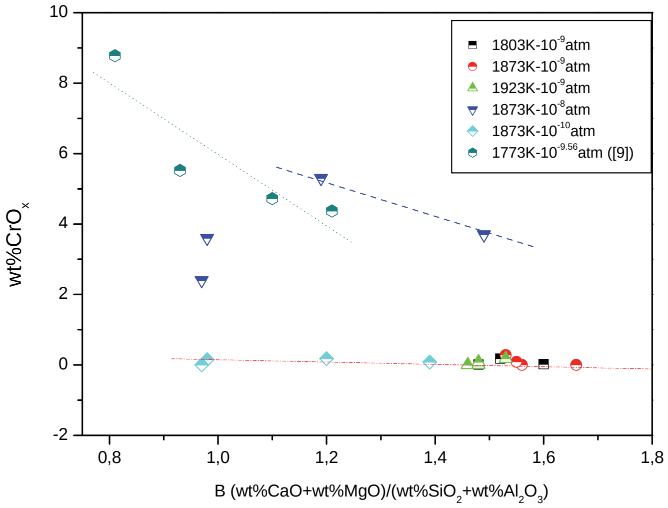


Fig.7 Final chromium oxide content in slag as function of slag basicity

($B = \dfrac{wt\%CaO + wt\%MgO}{wt\%SiO_2 + wt\%Al_2O_3}$ in present work; $B = \dfrac{wt\%CaO}{wt\%SiO_2}$ Pretorius and Muan marked (9) in the figure)

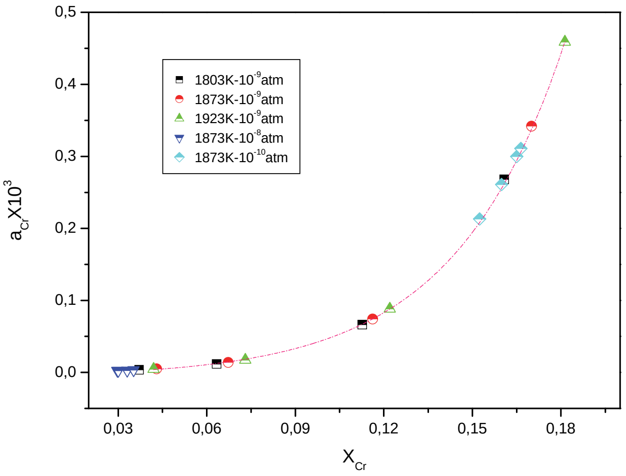


Fig.8 activity of chromium in Cr-Pt alloy (P_{O2}=10^{-8}, 10^{-9}, 10^{-10}; T=1803,1873,1923K), Pure solid Cr as the standard state

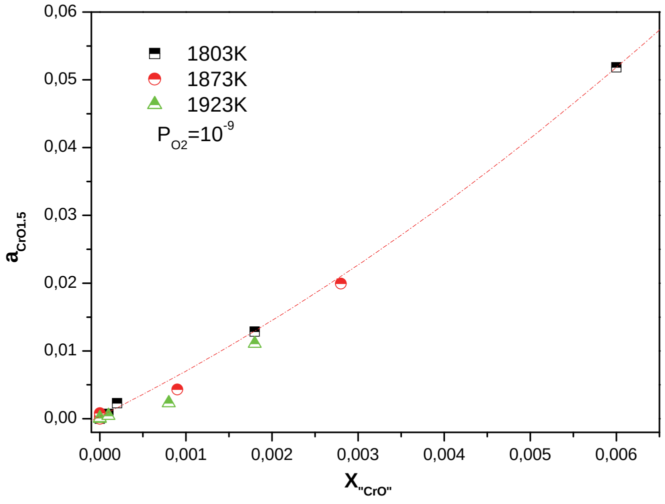


Fig. 9. The thermodynamic activity of $CrO_{1.5}$ as a function of content of Chromium(X) oxide in slag

Experimental temperatures are 1803, 1873, 1923K and $P_{O2}=10^{-9}$.

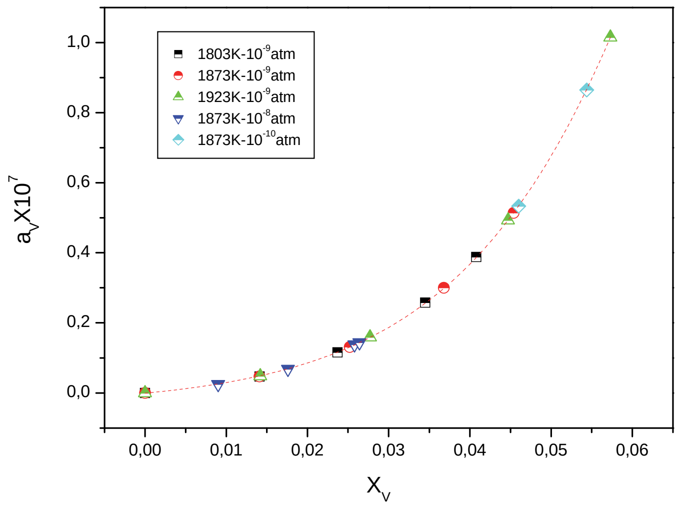


Fig. 10. Activity of V in Pt.V alloys as reported by Pretorius and Muan(J. Am. Ceram. Soc., 1992, Vol. 75, pp. 1361-63) ; ($P_{O2}=10^{-8}$, 10^{-9}, 10^{-10}; T=1803,1873,1923K), Pure solid V as the standard state

The variation of the activity coefficient of $VO_{1.5}$ as a function of basicity (defined as $B = \dfrac{wt\%CaO + wt\%MgO}{wt\%SiO_2 + wt\%Al_2O_3}$) is presented in Appendix A, Figure 8.

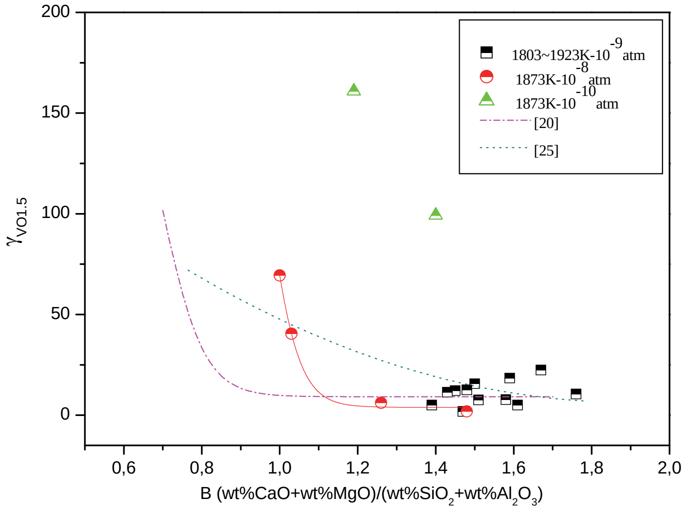


Figure 11 thermodynamic activity of vanadium (III) oxide as a function of content in slag

(Equilibrium temperature is 1803, 1873, 1923K respectively and $P_{O2}=10^{-9}$) Numbers 20 and 21 in the box refer to the results of Veermaak and Pistorius (*Metall.Trans B.*,2007, Vol.31B,pp. 1091-1097), as well as Werme (Doctoral thesis in KTH, stockholm,(1987) respectively.

It is seen that the results are in reasonable agreement with the earlier studies

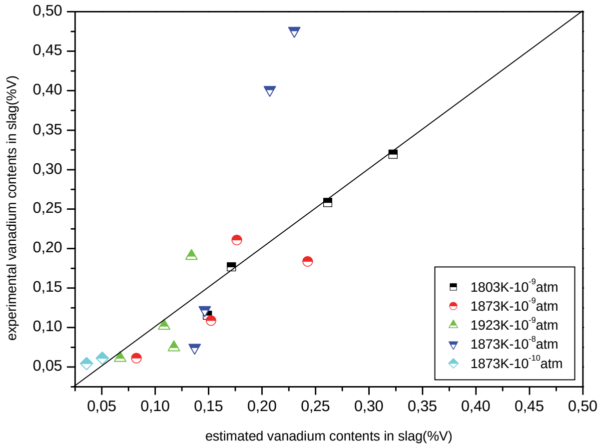


Fig.12 Estimated and experimental content of vanadium in slag

Fig. 12 Final Vanadium oxide content in slag as function of slag basicity; ($B = \dfrac{wt\%CaO + wt\%MgO}{wt\%SiO_2 + wt\%Al_2O_3}$ in present work; $B = \dfrac{wt\%CaO}{wt\%Al_2O_3}$ according to Veermaak referred to as [20] in the figure)

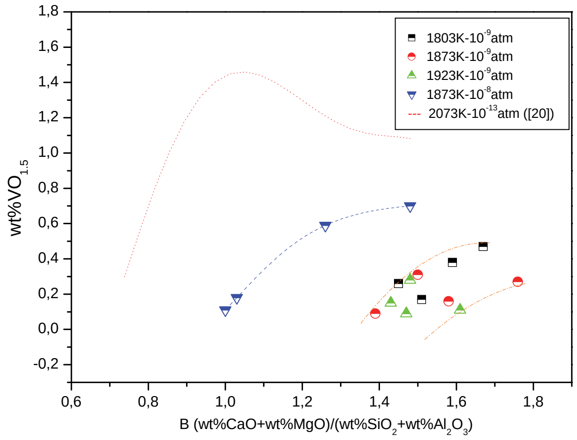
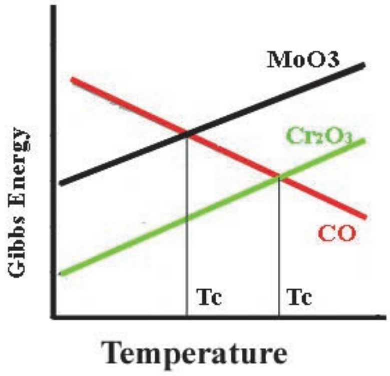


Fig. 13 Final Vanadium oxide content in slag as function of slag basicity; ($B = \dfrac{wt\%CaO + wt\%MgO}{wt\%SiO_2 + wt\%Al_2O_3}$ in present work; $B = \dfrac{wt\%CaO}{wt\%Al_2O_3}$ according to Veermaak (M.K.G.Vermaak, P.C.Pistorius:*Metall.Trans B.*,2000, 31B,1091-1097 (2000), referred to as [20] in the figure)

APPENDIX B

Oxygen partial pressure control during deoxidation



Fiig. 1 An Ellingham diagram showing the Gibbs energy lines of the oxides of Cr, Mo and C as temperature functions.

With increasing temperatures, beyond the crossing points with the CO line, carbon will be preferentially oxidized. It is to be noted that the oxides and the metals are in their standard state.

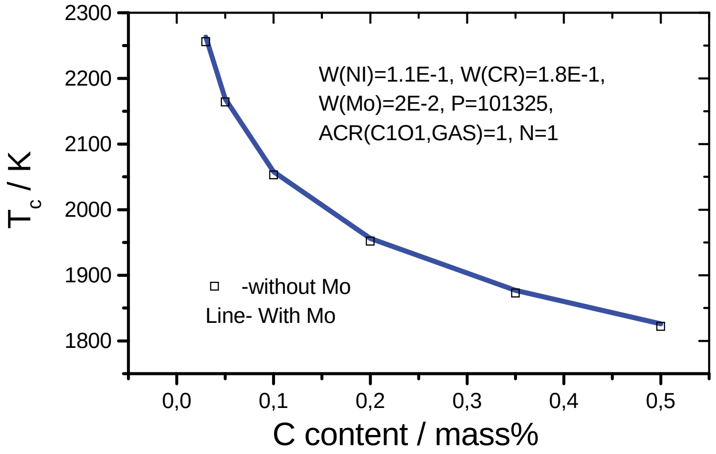


Fig. 2. Effect of carbon content on Tc

Cr content is expected to increase the Tc as shown in Figure 3.

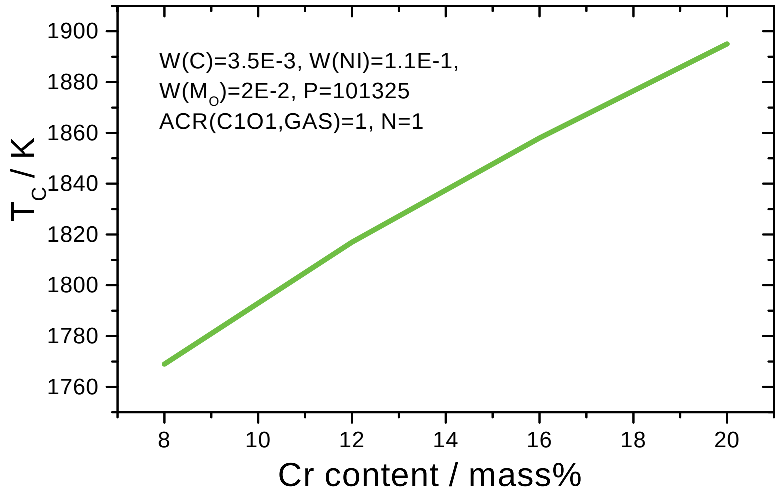


Fig. 3: Effect of Cr content on Tc

Decarburization rate according to chemical control

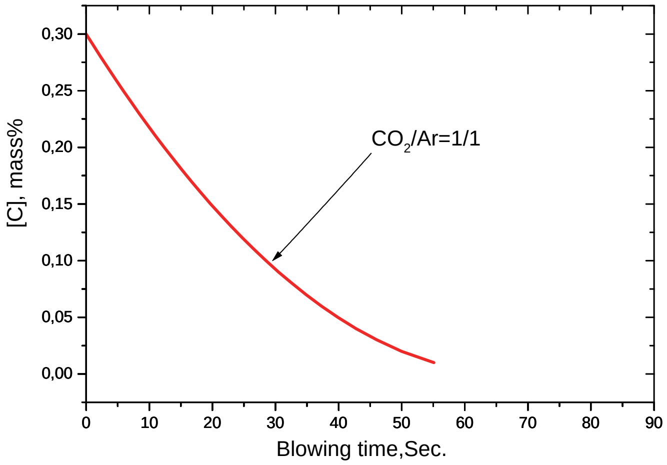


Fig. 4: The decarburization rate with CO_2/Air mixture assuming chemical reaction as rate-controlling, assuming equilibrium can be reached between gas and steel, 18t AOD, T=1873K, Flow rate 1200 Nm^3/h .

In the mean time laboratory experiments have been carried out comparing the decarburization with oxygen and CO_2 respectively. The melting was carried out in an induction furnace in collaboration with KIMAB. The apparatus used is shown in Fig. 5.

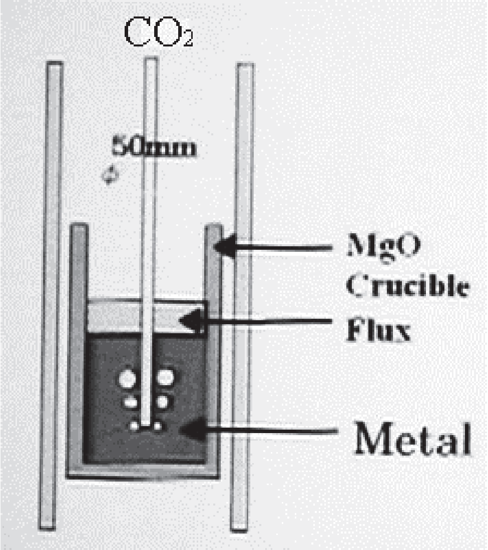
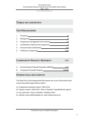
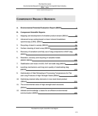


Fig. 5 Apparatus for studying decarburization of steel melt with CO_2.





APPENDIX C

Plant trials were conducted at Uddeholm Tooling AB during Mo-additions and sampling slag, dust and the metal. A Mo-mass balance wasworked out. The raw datae presented here.

Table 1. The slag analysis

Sample no.		**CaO**	**MgO**	**Al_2O_3**	**SiO2**	**FeO**	**MnO**	**Cr2O3**	**Mo**
ST1: before desl in EAF	**1-1**	**28**	**4.8**	**2.1**	**9.5**	**42.7**	**5.1**	**4.1**	**0.34**
ST1: before tapp	**1-2**	**48.1**	**15.2**	**2.1**	**24.8**	**2.8**	**1.0**	**2.6**	**0.19**
ST1: after tapp	**1-3**	**41.4**	**18.0**	**5.7**	**29.9**	**1.5**	**0.2**	**0.9**	**0.18**
ST2: before desl in EAF	**2-1**	**22.81**	**7.57**	**5.46**	**10.68**	**38.47**	**4.32**	**x**	**0.34**
ST2: before tapp	**2-2**	**40.2**	**17.7**	**1.6**	**22.3**	**8.6**	**1.3**	**5.9**	**0.021**
ST2: after tapp	**2-3**	**37.2**	**24.5**	**6.3**	**26.0**	**1.8**	**0.3**	**1.5**	**0.017**
ST3::before tapp	**3-2**	**30.5**	**17.2**	**3.9**	**34.9**	**2.4**	**1.8**	**6.1**	**0.012**
ST3:after tapp	**3-3**	**34.3**	**20.0**	**10.5**	**28.2**	**0.9**	**0.9**	**1.8**	**0.012**
4 met	**4-1**	**36.7**	**2.9**	**2.3**	**13.2**	**18.2**	**17.3**	**7.7**	**0.017**

Table 2. Mo-balance

Input				Output			
No.	**Amount**	**Content(%)**	**Result**	**No.**	**Amount**	**Content(%)**	**Result**
Ad.1	**250**	**63.81**	**159.525**	**Steel**	**67921**	**1.3**	**882.97**
Ad.2	**250**	**63.81**	**159.525**	**Slag**	**3700**	**0.34**	**12.58**
Ad.3	**800**	**63.81**	**510.48**				
Ad.4	**270**	**17.8**	**48.06**				
Ad.5	**540**	**17.8**	**96.12**				
Ad.6	**4960**	**0.03**	**1.488**				
Ad.7	**16560**	**0.01**	**1.656**				
Ad.8	**8420**	**0.01**	**0.842**				
Ad.9	**2520**	**0.01**	**0.252**				
Ad.10	**20340**	**0.01**	**2.034**				
Total			**979.92**				**895.55**

Loss of Mo by evaporation: 84.37 kg, 8.6 wt%; Loss of Mo to the slag: 12.58 kg, 1.3 wt% ; Total loss: 9.9 wt%; (The Mo input in the scrap has not been considered!)

Theaddition of Mo is n the form of two different types of oxides. The compositions of these at the time of trial given by the supplier are given below:

1. C= 0.02, P= 0.01, S= 0.05, Mo= 64.66, Cu= 0.46, Pb= 0.01, Fe= 2.46, O= 32.33
2. Si= 3, P= 0.5, S= 0.3, Mo= 30.92, W= 6.91, Cu= 0.05, Fe= 42.86, O= 15.46

An analysis of the raw materials reveals that a significant part exists as MoO$_3$. The Gibbs energies of formation of various Mo compounds are given in Figure 1. The vapor presure of MoO3 is very high (53.3 kPa at 1082 ^{o}C)

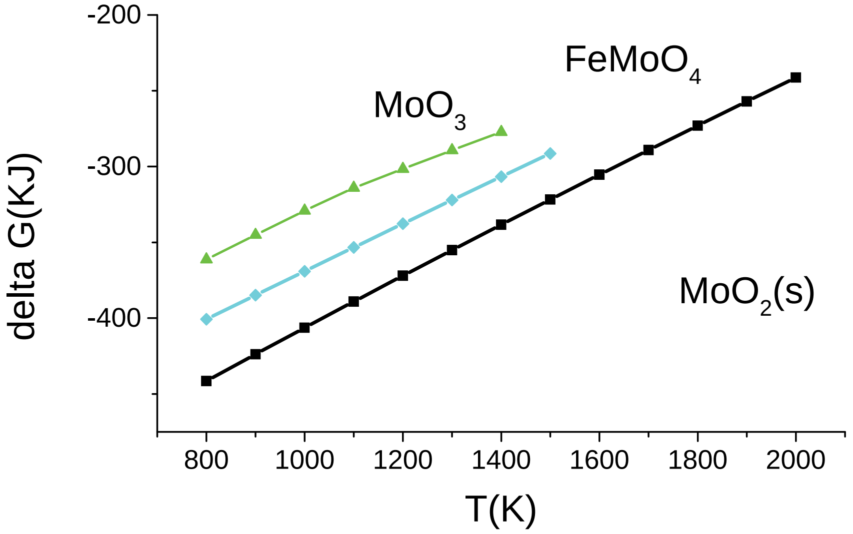
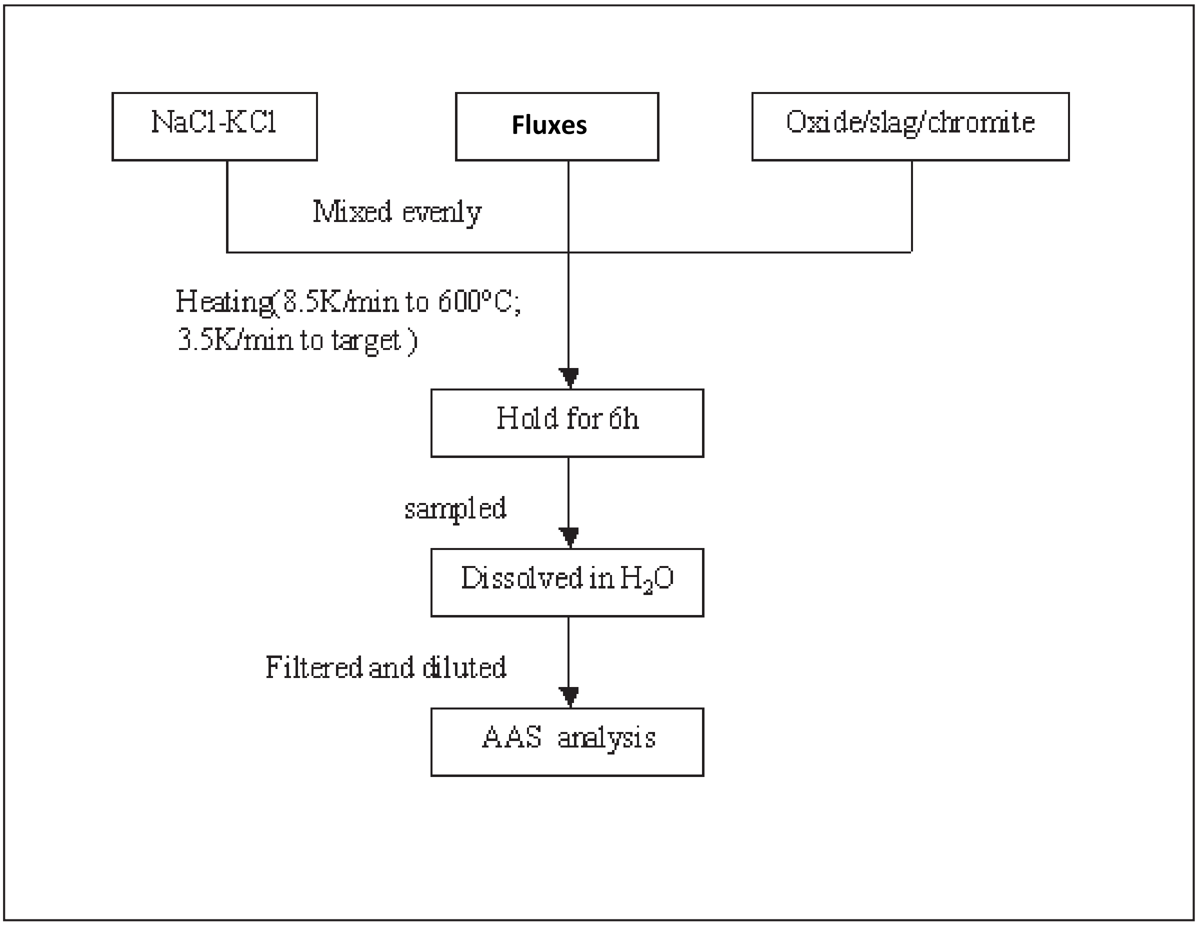


Fig. 1. The Gibbs energy of formation of various oxide compounds of Mo

APPENDIX D



Flow sheet for salt extraction

Fig. 1. Flow sheet for salt extraction

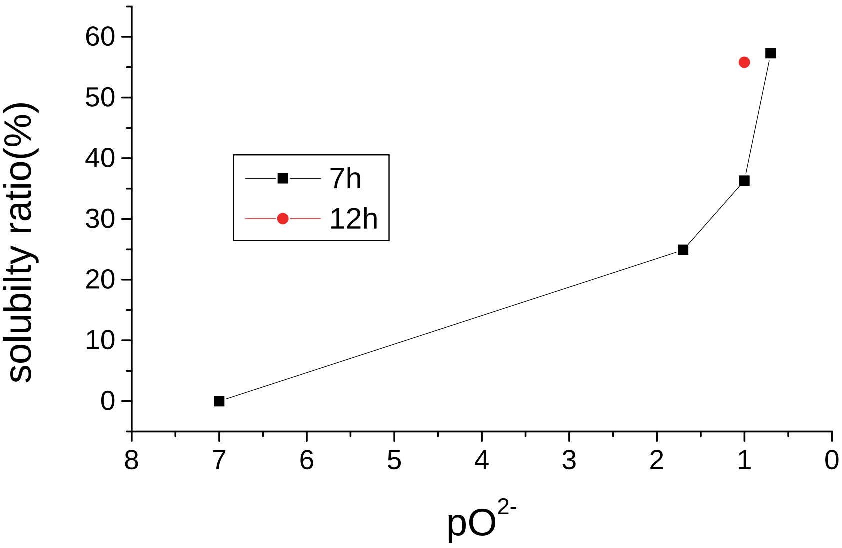
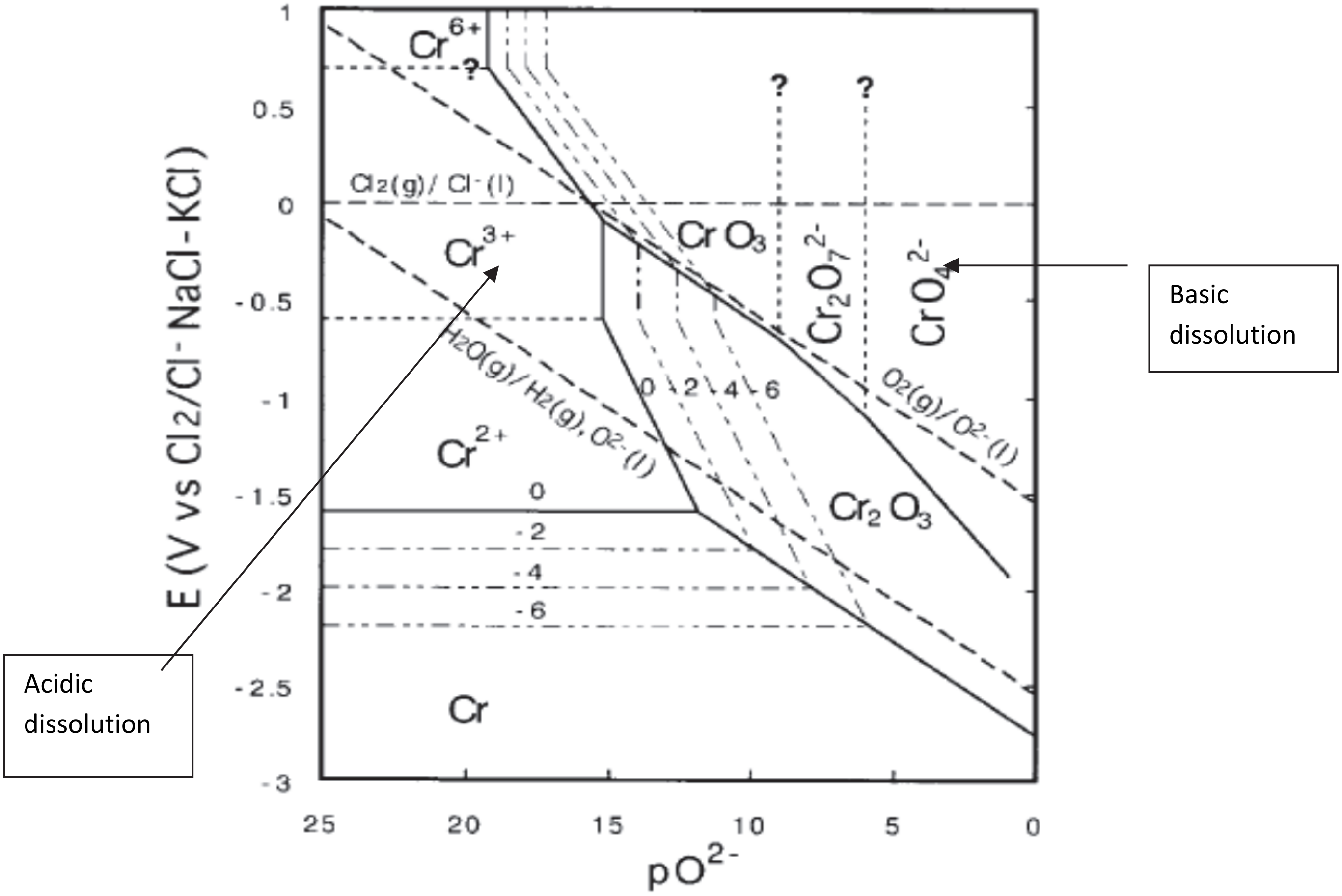


Fig. 2. The solubility ratio for Cr extraction at 1023 K



Basic dissolution

Acidic dissolution

Fig. 3 Porboux type of diagram for Cr-salt extraction

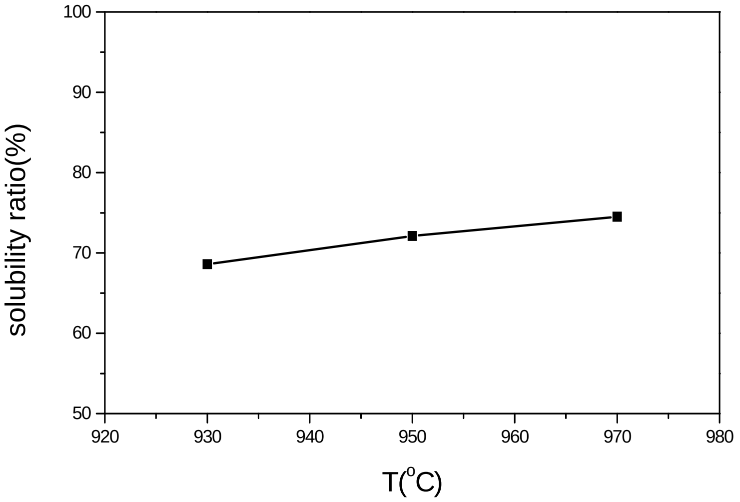


Fig. 4. Cr extraction by salt melt during acidic dissolution (present results).

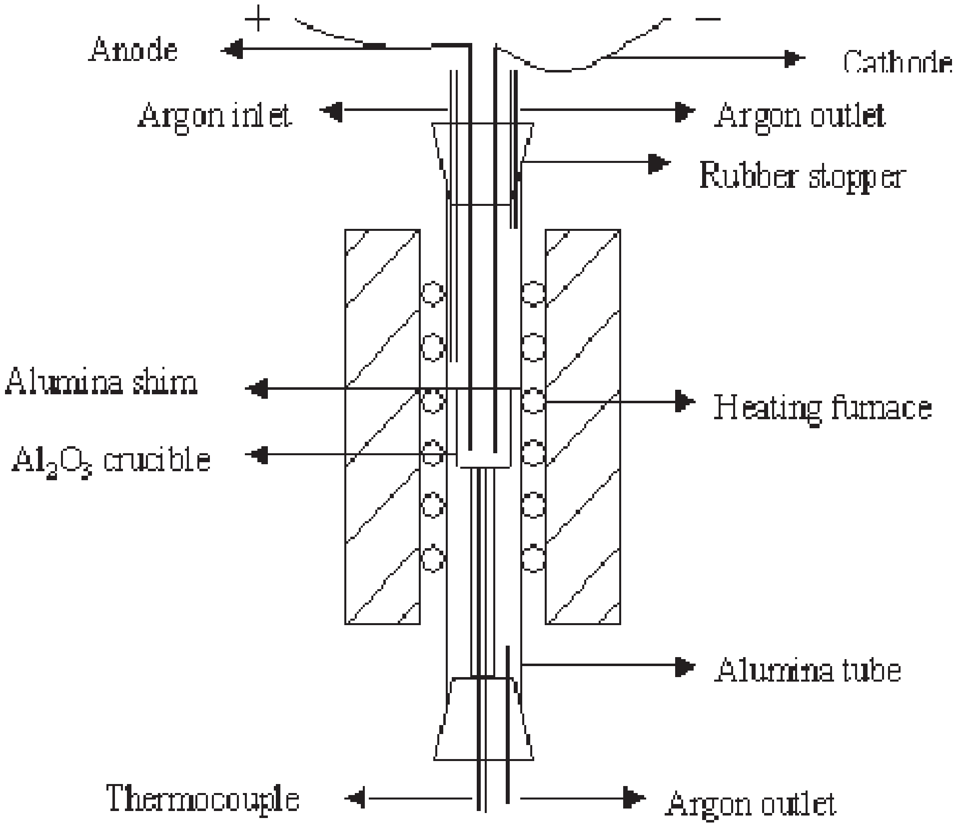


Fig. 5. The experimental set-up for electrolysis recovery of the valuable metals extracted from slags by salt extraction.

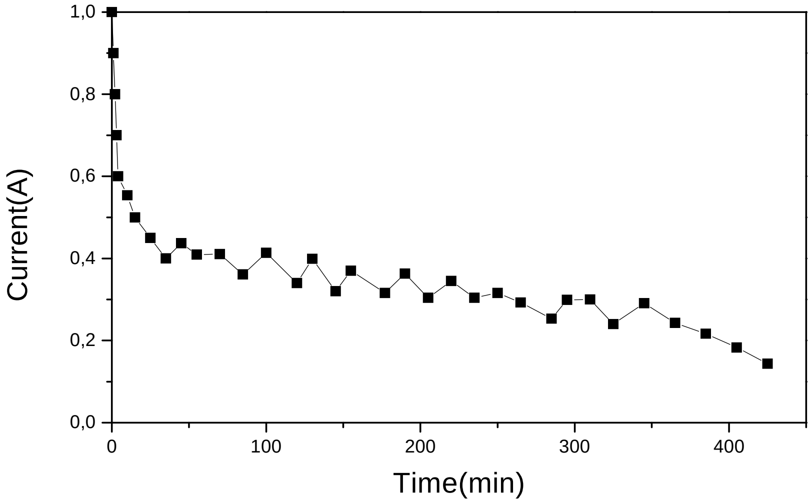


Fig. 6. Decrease of electrolysis current as a function of time in salt electrolysis process. Cathode material: Nickel wire, Anode material: Plantinium

STABILIZATION AND REUSE OF AOD-, EAF-, AND LADLE SLAG (88033)

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Abstract

Large amounts of slag from scrap-based steel industry in Sweden are landfilled. There is a need to find knowledge and methods that help to make this material a resource. The main problems with the slag are its volume instability, potential leaching of metals and disintegrating properties. Ageing of slag in natural environment, inert gas granulation, air granulation and volume stabilization by chemical additives are methods tested within this programme to gain knowledge and develop methods for slag processing. One of the results obtained from ageing in natural environment is that the materials show large variations regarding total ability to leach. New minerals are formed on the surface of slag and leaching of chromium decreases. It has been shown in the programme that gas granulation and additives of phosphorous-containing material prevent slag from disintegrating and give new physical characteristics to the material. This can result in new possibilities for using slag in different applications and thereby avoiding the need for landfilling of slag.

1 INTRODUCTION

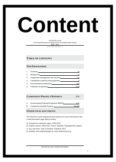
The slag production in the Swedish steel industry is about 1.5 million tonnes annually, of which more than 500 kton is generated in EAF- (Electric Arc Furnace), AOD- (Argon Oxygen Decarburization) converters and during the refining of steel in the ladle metallurgy. Some of the slags are used in different applications, but most of the steelmaking slags produced in Sweden are landfilled today. The chemistry, mineralogy, and physical characteristic of slags make it a suitable material in construction, replacing for example, gravel and rock. In some respects, in road construction, it may even be technically superior to virgin material. Slag from scrap-based steelmaking is used for road construction in Europe. The reason for the low utilization in Sweden is mainly due to potential leaching of harmful elements and competition with easily available natural raw materials. The technical and environmental obstacles for not using some slags in construction include:

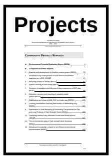
- Volumetric expansion
- Disintegration
- Leaching of metals.

The volumetric expansion is considered to be associated with the presence of free lime and free periclase (MgO) in the solidified slag [8]. Free lime and periclase react with moisture, resulting in an expansion due to the formation of hydroxides.

Disintegration of slags is a result of the phase transformation that occurs upon cooling. Pure dicalcium silicate undergoes a phase transformation from β-Ca_2SiO_4 to γ-Ca_2SiO_4 at approximately 500ºC, which results in a volume expansion of approximately 12 vol-% [9]. The polymorphic transformation of β-Ca_2SiO_4 to γ-Ca_2SiO_4 is known to occur in e.g., AOD slag depending on the cooling rate [10].

There are pricipally few ways to avoid disintegration of slags, namely quick cooling, adding chemical additives that stabilize the β-Ca_2SiO_4, or changing the total composition of the slag by adding quartz sand in order to avoid the composition that gives β-Ca_2SiO_4 [11]. However, the limited heat content and heat conductivity of slags make it difficult to dissolve large amounts of SiO_2. Kühn and co-workers have developed a method to dissolve large amount of quartz after slag/metal separation by co-injection of oxygen [12]. Oxygen reacts with FeO in the slag to form Fe_2O_3 and the reaction generates heat. The drawback of the method of changing composition is that the amount of slag is increased.





Quick cooling by water/air granulation is one way to stabilize the Ca_2SiO_4 phase in AOD-slag. The major problem associated with water granulation has been increased leaching of Cr^{6+}. The reasons for this are believed to be increased specific surface of the granulated slag, oxidation of Cr^{3+} to Cr^{6+} and metal droplets in the slag.

Chemical additives can be used to stabilize the Ca_2SiO_4 phase; for example, by addition of boron oxide and/or phosphate-containing material. Stabilization of the phase with boron oxide is a well established technique but may in addition to being expensive result in excessive leaching of boron from the slag [13,14]. The application of stabilization of Ca_2SiO_4 phase through phosphate additions has yet not been established in steel-making. Stabilization with phosphates also enables use of much cheaper residue materials from e.g., the mining industry.

Very little is reported in the literature regarding the influence of cooling on the properties of slag, especially for steelmaking slags. The formation of a glassy material depends on both the chemical composition and the cooling conditions. According to Daugherty et al. [15], glass was easier to produce, as the acidity of the slag increased for a series of synthetic slag compositions that was quenched and annealed. If the cooling is rapid, the slag passes from a liquid state to a solid without development of a crystalline structure [16]. Glasses, such as granulated slags, can be regarded as super-cooled liquids having a very high viscosity. Besides glass formation, controlling cooling conditions can be a means of affecting mineral transformation and consequently the solubility of elements like chromium [1]. Leaching from steel slags is generally characterized as a surface reaction, followed by a solid-solid diffusion process, in order to retain equilibrium in the materials [17].

Slag has long been used in different applications and many efforts have been made to characterize, test and develop handling techniques. Still, there is a gap of knowledge regarding the factors controlling the ability to leach, the long-term quality and control of properties of the final slag product. In this study the main effort is to investigate inert gas granulation of AOD slag as a method to prevent disintegration and dusting of slag and to test if leaching of chromium is prevented thereby. Air graulation will be studied as another method to prevent dusting. Additives of phosphate-containing material to slag in order to control the volume expansion of the Ca_2SiO_4 phase will also be undertaken. Leaching of metals from the material as well as long-term quality of slag will be studied.

2 OBJECTIVES

To minimize the amount of EAF-, AOD- and ladle slag that has to be depositioned, there is a need to:

- Obtain basic knowledge regarding the leaching mechanisms that control the leaching of harmful elements.
- Develop methods to prevent disintegration of slag during cooling.
- Develop the slag processing and adjust the slag composition to avoid high leaching of harmful elements and to give the slag a composition and properties more suitable for a given application.
- Develop new applications and products where the unique properties of the slag are fully utilized.

The present programme deals primarily with the two first items but to a certain extent also with possible development of the slag processing.

The aims of the project are:

- To provide knowledge that will enable the steel industry to develop the slag composition and slag practice in such a direction as to avoid high leaching of harmful elements, i.e. chromium and molybdenum, and to ensure the mechanical integrity of the slag product.
- To deliver methods for controlling environmental and technical properties of steel slag that will enable increased reuse of the slag.

For the environment this would mean an increase in the reuse of slag from scrap-based steel production. The long term aim is to turn 200 000 tonnes of steelmaking slag that otherwise would be land-filled into marketable products.

3 METHODS

3.1 NETWORK AND DISCUSSIONS

Important during the work within this programme has been the vivid discussions among all researchers and representatives from industry. Regular meetings have been held to discuss results and to decide if the outcome can be used in industry and the best way to undertake the research assignment, depending on the outcome. Researchers from other institutes have also been invited to discuss and give there view and experience on e.g., gas granulation.

Industry partners in the work have been AB Sandvik Materials Technology, Höganäs AB, MultiServ AB, Ovako Steel AB, Ovako Bar AB, Outokumpu Stainless AB, Outokumpu Stainless Oy, and Uddeholm Tooling AB.

3.2 AGEING OF EAF-SLAGS IN NATURAL ENVIRONMENT

Over a period of two years, five different types of EAF slags from domestic steel plants were investigated regarding their long-term leaching behaviour, when kept outside, in the natural environment. To guarantee a freshly produced and homogenous slag material for the experimental work, sampling was preformed in collaboration with industry and MiMeR (Minerals and Metals Recycling Research Center) representatives. The chemical compositions of the EAF slags used are shown in Table 1.

Table 1. Chemical composition of used EAF slags.

	EAF 1 wt%	EAF 2 wt%	EAF 3 wt%	EAF 4 wt%	EAF 5 wt%
Na_2O	0.18	0.58	0.33	0.45	0.03
MgO	18.16	4.72	4.97	8.52	11.27
K_2O	0.36	0.05	0.04	0.02	0.01
CaO	26.39	40.99	42.41	28.75	36.94
TiO_2	0.37	3.24	1.07	0.6	0.35
V_2O_5	0.32	0.15	0.24	0.52	0.14
Cr_2O_3	7.03	5.7	6.82	1.95	3.24
MnO	2.15	3.15	2.73	6.06	5.13
NiO	0.02	0.11	0.1	0.02	-
CuO	0.32	0.31	0.31	0.33	0.01
ZnO	0.07	0.07	0.07	0.07	0.02
Al_2O_3	9.39	10.12	3.22	4.93	6.06
SiO_2	31.01	28.41	30.13	11.81	14.09
P_2O_5	0.04	0.02	0.02	0.61	0.38
PbO	0	0	0	0	0.00
MoO_3	0.01	0.01	0.01	0.01	0.01
C	0.07	0.06	0.12	0.05	0.15
S	0.05	0.08	0.07	0.09	0.16
Fe met.	0.44	0	0.32	4.83	0.65
FeO	3.61	2.24	7.02	25.46	10.97
Fe_2O_3	0	0	0	4.93	10.37

All slags in the experiment were crushed and sieved to reach a fraction 100%, 1-4 mm. After splitting, the materials were well distributed on wood frames covered with two layers of plastic net, measuring 0.5 mm, securing a good permeability through the materials, see Figure 1.

Fig. 1. The experimental setup for ageing of slags in natural environment.

The slags were sampled and characterized after 0, 6, 12, 18 and 24 months to evaluate the influences of ageing. Scanning electron microscope (SEM), x-ray diffraction pattern (XRD) and a standard test for leaching were used when characterising the slags. Data on the weather, including temperatures and precipitation, were taken from the Swedish Meteorological and Hydrological Institute (SMHI).

3.3 STABILIZATION OF DISINTEGRATING SLAGS.

3.3.1 Inert gas granulation

A pilot test facility was built (see Figure 2), in which two pilot campaigns have been carried out at MEFOS to investigate the N_2-granulation concept. The same granulation equipment was also used for preliminary plant tests at Outokumpu Stainless Oy, financed by Outokumpu Stainless Oy in Tornio, Outokumpu Stainless in Avesta, MultiServ and Jernkontoret.

B-stabilized AOD-slag was collected from Outokumpu Stainless Oy in Tornio for the pilot tests; the slag in the bottom of the slag pot was separated from the top slag due to its higher steel content. In the two pilot campaigns an induction furnace was used for melting AOD-slag inside a graphite crucible. Upon attainment of a bath temperature of approximately 1700 ºC, a reference slag sample was taken. The furnace was tilted and approximately 30 kg liquid AOD-slag was tapped into a pre-heated tundish, which was lined with ceramic bricks and an Al-silicate nozzle. The reason for using a tundish was to force the slag beam into a proper position with respect to the injected N_2-gas through the gas split (see Fig. 2) 200 mm underneath the nozzle, to control the flow of the slag and to minimize air leakage. A portable Testoterm instrument was used for gas and temperature measurements inside the granulation facility.

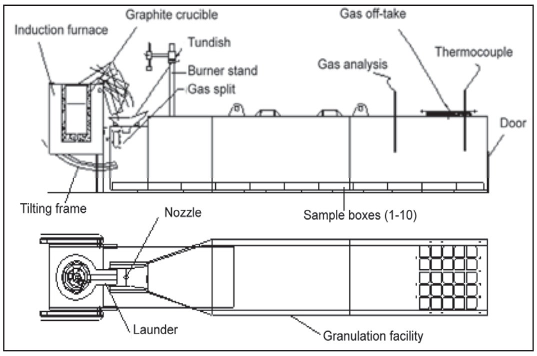


Fig. 2. Schematic drawing of the experimental set-up

Three design parameters were tested in the two pilot test campaigns (see Table 2):

- AOD-slag with low (L) and high (H) metallic content, i.e. slag from the top and bottom of the slag pot, respectively.
- Open (O) and closed (C) system; i.e. the amount of air leakage during granulation. An open and closed system corresponds to an oxygen content of 6-10% and 1-3% inside the granulation facility, respectively.
- Blast speed at three different levels, low (L ~350 m/s), medium (M ~430 m/s) and high (H ~500 m/s). The blast speed could be controlled either by changing the nitrogen gas flow or the gas split dimensions.

Table 2. Design parameters for the two pilot campaigns.

Test	**Slag**[1]	**Open/ Closed**[2]	**Blast speed (m/s)**[3]
1	L	O	L
2	L	O	L
3	L	O	L
5	L	O	L
6	L	O	L
7	L	C	M
8	L	C	H
9	H	C	H
10	H	C	H
11	H	C	L
12	L	C	M
13	H	O	L
14	H	O	H

[1]Low (L) and high (H) metallic content respectively [2]Open- (O ~6-10% O_2) and Closed (C ~1-3% O_2) system [3]Blast speed varied at three different levels, low (L ~350 m/s), medium (M ~430 m/s) and high (H ~500 m/s)

The preliminary plant tests were performed at the slag yard at Outokumpu Stainless Oy in Tornio to further verify the concept, i.e. using slag directly from the converter instead of remelting the slag inside the induction furnace. The granulation facility was placed on a platform and the slag pot from the steel shop was placed at the short side of the platform closest to the tundish. In each test, 5 to 10 kg slag was poured into the tundish with 2-3 long slag dippers. Four gas batteries were used for the nitrogen supply; a compressor was used for the air supply. Gas flow was approximately 5 Nm^3/min. The main design parameter, in addition to the gas type, was the slag composition, see Table 3.

Table 3. Design parameters for plant tests.

Test	Reference-sample	Slag-type	Addition	Gas
1-2	1	AOD	Bor	Air
3	1	AOD	Bor	N_2
4-5	4	AOD	Bor	N_2
6-7	6	AOD		N_2
8-10	8-10	AOD*	Bor	N_2
11-13	11	EAF		N_2
14	14	CRC**		Air

*AOD-slag with increased Al_2O_3 content and lower addition of CaF_2. **CRC= Chromium converter slag

The granulated slag in all tests was collected from the 10 sample boxes inside the granulation facility and was to some extent classified according to their size and weight; hence finer fractions in the boxes closest to the gas off-take. Chemical analysis (X-ray fluorescence (XRF) by lithium tetraborate fusion) and leaching test (two-step batch leaching shaking test, prEN 12457-3) were performed by Outokumpu Stainless in Tornio.

3.3.2 Air granulation of EAF-slag

A disintegrating EAF-slag was used in the tests. Slag samples were melted in MgO crucibles and were introduced into laboratory equipment, which included a blowing device and granulation box, to realize rapid slag cooling by air granulation. The laboratory equipment for air granulation was constructed with financial support from Höganäs AB.

3.3.3 Stabilization by P additives

A disintegrating EAF-slag was used in the tests. Stabilization agents were mixed together with the slag samples to form test mixtures for melting tests. A mining by-product containing P_2O_5 of 9% was used with weights of 1-8% in the mixtures. The second additive tested was an agricultural product containing up to 45-47% P_2O_5, of which amounts of 0.3-1.2% were added. The samples contained in MgO crucibles were melted at 1600°C and then cooled in the furnace. The slag was considered as stabilized when no fines were generated and the crucible was not damaged after the melting and cooling.

3.4 RECYCLING OF LADLE SLAG AS SLAG FORMER.

Chemical analyses of ladle slag, EAF slag and steel were collected from the companies involved in the project, as well as information on the conditions for their EAF operations. Samples of ladle slag were subjected to characterization procedures such as sieving, analysis and XRD analysis at Luleå University of Technology. The data and information collected were used in HSC Chemistry and FactSage computer software for calculations of heat and material balance and equilibrium compositions of the steel and slag from the EAF with ladle slag recycling.

4 RESULTS AND DISCUSSION

4.1 AGEING OF SLAGS IN NATURAL ENVIRONMENT

Data on the precipitation and temperature were collected during the 24 months the experiments were conducted. The total precipitation for the first year and the second year was 564 and 552 mm, respectively. The highest and lowest temperatures measured year one were 22.0/-20.0ºC and year two, 22.0/-24.5 ºC.

When ageing, the materials show large variations regarding total ability to leach, measured as conductivity, see Figure 3.

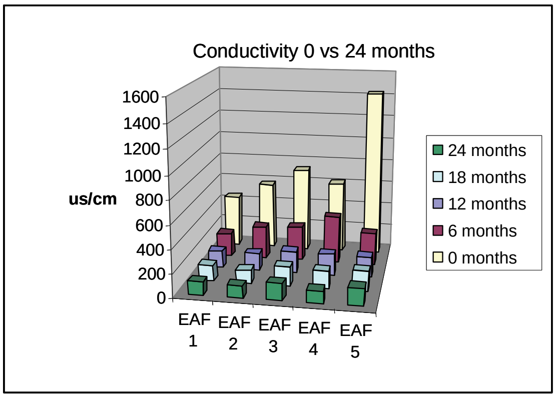


Fig. 3. Conductivity as a function of time.

The conductivity shows a pronounced decrease already after 6 months. Leaching of chromium as well as molybdenum decreases for all five slag types compared with the initial materials. Fig. 4 shows values of leaching from one of the EAF-slags. The trend is the same for all of the slags, even though the absolute values differ.

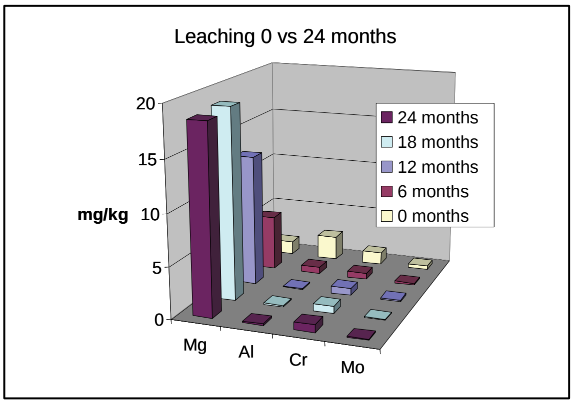


Fig. 4. Leaching from one of the EAF-slags as a function of time.

Only magnesium and calcium increase in leachability when ageing. This increase may be explained by the hydration that takes place when calcium and magnesium react with water.

After 6-12 months, a new mineral starts to form on the surfaces of all the five slag types, see Figure 5.

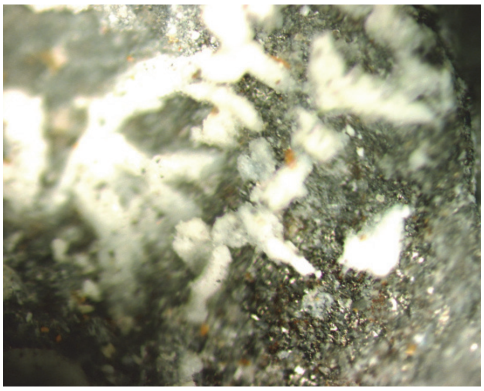


Fig. 5. $CaCO_3$ (white) on EAF slag 4 after 12 months.

The new mineral is white in colour and has a needle-like structure. XRD investigations reveal that calcium carbonate, $CaCO_3$, is formed on the surfaces. Calcium carbonate is formed when calcium hydroxide reacts with CO_2 from air (1).

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 \quad (1)$$

Since no free lime was identified in the slag samples, the calcium source for the reaction is most likely correlated to the dissolution of calcium silicates present in the slag.

4.2 STABILIZATION OF DISINTEGRATING SLAGS

4.2.1 Inert gas granulation

The results from the two pilot campaigns, totally 14 tests, were evaluated by comparing granulated slag with original samples, i.e. normally air-cooled slag from the slag yard, and with reference samples, i.e. semi-rapid cooled slag taken before each test. The results from the pilot campaigns can be summarized as follows [5]:

- The trials resulted in a well granulated slag.
- Leaching of chromium and molybdenum has decreased compared to reference- and original samples. The leaching results for chromium and molybdenum in some of the tests are shown in Figure 6 and 7, respectively.
- There is no correlation between the amount of air leakage inside the granulation facility and leaching of chromium.
- No difference in leaching of chromium between AOD-slag with high and low metallic fraction.
- Increased specific surface of the granulated slag, i.e. the particle size distribution, is of minor importance for leaching values.
- Leaching of fluorine has increased compared to reference- and original samples. The F-leaching for the granulated slag was in the range from 75 to 305 mg/kg, for the reference sample from 49 to 126 mg/kg and original sample ~50 mg/kg.

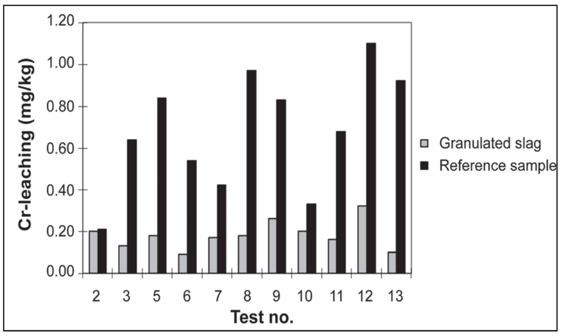


Fig. 6. Chromium leaching results for the pilot campaigns. The granulated AOD-slag is plotted in comparison with reference samples. The Cr-leaching in the original sample is typically ~0.3 mg/kg

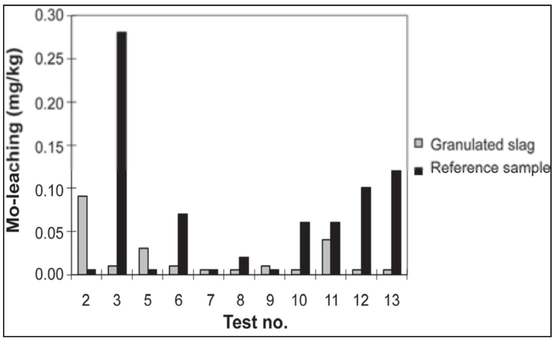


Fig. 7. Molybdenum leaching results for the pilot campaigns. The granulated AOD-slag is plotted in comparison with reference samples. The Mo-leaching in the original sample is typically ~0.2 mg/kg

So far, the validity of inert gas granulation has been confirmed by simulating the process in pilot scale, i.e. the control of the leaching properties for chromium and molybdenum seems possible.

The promising results could not be confirmed in the initial plant trials, which can be summarized as follows:

- AOD-slag without B-addition was stabilized by N2-granulation.
- Granulated slag samples from the plant trials show an increased Cr-leaching compared to the reference samples, which is opposite to the results from the pilot trials.

- Mo-leaching values are below the lowest detectable limit for all slag types.
- Relative unchanged leaching levels for fluorine in the AOD-slag (except for the Al_2O_3-rich AOD-slag)

Figures 8 and 9 show leaching results for chromium and fluorine, see Table 3 for the experimental set-up in test 1-14.

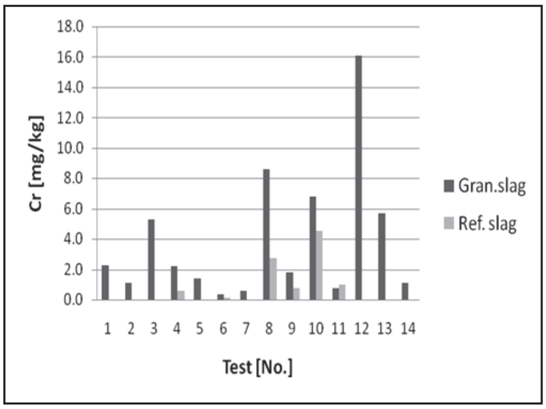


Fig. 8. Chromium leaching results for the plant tests.

The chromium leaching of reference 1 is very low (<0,01 mg/kg), otherwise, leaching of reference samples for plant tests and pilot tests is at the same level.

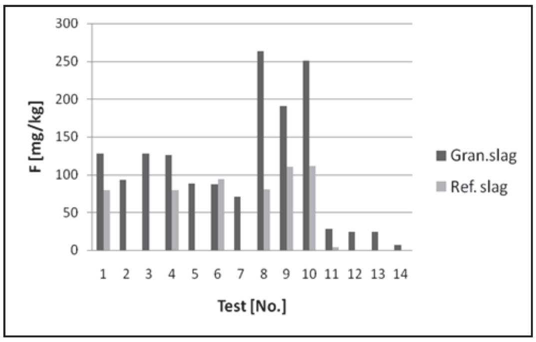


Fig. 9. Fluorine leaching results for the plant tests.

The results differ between pilot and plant trials, the pilot tests resulted in low Cr-leaching and high F-leaching and plant tests gave high Cr-leaching and F-leaching at the same level as the reference samples. A possible explanation of the difference may be that when re-melting AOD-slag in graphite crucible gives a lower oxygen potential, leading to a lower fraction of chromium with higher valences. For the industrial tests, the oxygen potential in the slag is higher and more readily oxidized to Cr(VI). This makes it more difficult to protect the oxidation of the slag. There can be difference in slag temperature and structure of granular slag. A lower temperature, when granulating, in the plant tests, leads to higher slag viscosity in combination with less stable slag stream through the nozzle, thereby resulting in granules that are less spherical and have a less dense surface structure. The loss of heat before granulation, caused by the handling procedure, also led to a slower cooling in plant tests compared with pilot tests.

Based on the results from the pilot campaigns the granulated slag has the potential to be used as an insulating material, as a filler in concrete and/or in cement industry, depending on its hydraulic properties. The material obtained from the pilot and plant tests must be further characterized, (mineralogy, structure) to understand the leaching result before a recommendation of the usefulness of the method can be given.

4.2.2 Air granulation of EAF slag

The air jet impinging on the liquid slag generated large amounts of small droplets, which were then cooled rapidly in the air stream and landed on the base of the box as granules. Over 75% of the granules ranged in diameter from 0.425 to 4.75 mm. Figure 10 shows both granulation and a picture of the obtained granules.

Fig. 10. The picture on the left shows air granulation of EAF slag. Air pressure was 5 bar and flow rate 67.15 Nm^3/h for the granulation. The picture on the right shows granules obtained with sizes 425-600 µm

By the air oxidation the content of Fe_2O_3 in the granules increased from 7.9% to 18.4% and FeO decreased from 14.3% to 7.8%. The Fe_2O_3 formed from oxidation can combine with CaO forming dicalcium ferrite ($2CaO \cdot Fe_2O_3$), thereby minimizing the content of free CaO in the slag. Figure 11 shows diffractograms obtained from XRD-analysis of granulated material.

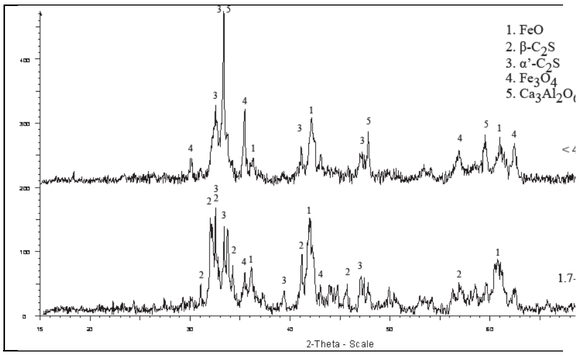


Fig. 11. XRD analysis of phases in granules, <425 µm (upper XRD graph), and with sizes of 1.7-2.36 mm (lower XRD graph) obtained from air granulation of the EAF slag. The abbreviation C_2S in the figure stands for Ca_2SiO_4.

No γ-Ca_2SiO_4 phase was detected, but Fe_3O_4 (especially in the smaller granules) and β-Ca_2SiO_4 as well as α′-Ca_2SiO_4, which is a high temperature polymorph of dicalcium silicate, were seen.

The contents of metal elements, such as As, Cd, Cr, Hg, Mo, Pb and Zn in the leach liquid from all the samples were much lower than the limiting values for leaching of land-filled inert waste pursuant to Directive 1999/31/EC. The amounts of leached Ca and Al, pH and conductivity values of the leach liquid for the granulated samples were lower than those for slowly cooled samples.

The slag fines generated from the Ca_2SiO_4 transformation and from the hydration of free lime/magnesia are often difficult to handle or use in some building applications. The present project work has been carried out to stabilize β phase of the Ca_2SiO_4 in order to prevent the slag dusting and to increase volume stability by minimizing free lime in the slag. This not only improves the working environment but also enhances the possibility for using the stabilized slag as building materials.

4.2.3 Stabilization by P additives

The disintegration of slag could be prevented by addition of the mining by-product, see Fig. 12.

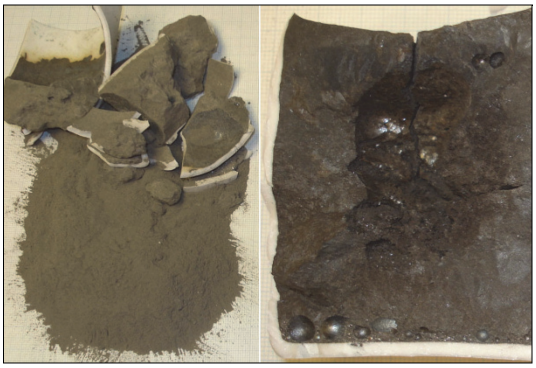


Fig. 12. The picture to the left shows EAF slag re-melted without stabilizing agent and the picture to the right shows EAF slag re-melted with 3% added mining by-product from LKAB.

In Fig. 13 the result of the XRD characterization of obtained material when adding the phosphorus containing material from LKAB is shown. The upper graph is recorded on a disintegrated material and clearly shows the content of γ-Ca_2SiO_4. The lower graph shows the result when P-containing material had been added. The β-Ca_2SiO_4 phase was stabilized by addition of P-containing material.

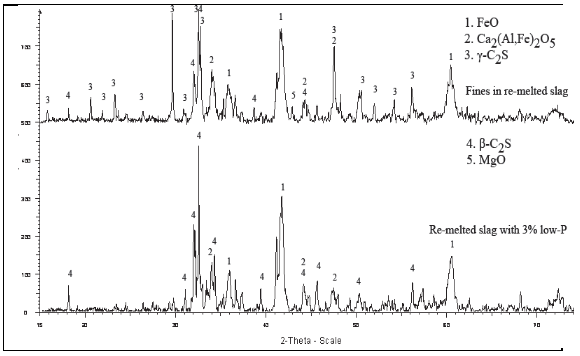


Fig. 13. XRD analysis of phases in fines from re-melted EAF slag (upper XRD graph) and re-melted EAF slag with 3% stabilizing agent Low-P (lower XRD graph)

Leaching values of the stabilized slag were at the same level as the original samples. To verify that this is a method that can be used to produce e.g., construction material, industrial tests will be performed.

4.3 RECYCLING OF LADLE SLAG AS SLAG FORMER.

Results of the calculations were presented in a report, [6], which may be referred to for operation designs to recycle ladle slag to the EAF. It may also be possible to use the results to improve operations and methods for recycling other by-products in EAF. The risk of increased levels of sulphur and phosphorous as well as increased energy consumption were the main reasons why no campaign was performed at the steelworks.

5 CONCLUSIONS

When slag is aged its leachability is changed; therefore, slag material should be tested in correspondence to the planned time of use. Steel slags should be aged at least 6 months before usage in external applications. All pre-treatment of materials for external applications should be completed before the ageing period starts.

By gas granulation the slag loses the disintegrating properties and has the potential to be used as an insulating material, as a filler in concrete and/or in cement industry, depending on its hydraulic properties.

P-additives, from e.g., mining by-products, can be used as a stabilizing agent for disintegrating slags.

Inert gas granulation cannot be recommended as a method for industrial use at this moment. The reason for the increased leaching of chromium from slag obtained in plant test has to be determined.

The potential use of ladle slag as slag former in EAF is limited because of sulphur and phosphorus content in ladle slag and the increase in energy consumption.

6 FURTHER RESEARCH

Characterization of samples, which have been obtained from the different activities, have to be analyzed before conclusions on ageing of slags as well as granulation and stabilization with P-additives can be concluded. The planned plant trials have to be fulfilled before determining whether slag processing can be implemented in industry.

The procedure for turning slag waste into a useful product will need a lot of development at each steel plant, since slag is a complex and uniqe material for each company.

From the ongoing project, it is evident that there is a need to gain more knowledge regarding the leaching mechanisms of Cr, Mo, and F, to determine the long-term quality of stabilized slag, and also to gain a deeper understanding of slag-steel equilibria as well as slag-solid phase equilibria. The possibility to minimize losses of Cr and maximize the uptake of phosphorous to slag is probably dependent on the composition of slag phases. Therefore, there is a strong need to increase the fundamental thermodynamic knowledge of slag-solid phase reactions and the distribution of e.g., chromium between different solid phases in the solidified slag to be able to recommend the most favourable slag compositions and cooling conditions of steelmaking slag.

There is today a trend towards the use of a larger quantity of Mn as alloying metal in the production of both ordinary and stainless steel. This will result in slags with higher Mn-content and from basic knowledge of the chemical bonding in oxide phases it can be expected that a higher Mn-content in the slag could favour a higher solubility of Cr in more soluble phases than the spinell phase, thereby also influencing the leaching.

Distribution of metals between slag and solid phases and mechanisms for leaching of Cr, Mo, Mn and F will be studied in next phase.

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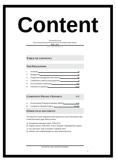

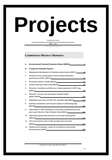

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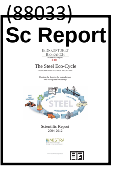

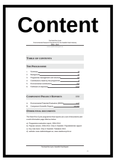

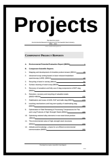

Leaching mechanisms and long term quality of steelmaking slag (88035)

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Abstract

Parts of the slag from scrap-based steel production in Sweden are landfilled. There is, therefore, a need to increase knowledge and find methods that help making this material a resource. The obstacles for the use of slags are volume instability, potential leaching of metals and disintegrating properties. Studies of ageing of ordinary and modified slag in natural environment and the leaching from these slags was one part of the research conducted within the Steel Eco-Cycle. Special emphasis was on the Cr and Mn content in steelmaking slag.

Another purpose was to get an understanding of the phase relationships in the $CaO\text{-}MgO\text{-}SiO_2\text{-}Cr_2O_3$ *slags with a view to control the precipitation of Cr-spinel in the slag phase in order to decrease Cr leaching. The equilibrium phases in* $CaO\text{-}MgO\text{-}Al_2O_3\text{-}SiO_2\text{-}Cr_2O_3$ *slag system at 1200-1600 ºC have been studied. The impact of slag basicity, temperature, oxygen partial pressure and* Al_2O_3 *addition on the phase relationships have been determined in a number of Cr-containing slags using SEM, EDS and XRD techniques. The experimental results show that a slag composition with a basicity of around 1.0-1.6 shall be chosen in order to obtain a Cr-spinel phase at a temperature of 1600ºC in air atmosphere. The impact of the slag basicity on chromium partition at lower oxygen partial pressures* ($p(O_2)=10^{-10} – 10^{-8}$ atm) *is negligible compared to that in air.*

1. INTRODUCTION

Before the start of the project 8 years ago, slag from steelmaking was one of the steelmaking residues that had the lowest degree of recovery and reuse in Sweden. There is still today a considerable amount of the steelmaking slag that could be utilized in a better way or are not used at all, the reasons mainly being the potential leaching, competition with easily available natural raw materials and the disintegrating property for some slags Parallel to the research, a large number of activities are also carried out within the Swedish steel industry to enhance the quality as well as to test the material in new applications together with contractors and construction companies.

Within the earlier project “Stabilisation and reuse of AOD-, EAF-, and ladle-slag”, one of the projects in the “Steel Eco-Cycle”, the long time behaviour of some EAF-slags was studied as well as different methods for stabilization of slag. The studied stabilisation methods have been gas granulation with inert gas or air and chemical stabilisation through additions to the slag. The purpose of the stabilization methods was to minimize leaching of metals and to avoid disintegration due to the phase transformation in the dicalcium silicate. The tests with inert gas granulation in pilot scale resulted in a material with decreased leaching of chromium and molybdenum but increased leaching of fluoride However, the full scale trials did not show as promising results as the pilot scale trials.

A number of untreated EAF-slags from ordinary production were studied in an ageing test. The slag was exposed to natural environment for two years and was then tested regarding leaching and changes of the surface after each half year, in total five times. The total leaching decreases as well as the Cr and Mo leaching. A change of mineral occurs at the surface. The matrix mineral dissolves to some extent, which can be concluded by the increased Mg leaching, and limestone forms on the surface.

Chromium in spinel phase has been reported to have lower leaching levels in the chromium containing slags[27]. It might be possible to increase the slag stability by increasing the Cr-spinel phase content with controlled solidification of slag. In earlier studies a so called spinel factor involving the spinel forming oxides has been defined[28] and it has been possible to relate the leaching of chromium to this spinel factor. However it has also been shown[11,29] that chromium may dissolve in other phases than the spinel phase and the leaching of chromium will then depend on the extent to which these phases form during cooling of the slag and the leachability of these phases.

In slag chromium can be present in different valence states, where Cr_2O_3 and CrO are most common. The ratio of $X_{CrO}/X_{CrO1.5}$ in the $CaO\text{-}MgO\text{-}(FeO)\text{-}Al_2O_3\text{-}SiO_2\text{-}CrO_x$ slags systems increases with increasing temperature, decreased oxygen partial pressure and higher slag basicity[30]. Thus in order to stabilize the spinel phase in slag the treatment conditions shall be strictly controlled.

Very little is reported in the literature regarding the influence of cooling on the properties of slag, especially for steelmaking slag. The formation of a glassy material depends on both the chemical composition and the cooling conditions. According to Daugherty et al. [31], glass was easier to produce, as the acidity of the slag increased for a series of synthetic slag compositions that was quenched and annealed. If the cooling is rapid, the slag passes from a liquid state to a solid without development of a crystalline structure[32]. Besides glass formation, controlling cooling conditions can be a means of affecting mineral transformation and consequently the solubility of elements like chromium[11]. Leaching from steel slags is generally characterized as a surface reaction, followed by a solid-solid diffusion process, in order to retain equilibrium in the materials[33].

Nowdays increased amounts of high-Mn stainless steel are produced around the world and in Sweden as an attempt of using Mn to replace the expensive Ni, in order to reduce the production cost of austenitic stainless steel. Sound mechanical properties, high wear resistance, and at least the same corrosion resistance as traditional stainless steel (304 and 316 grades) can be achieved with Mn used in combination with N, C and Cr in the new types of high Mn stainless steel.

Loss of Mn to the slag through oxidation will occur during production of high-Mn stainless steel. It has been expected that a higher Mn-content in the slag could favour a higher solubility of Cr in more soluble phases and, hence, enhance Cr leaching from the slags. Some of the results of early slag tests peroformed at LTU, MEFOS and Outokumpu Stainless Oy in Tornio during Mistra stage I revealed no clear relations between MnO content and Cr leaching from the EAF and AOD slags. There is no information available in the literature about influence of Mn oxides on leaching properties of the steel slags. There are however several studies of the Cr (III) oxidation reaction at the surface of various types of MnO_2 in an aqueous environment[34-37]. These studies show that manganese oxides are capable of oxidising trivalent chromium in aqueous phase to a significant extent. The manganese may act effectively as an electron transporter between Cr(III) and dissolved oxygen during Cr(III) oxidation that results in the reduction of MnO_2 solid phase to $[Mn^{2+}]$.

In the pH range of 3–10, and at oxygen partial pressure of 10^{-6} atm or higher, equilibrium conditions stipulate nearly complete conversion of dissolved trivalent chromium to hexavalent chromium through interaction with a MnO_2 surface.The coversion of Cr(III) to Cr(VI) by Mn oxides can occur at room temperature, in a time frame of days and months, and over a wide range of Cr(III) concentrations.

Slag has long been used in different applications and many efforts have been made to characterize, test and develop handling techniques. Still, there is a gap of knowledge regarding the factors controlling the ability to leach, the long-term quality and control of properties of the final slag product.

Earlier results indicate that the leaching of elements as chromium depends on a number of parameters. In the practical process these would be e.g. the overall composition of the slag, the oxygen potential, the temperature, the cooling of the slag and the handling or processing of the slag at the slag yard. These parameters will influence the extent of formation of spinel phases, the overall mineralogy of the slag, the particle size of the slag product and the grain structure in the solidified slag.

Hitherto when recycling of slag has been studied, the cold slag and its properties are in most cases considered to be fixed. However, it has been shown that, at least to a certain extent, the properties can be tailored to the requirements of the targeted application. In studies performed up to now, leaching of metals from slag has been a measure to determine whether a slag can be used or not, depending on regulations. Now the focus will be to understand how phases are formed during crystallisation and how leaching of these phases can be avoided. By combining theories of thermodynamics (phase distribution steel / slag), leaching (diffusion / dissolution) and crystallisation this will be achieved. A schematic figure of the realization is shown in Fig. 1.

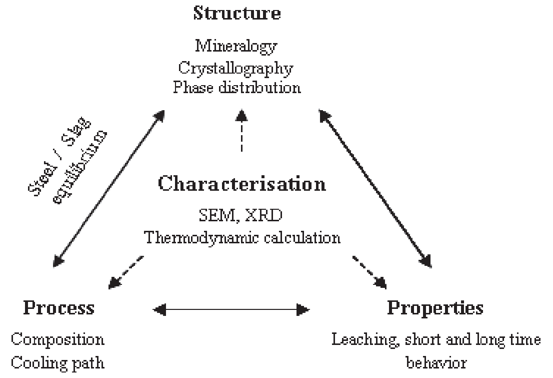


Fig. 1. *Research design and methods of use.*

To be able to recommend the most favourable slag compositions and cooling conditions of steel making slag, where the leaching of Cr, Mo and F is kept as low as possible, this project was planned to carry out:

* A number of full scale trials where the obtained products would be characterized and tested at lab scale as well as used in long term ageing tests.

* The dependence of chromium distribution between spinel phase and other mineral constituents in the

solidified slag would be determined through equilibrium lab scale studies at carefully controlled conditions.

* A thorough characterization of samples from the pilot scale and full scale trials as well as ageing test carried out during stage 1 of the project.

* Determination of the influence of Mn on the slag quality.

The slags of interest for this work were steel making slags containing higher amount of chromium and other alloying elements both from the EAF and AOD process.

2. OBJECTIVES

2.1 General

Through increased understanding of the mechanisms controlling leaching of elements as Cr, Mo, F and Mn, their leaching will be kept within limits that makes it possible to market steelmaking slag as construction materials. No rules for when a material can be used in e.g. construction exist today. Instead it is to large extent dependant on the local environmental authorities.

2.2 Industrial

Provide recommendations on necessary composition and slag handling procedures in order to make steelmaking slags into marketable products for e.g. construction. The long term aim at the start of the project was to turn 300 000 t of steelmaking slag that otherwise would be land filled into marketable products.

2.3 Environmental

The project was planned to deliver recommendations on slag handling praxis that would enable the steel industry to make use of the slag in applications e.g. within the construction sector. Thereby contributing to decreased use of natural resources, decreased amount of material that have to be land filled and thereby decreasing the accompanying risk for leakage from the landfill.

3. METHODS

3.1. Ageing of EAF-slags in natural environment

During, Mistra stage I, five different types of EAF slags from domestic steel plants were investigated regarding their long-term leaching behaviour, when kept outside, in the natural environment. Two different types of ageing experiments have been carried out during stage II. On one hand similar tests as in stage I have been continued using seven modified slags obtained during stage I The chemical compositions are shown in Table 1. The slags were crushed and sieved to reach a fraction 100 %, 1-4 mm. After splitting, the materials were well distributed on frames covered with two layers of plastic net, measuring 0.5 mm, securing a good water permeability through the materials, see Fig. 2.

Table 1. *Chemical composition of used slags.*

	Slag 1	Slag 2	Slag 3	Slag 4	Slag 5	Slag 6	Slag 7
	wt %	wt %	wt %	wt %	wt %	wt %	wt %
CaO	1.2	26.7	53.1	34	53	39	38
SiO2	25.3	21.6	30.3	29.6	16.5	7.2	7.9
MgO	33.5	7.3	7.9	12.8	5.3	7.4	6.6
Al2O3	27.3	6.2	5.3	6.9	21.6	5.9	5.5
FeO	3	22.4	0.3	1	0.4	30.8	30.8
MnO	0.2	3.1	0.6	2.8	0.3	3.9	3.9
Cr2O3	10.3	6	0.8	6	0.7	0.3	0.3

Fig. 2. *The experimental setup for ageing of slags in natural environment.*

The slags were sampled and characterized after 0, 6, 12, 18, 24, 36 and 48 months to evaluate the influences of ageing. X-ray diffraction pattern (XRD) and the standard leaching procedure EN12457-2 was used to characterize the slags. Data on the weather, including temperatures and precipitation, were taken from the Swedish Meteorological and Hydrological Institute (SMHI).

Tests were also carried out in stage 2 to investigate long time properties of slag with respect to leaching in the column setup depicted in Fig. 3A. Slags used contained varying amounts of Cr and Mn oxides. The test samples, 1.168-4.0 mm, were prepared from two AOD slags and four EAF slags, including slag from the production of high-Mn stainless steel. Two synthetic slag samples for the tests were also produced in lab by melting pure oxide chemicals.

The apparatus was made of plastic material and consisting of an upper and a lower container, see Fig. 3. A bed of slag sample (1 in Fig. 3A) was placed inside the upper, slag container. The rain water was collected in the lower, water container.

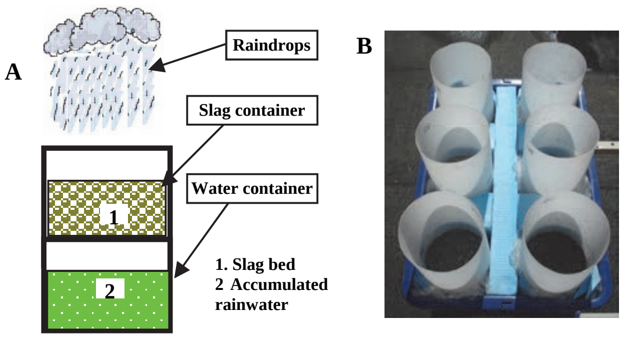


Fig. 3. *Schematic drawing, A, and a picture, B, of apparatus for the long time slag leaching tests in natural environment.*

When necessary due to the amount of rain water or at elast spring and autumn, the accumulated water (2 in Fig. 3A) was removed from the water container, with a sample taken for analyses of element content, pH and conductivity and with the water volume measured and registered for determining L/S ratio. After the water removal, the empty water container was cleaned for a new period of long time slag leaching. The slag leaching tests have been carried out for 1.5-2 years. The slag samples in the upper container (1 in Fig. 3A) has also been characterized after the end of the leaching tests.

3.2.Characterizatrion of samples from inert gas granulation

In stage I of the program, two pilot campaigns have been carried out at MEFOS to investigate the concept of inert gas granulation. The same granulation equipment was also used for preliminary plant tests at Outokumpu Stainless Oy. The Cr leaching results for slag granules from the MEFOS tests were quite different from the results for slag granules from the plant tests.

Characterization of samples obtained during the pilot and full scale campaign, carried out during the first stage of the project have been conducted using SEM and XRD. Six samples with corresponding reference from the pilot campaign at MEFOS together with four samples (Electric Arc Furnace and Chromium Converter) from the full scale campaign at Outokumpu Stainless Oy in Tornio have been analyzed.

3.3. Cr Partition between $MgCr_2O_4$ Spinel Phase and Silicate Matrix Phase

Phase equilibrium studies of a set of synthetic CaO-MgO-Cr_2O_3-SiO_2 slags, each containing 6 wt % Cr_2O_3 and 8 wt % MgO, with basicities (CaO/SiO_2) in the range of 1.0 to 2.0 have been conducted. The compositions of the slag samples are presented in Table 2. CaO and MgO powders were calcined at 1273K in a muffle furnace for 12 hours in order to decompose and remove any undesired compounds such as hydroxide and carbonate. SiO_2 and Cr_2O_3 powders were heat treated at 383K for 10 hours in order to remove any moisture. After mixing of chemicals in appropriate proportions, the powder mixtures were pressed into pellets (Ø 15mm). Platinum foil (Purity of 99.9 %, Alfa-Aesar, Germany) with a thickness of 0.127mm was used to make crucibles.

The Pt crucibles containing the sample pellets were positioned inside an alumina holder and then put into a high temperature furnace, as presented in Fig. 4. The furnace was heated with a heating rate of 5K/min. After an appropriate temperature was reached the samples were equilibrated for 24 hours. The air or CO/CO_2 mixture ($p(O_2)$ of 10^{-10} – 10^{-8} atm) gas was delivered to the furnace tube during the whole heating process. The impact of oxygen partial pressure and Al_2O_3 addition on the phase relationships was determined in a number of Cr-containing slags. Al_2O_3 contents in the slag varied in the range of 3-12 wt %.

After equilibrating, the samples were quenched by pulling them quickly to the cold end of the reaction tube. The samples were analyzed using SEM, EDS and XRD techniques.

Table 2. *Chemical composition of the original slag samples.*

Sample No.	Composition (wt %)				
	Basicity	CaO	SiO_2	MgO	Cr_2O_3
S1	1.0	43.0	43.0	8.0	6.0
S2	1.2	46.9	39.1	8.0	6.0
S3	1.4	50.2	35.8	8.0	6.0
S4	1.6	52.9	33.1	8.0	6.0
S5	1.8	55.3	30.7	8.0	6.0
S6	2.0	57.3	28.7	8.0	6.0

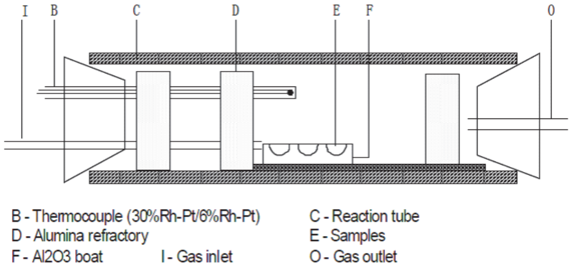


Fig. 4. *Schematic arrangement of the furnace* [21]

4. RESULTS AND DISCUSSION

4.1. Ageing of slags in natural environment

4.1.1 Ageing of modified slags

When ageing, the materials show large variations regarding total ability to leach, measured as conductivity as well as variations in pH, see Figs. 5-6.

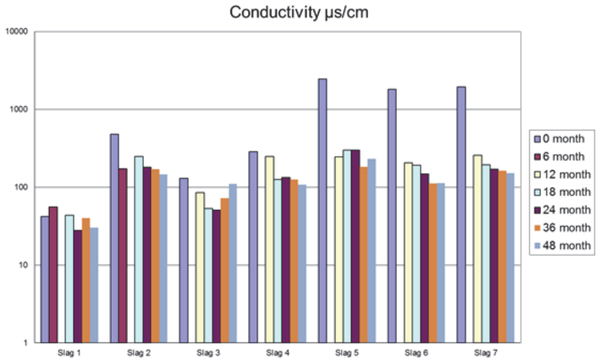


Fig. 5. *Conductivity as a function of time.*

For some of the slags the conductivity shows a pronounced decrease already after 6 months of ageing. Fig. 6 shows the pH value of the leachate as a function of time. The trend is similar for all of the slags, even though the absolute values differ.

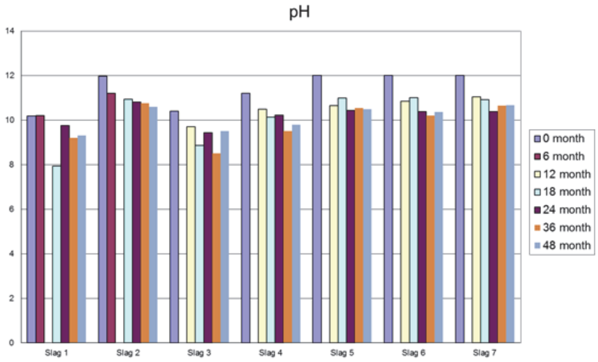


Fig. 6. *pH of leachate as a function of time for the slag.*

4.1.2 Ageing of slags in column test under natural conditions

AOD slag A and B, with compositions as given in Table 3, were used in the natural column tests to study the long time trend for the influence of Mn-content on Cr-leaching. Slag AOD-B has higher contents of Mn oxides and a higher basicity value, CaO/SiO2, than AOD-A sample.

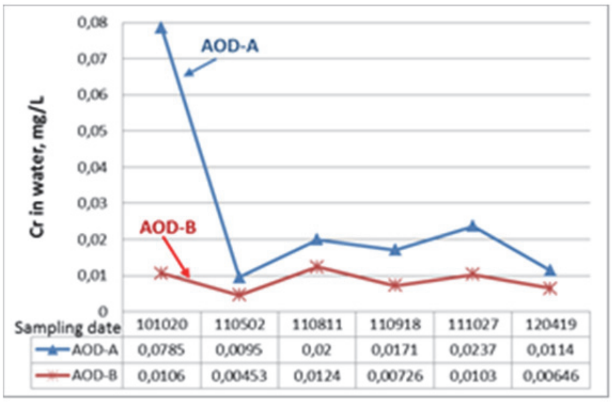
Table 3. *Composition of slags used in column test.*

	Weight % of MnO	Weight % of Cr2O3	Slag basicity
AOD-A	0,7	0,8	1,89
AOD-B	1,9	0,5	2,99

Fig. 7 shows result of Cr content in water samples obtained during sampling of water in the lower containers. Cr content is 0,08 mg/l in water flowing through slag in the first sampling but decreases sharpely to the level of 0,02 mg/l at later sampling occasions. It is also observed that Cr leaching from both of the slags decraeses at the sampling dates just after the winter, 2011-05-02 and 2012-04-19, which may be due to a water freezing in slag pores, limiting the rates for water-slag reactions during winter time.

A sample was also prepared by mixing 2 % of fine MnO_2 powder into sample AOD-A and AOD-B in order to examine the long time effect of MnO_2 particles on oxidation of Cr (III) in the slag samples in an aqueous environment. It is seen in Fig. 8 that there was only a moderate increases in Cr leaching from sample AOD-A with addition of 2 % MnO_2 powder.

Cr leaching when adding 2 % MnO_2 to sample AOD-B shows similar results, except a more pronounced increase for the later samplings. The results may indicate a long time effect of MnO_2 particles to oxide Cr (III) in an aqueous environment, hence, inducing an increased Cr leaching from slag.



Sampling date	101020	110502	110811	110918	111027	120419
AOD-A	0,0785	0,0095	0,02	0,0171	0,0237	0,0114
AOD-B	0,0106	0,00453	0,0124	0,00726	0,0103	0,00646

Fig. 7. *Cr content in samples obtained during water samplings in period from 2010-10-20 to 2012-04-19.*

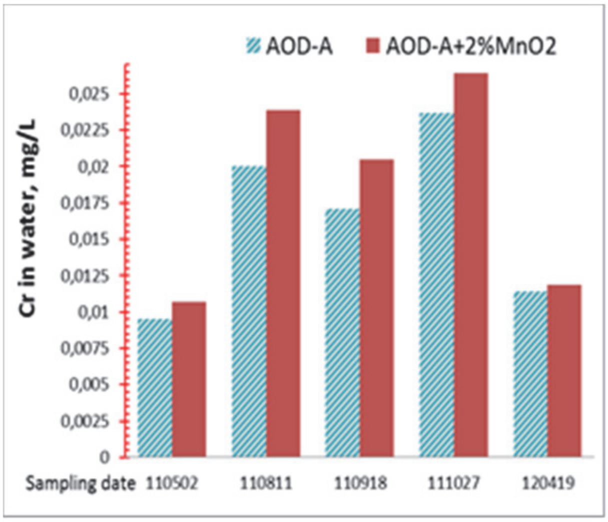


Fig. 8. *Cr content in leachate from sample AOD-A and AOD-A+2 % MnO_2.*

It is seen in in Fig. 7 that Cr leaching from sample AOD-B is lower than from AOD-A. Slag AOD-B has lower content of Cr_2O_3 and higher basicity as well as higher MnO content. It is obvious that there exist no clear relation between manganese content and the chromium leaching, but probably more related to the overall slag chemistry and mineralogy. The higher leaching of chromium from sample AOD-A in the very beginning may be due to chromium present in an easy solvable mineral being leached out in the beginning of the ageing.

4.2.Characterizatrion of samples from inert gas granulation

Results from characterization of samples from inert gas granulation shows that the mineralogical composition of the samples and corresponding reference samples are similar. Three chromium containing minerals were identified in the samples using SEM of which two, MgO (ss) and Merwinite (ss) are believed to contribute to the differences in leaching behavior.

Table 4. *Leaching results for slag granules from plant tests in stage 1, boron stabilized AOD slag, and for slag samples obtained by re-melting the same slag granules in MgO crucibles at LTU.*

Plant test	Cr leaching, mg/kg, slag from plant test	Cr leaching, mg/kg, re-melted samples
8	8.6	1,05
9	1.8	0,005
10	6.8	0,05

Tests were also conducted to study the Cr-leaching from AOD-slag with low and high metallic content. Selected slag granules from the tests were re-melted in MgO crucibles in order to obtain metal droplets at the bottom for characterization and for estimations of metal-slag mass balance. Leaching of the slag samples from the re-melting was also performed. Results in Table 4 indicate a considerable decrease in Cr leaching for the slag granules from the plant tests after re-melting. The re-melting and cooling was performed under a weakly reducing or low $p(O_2)$ atmosphere. It can be inferred, based on this result, that the different Cr leaching results may be related to different oxidizing/reducing conditions for the slags during the granulation in the plant and pilot scales.

4.3. Cr Partition between $MgCr_2O_4$ Spinel Phase and Silicate Matrix Phase

4.3.1 Slag basicity effect

In order to obtain a Cr-rich spinel phase at a temperature of 1873 K, a slag composition with basicity of around 1.0-1.4 is required. Higher basicities have to be avoided since it can lead to formation of leachable, chromium-containing solid solutions, which are potentially harmful to the environment. The chromium content in the spinel phase was found to decrease with basicity. Cr content dissolved in matrix phases is increased as a function of basicity (CaO/SiO_2). Some of the results obtained are highlighted below.

In the sample S5 (basicity=1.8), porosities could be found in the samples, as show in Fig. 9. Periclase crystals (MgO) containing dissolved chromium could be observed in this sample by EDS, as shown in Table 5. When the slag basicity is 2, for sample S6, the slag sample is not well melted and thus could not be analyzed by EDS. In this sample, bredigite phase, periclase and hatrurite are found by XRD analysis. Since the amount of the slag matrix phase is significant compared to the spinel phase, the increase in the concentration of Cr_2O_3 in the silicate matrix phase will have an impact on leaching behavior.

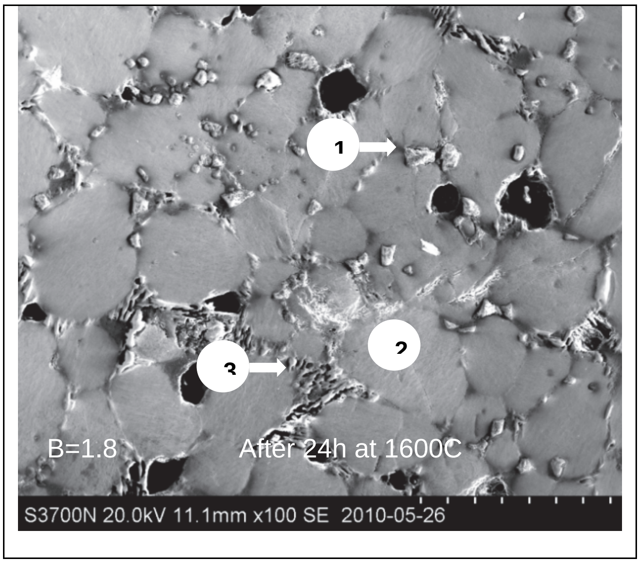


Fig. 9. *Slag sample S5 with basicity 1.8 after heat treatment at 1600°C for 24h. Periclase crystals ~50μm (1), Ca_2SiO_4 grains (2), divorced eutectic (3). The sample was not well melted, since the porosities in the grain boundaries can be observed.*

Table 6. *Phase composition of slag sample S5 measured by EDS analysis (at. %).*

Phases	**Ca**	**Mg**	**Si**	**Cr**	**O**
(1) periclase	0	39	0	6	55
(2)matrix	26	1	11	2	61
(3)eutectic	21	6	12	1	60

4.3.2 Heat treatment effect

The spinel grain size has increased by one order of magnitude in all samples after slow cooling to 1673 K compared to the samples which were directly quenched from 1873 K. The dissolved content in the spinel phase of elements as Ca and Si is decreased after slow cooling. The amount of Ca dissolved in the spinel phase is found to be a function of basisity. Cr content in the matrix decreased after slow cooling as a result of efficient spinel phase growth. Spinel phase was found to get precipitated from merwinite and Ca_2SiO_4 phases on cooling and was found to grow due to low solubility of Cr in the matrix phases at lower temperature.

Samples with basicity 1.4 annealed at 1673 K after quenching from 1873 K consists of wollastonite, merwinite and spinel, as show in Fig. 10. The Cr content in the spinel phase increase after heat treatment and the Cr/Mg ratio is close to 2. The eutectic phase observed after quenching from 1873 K is transformed to wollastonite. Wollastonite contained some remaining Cr.

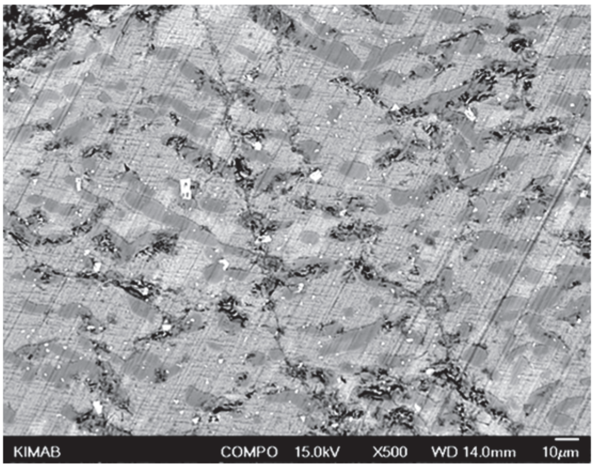


Fig. 10. *Sample S3 after the heat treatment at 1873 K for 24 hours and at 1673 K for 24 hours.*

The chromium content in the merwinite has on the other hand decreased compared to the sample quenched from 1873 K. It is very interesting to find that heat treatment at lower temperature will increase the precipitation of Cr-spinel phase in sample S4. Fig. 11 shows the SEM photo of S4 after heat treatment at 1873 K for 24 hours and then retreated at 1573 K. A considerable amount of Cr-spinel phase can be observed. The high Mg content in the solid solution indicates that the spinel phase started to grow from the periclase crystals precipitated earlier.

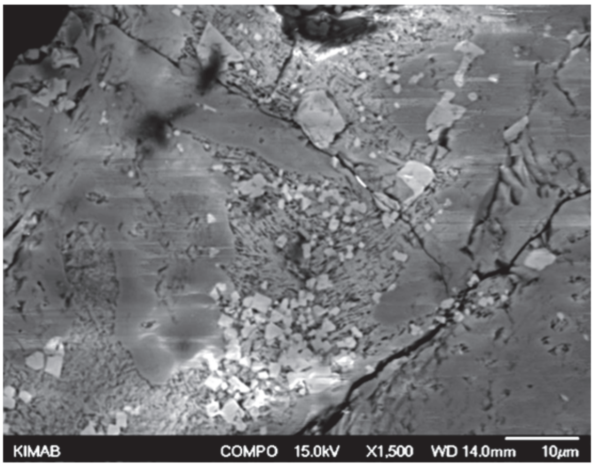


Fig. 11. *Sample S4 after the heat treatment at 1873 K and then treated at 1573 K for 24 hours.*

4.3.3 Effect of $p(O_2)$ and Al_2O_3 addition

The experimental results for a number of Cr-containing synthetic and industrial slags show that slow cooling and soaking of slags at oxygen partial pressure of 10^{-10} – 10^{-8} atmosphere facilitate the formation of spinel phase and give extremely low Cr –content in the matrix. Formation of the spinel phase at higher $p(O_2)$ on the other hand was hindered in slags with (CaO/ SiO_2) higher then 1.4. After the soaking for 72 hours at 1673K and at a $p(O_2)$ of 10^{-8} atm, Cr-content in the matrix phases was below the detection limit according to WDS analysis. All Cr was bound to spinel and metallic phases. Cr content dissolved in the Pt foil decreased with alumina content in slag. From 4.5at % Cr dissolved in Pt at 3 % alumina addition to 0.5 at % at 12 % of alumina addition. This indicates that alumina stabilizes chromium in spinel phase.

Cr content is decreased in the matrix as a result of efficient spinel phase growth. Low $p(O_2)$ improves the spinel precipitation. The amount of spinel phase (solid solution $MgAl_2O_4$-$MgCr_2O_4$) increases with alumina content, but do not affect the amount of chromium dissolved in the matrix phases. The chromium in the spinel phase is replaced by Al ions. Very low Cr content in the matrix phase is the results of efficient $MgCr_2O_4$ formation.

EAF slags supplied for the study contained numerous metallic droplets which dissolved in the slag during heat treatment. The Cr content in the matrix phases did not change much after the heat treatment, due to the dissolution of metallic droplets into slag. Most part of Cr went to spinel and wüstite phases. Slow cooling at lower $p(O_2)$ facilitates spinel precipitation.

5. CONCLUSIONS

The phases contained in a number of Cr-containing synthetic and industrial slags have been studied. The results show that slow cooling and soaking of slags at an oxygen partial pressure of 10^{-10} – 10^{-8} atmosphere facilitate the formation of spinel phase, which is desirable to minimize the Cr leaching from the slag. Formation of the spinel phase at higher $p(O_2)$ on the other hand was hindered in slags with (CaO/ SiO_2) higher then 1.4.

In order to obtain a spinel phase at a temperature of 1873 K, a slag composition with basicity of around 1.0-1.6 shall be chosen. The slag with basicity 1.6 contained considerable amount of Mg chromite solid solution (spinel) after annealing at 1573 K. The high Mg content in the solid solution indicates that the spinel phase started to grow from the existing periclase (MgO) crystals, precipitated earlier at 1873 K.

For the samples with basicity 1.8-2.0 no considerable structural changes could be found, after the different heat treatment procedures. All the samples were porous and contained un-dissolved periclase crystals. Thus it can be concluded that the samples remained un-melted at the temperature 1873 K. Chromium contained in metallic droplets in the slag will during heat treatment dissolve in the slag and increase the content in the matrix phases.

It was found that oxygen partial pressure has a strong impact on chromium partition. Low oxygen partial pressure enhances the precipitation of spinel phase. High oxygen partial pressure had a negative effect on the chromium partition to the spinel phase. Slow cooling of slag and soaking at low oxygen partial pressure would improve the spinel phase precipitation as well as it will give less Cr dissolved in the soluble matrix phases. The impact of the slag basicity on chromium partition at lower oxygen partial pressures ($P_{O2}=10^{-10}$ – 10^{-8} atm) is negligible compared to that in air.

The amount of spinel phase increases with increased Al_2O_3 content. The results show that alumina addition to molten slag can be used to control Cr partition between slag and metallic phases. The amount of spinel phase (solid solution $MgAl_2O_4$-$MgCr_2O_4$) increases with alumina content, but does not affect the amount of chromium dissolved in the matrix phases.

Several types of slags have been evaluated with respect to their leaching properties when exposed to natural weather conditions. From this investigation the following conclusion can be drawn: 1) When slags are aged, the total leachability is dramatically lowered. 2) Steel slags should be aged at least 6-12 month before used in external applications. 3) Slags should be tested at the time for its use. A leaching test performed on a non-aged sample will not reflect how the material would behave after 12 month of ageing. 4) All pre-treatment of slags for external applications should be completed before the ageing starts. If the pre-treatment is conducted after ageing, new fresh surfaces will be liberated and the ageing must be performed once again. 5) The concentration of a certain element in the slag can never be directly correlated to the leaching without considering in what phase it is present and how that certain phase is behaving in the slag system.

No clear correlation between Manganese content in slag and Chromium leaching could be found. Differences are more related to mineralogical differences in the slag. Higher oxidations states of Mn present where the slag is used may oxidize Chromium into soluble compunds.

Differences in leaching of chromium from granulated slag in pilot- and plant tests can be explained by differences in oxidizing conditions.

To summarize:

* The project has together with other ongoing slag related projects, contributed to a considerable increase in the understanding of parameters influencing leaching of metals from steelmaking slags.

* Based on results from this project and other ongoing projects a recommendation for handling and modification of steelmaking slags have been delivered to the Swedish steelmaking industry.

* The long term goal formulated in the beginning of the project to decrease the amount of landfilled slag from steelmaking by 200 kt has already partially been fulfilled.

6. FUTURE UTILIZATION

During the last decennia, certain metallurgical slags, such as air-cooled and granulated blast furnace slag, have made an evolution from an essentially costly stream to a valuable by-product as a secondary resource. In the future it is to be expected that also other slag types will be used in higher extent as valuable materials, thereby improving the industrial ecology of steelmaking and non-ferrous production. A systematic evaluation of the properties required of the cooled slag product, starting from the metallurgical requirement, will lead to a better control of the properties and will decrease their variability.

Moreover, by consciously altering slag compositions and cooling paths, new fields of applications will be opened. For example, the production of paving stones or even table tops by slag casting could be promising applications. The fact that its properties can be adjusted to the wishes of the customer could be a clear advantage over the common primary resources.

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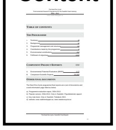

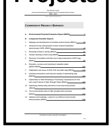

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Optimization of Slab Reheating & Processing Temperatures for Flat and Long Products of High Strength Steels (88041)

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Abstract

The present work was carried out with the aim of reducing the initial slab reheating temperature before rolling while at the same time improving properties by optimisation of the steel composition and process parameters. Optimisation of slab reheating and hot rolling/cooling parameters in connection with heavy plate, strip and long products rolling has been carried out on a laboratory scale for high strength steels.

The investigation has concerned six steels originating from SSAB EMEA (Borlänge and Oxelösund) and OVAKO Bar AB (Smedjebacken).

Effects have been investigated of reduced slab reheating temperature (T_{reh}), finish rolling temperature during thermo-mechanical processing (TMCP) and accelerated cooling rates (ACR=20-80°C/s) following hot rolling to the coiling temperature of 550°-600°C or to room temperature (RT).

The results obtained for strip steels show also that a reduced reheating temperature (1220°C) combined with a high finish rolling temperatures and cooling rates over 20°C/s to coiling temperatures (T_{coil}) of 550°-600°C produce very positive mechanical properties in the present steels.

Improvements in the yield strength of heavy plate have been obtained by lowering the slab reheating temperature from 1240°C to 1160°C, especially in combination with high pass reductions of 15% and rapid cooling (~100°C/s) to RT.

Yield stress improvement for the long product was obtained by lowering the slab reheating temperature from 1250°C to 1180°C and by increasing the cooling rate up to 5°C/s to RT. The results obtained in laboratory scale have been compared with full scale strips and long products of the present steels processed industrially in a same manner and a good agreement between these results has been observed.

Analyses of precipitates (particles size and chemistry) in the specimens after TMCP processing were carried out using transmission electron microscopy. The results agree with expectations from ThermoCalc predictions of precipitate dissolution and show a close relationship with the observed microstructures and properties.

Lowering the slab reheat temperature by 60-80°C reduces energy consumption by up to 14000 MWh per year and, as a result, reduces the release of CO_2 emissions into the atmosphere by 3 600 tonnes per year during production of the present steels.

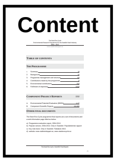
Key words: *Energy, environment, high strength steel, microalloying, hot rolling, cooling, coiling, microstructure, mechanical properties.*

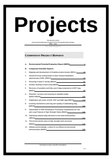
1. INTRODUCTION

Advanced steel products represent a strongly growing market segment and one that continues to show good profitability. These have a potential for cost reduction during both the processing of the steel and in its subsequent service. High quality high strength steels imply large environmental advantages by decreased material consumption (weight savings) increased load capacity and prolonged service life in constructions.

The influences of consumption of energy and material in both the production and the final use of products have been studied in MISTRA projects No 88041(Improving high strength steels with energy efficient process routes) and No 88044 (The environmental value of high strength steel structures). These influences have been discussed together with the possibility of making constructional changes and thereby saving weight in different applications, where the use of high strength steel can reduce both cost and environmental impact. Improving the steel properties and production processes for high strength steels requires, however, also improved process control in close relation to the steel composition (1 – 10).

Reheating prior to rolling is a very energy consuming step in the production of steel products. Higher strength often requires more alloying elements but to some extent this can be avoided by more efficient processing during rolling or by separate heat treatments. The reheating process needs to be efficient enough to dissolve the alloying elements in the as-cast structure so that these can have their full effect on the material properties. Reduced reheating temperature/time saves energy but cannot be accepted if the mechanical properties of the product are impaired (12-15).





Optimisation of slab reheating and hot rolling parameters can reduce energy consumption and in this way also release less CO_2 into the atmosphere during the thermo-mechanical processing. There is accordingly a strong incentive to reduce energy demand during the continuous production of structural to give both cost reduction and environmental benefits. Furthermore it is vital that the correct final condition is obtained directly from the hot rolling mill since reprocessing is expensive or often impossible.

Plate production based on using continuously cast (CC) slabs is much more effective process than the plate production based on ingot casting. Reheating of the ingots and rolling to slabs are energy consuming processes that can be saved. Furthermore the prime yield is better when CC slabs are used and this gives an extra benefit for this process route.

The problem is that both conventional processing and many standards set up an upper limit for the maximum plate thickness depending on the slab thickness. A reduction ratio from cast steel to final plate thickness of 1:3 or even 1:4 is common. Important goal for the plate part of the project is to search for optimization of the rolling process in order to produce a high quality in thicker gauges from high quality slabs. When thicker dimension plates are rolled the special attention has to be paid to the problem where the reductions at the surface will be larger than the ones at the mid thickness. Therefore the rolling schedule representing both the surface region and the mid-thickness, with lower reductions, is important to study.

Previous research (see report & papers of MISTRA project No 88041) and production experience have demonstrated the advantages of lower reheating temperatures and recrystallization controlled rolling for the cost efficient production of high strength microalloyed steels (12-15). This processing is finished at relatively high temperature and grain growth is inhibited by the presence of finely dispersed particles to ensure a fine recrystallized austenite grain structure.

If the reheating temperature can be substantially reduced in this way, energy consumption can be lowered significantly. Steel chemistry and process conditions should be controlled to give a balance with a suitable content of micro-additions for grain control and precipitation strengthening. There may also be a reduction in the processing time when aiming at an optimal finish rolling temperature which is beneficial for the productivity. This approach should be applicable to plate products and also to relatively large sections.

Knowledge of the microstructure development in association with thermo-mechanical controlled processing is very important for optimising rolling schedules with the aim of improving properties of steels in the as-hot rolled condition. The key to success with thermo-mechanical processing is to define rolling schedules combining a maximum degree of microstructure refinement with an effective utilization of the strengthening potential of the micro-additions. The improvement in properties of steel products is associated with different strengthening mechanisms of which the most important is structure refinement whereby both strength and toughness are improved at the same time. The results are usually discussed in terms of grain refinement according to Hall-Petch together with precipitation strengthening theory.

The present project focuses on the modification of coarse solidification structures in slabs and homogenization of segregations, making use of thermodynamic calculations as well as heat treatments in laboratory scale. The experiments will also study the re-precipitation of the phases during rolling and air/accelerated cooling, depending on the actual rolling process.

When a separate heat treatment is required, precipitation during the subsequent process route is studied as well as the influence of the process parameters on the final mechanical properties.

2. GOALS / OBJECTIVES

The aim is to optimise the slab reheating temperature/time, TMCP-processing parameters, (reductions, FRT), (accelerated) cooling parameters in relation to grain refinement and improved mechanical properties of high strength microalloyed steels for:

i.) heavy plate,
ii.) strip and
iii.) long products.

These developments place technological demands for modification of the chemical composition of microalloyed steels that must be applied in connection with the lower reheating temperatures.

In the case of heavy plate the possibility to produce thicker plates from continuously cast slabs is, however, of major importance compared with reduced slab reheating temperature.

The specific goal is to find optimal slab reheating parameters prior to hot rolling for different products in respect of environmental gains, namely energy reduction and less release of CO_2 into the atmosphere in slab reheating furnaces.

3. METHODS AND MATERIALS

Three group of high strength steels have been investigated in this work.

- Three steels for investigation of strip rolling are low C - Mn steels microalloyed with Nb.
- Two steels for heavy plate investigation having medium carbon contents, alloyed with Mn, Ni, Cr, Mo as well as micro-alloyed with Ti, Al, V, Nb and B,
- One steel for the long product investigation is a low C- Mn-Cr-Cu steel microalloyed with Nb.

Table 1. Chemical composition of steels for strips, heavy plates and long products (wt %).

	Chemical composition, wt%									
Steel	C	Si	**Mn**	**Ni**	**Cr**	**Mo**	Ti	**Al**	**V**	**Nb**	N
S1	0.062	-	0.59	-	-	-	-	.056	-	**.052**	.0032
S2	0.06	-	0.6	-	-	-	-	.044	-	.022	.0024
S3	0.066	-	**1.36**	-	-	-	-	.039	-	**.055**	.0044
S1_FS	0.067	-	**0.6**	-	-	-	-	.041	-	**.049**	.0037
S2_FS1	0.066	-	**0.62**	-	-	-	-	.053	-	**.023**	.0022
S2_FS2	0.073	-	**0.61**	-	-	-	-	.041	-	**.022**	.002
P1	0.32	1.10	**0.80**	-	**1.35**	**0.8**	**.014**	.011	**.14**	**.017**	.0032 B
P2	0.l7	0.24	**1.10**	**1.0**	**0.44**	**0.5**	.003	**.06**	**.03**	**.017**	.0034 B
L1	0.05	0.29	**1.00**	**0.25**	**3.92**	**.05**	0.3Cu	.024	-	**.059**	.0130
L1_FS	0.039	0.34	**0.95**	**0.14**	**3.98**	**.03**	0.23Cu	.023	-	**.055**	.0140

%P (0.006-0.0114) and %S (0.001-0.0012);
** S1, S2, S3, S1_FS - slab for strips, P1, P2 – for plate and L1, L1_FS – for long product, (FS=full scale).*

The steels were delivered from SSAB EMEA and OVAKO Bar AB. The chemical compositions of the steels for plates (SSAB EMEA in Oxelösund), strips (SSAB EMEA in Borlänge) and OVAKO Bar AB in Smedjebacken are shown in Table 1.

The steels from SSAB EMEA in Oxelösund were delivered in the as cast condition with slab thickness of 280mm for heavy plate hot rolling simulation and for strip rolling with slab thickness of 220mm. The steel from OVAKO Bar AB were prepared as a hot rolled narrow plate product of 15mm thick (150 x 600mm).

Cylindrical compression specimens (Ho ∗ ∅ = 10.0 ∗ 5.0 mm) were machined from the surface and from the ¼ thickness of slabs (centre) for a study of the TMCP simulations of heavy plate in the Bähr deformation dilatometer (hot compression). For strip rolling simulation the specimens were machined from the central part (L1) and the corner (T1) of the slab. These were machined in the longitudinal and transverse directions.

All specimens were given a prior austenitization treatment comprising 30 min at T_{reh} temperatures followed by water quenching. For plate, Treh was 1160° and 1240°C, for strip it was 1220° and 1280°C and for long product, 1180° and 1250°C.

For hot-rolling simulations coupled with accelerated cooling/coiling, simplified deformation schemes were adopted involving three individual steps. Samples were first reheated for 5min at their respective T_{reh} and then subjected to one of the following hot deformation schedules to simulate heavy plate, strip rolling and long products, followed by various finish rolling temperatures and reductions.

Programs for hot rolling /TMCP simulations of the present steels were as follows;

3.1 For Strip Steels:

Table 2. Process parameters for strip rolling simulations of S1, S2 and S3 steels.

Process parameters	**High Treh**	**Low Treh**
Furnace temperature	1280°C	1220°C
FRT temperature	870°C	870°C
Cooling rate	20-80°C/s	20-80°C/s
Coiling temperature	600°C	600°C
Finish temperature	RT	RT

A. 1280°C/5min→(CR=2°C/s)→1150°C/20%→1050°C/20%→890°C/20%→870°C (ACR=20, 40, 60°C/s) →600°C → (0.2°C/s) → RT,
B. 1220°C/5min→(CR=2°C/s)→1105°C/20%→1020°C/20% → 890°C/20% →870°C(ACR=20, 40, 60, 80°C/s) →600°C→ (0.2°C/s) → 250°C→ RT.

3.2 For Heavy Plate Steels:

I. Treh = 1240^{0}C/5min

C. Surface:1240^{0}C/15%→(10s)→1235^{0}C/15%→(10s → 1230^{0}C/15%→(10s)→ 0.2°C/s to 900°C→DQ,
D. Surface: 1240^{0}C/15% →(tp=10s) →1235^{0}C/15% →(10s)→1230^{0}C/15% →(10s)→ Air Cool (0.2°C/s to 300°C),
E. Centre:1240^{0}C/8%→(tp=10s)→1240^{0}C/8%→ (10s) → 1240^{0}C/8% →(10s)→ 0.2°C/s to 900°C → DQ,
F. Centre:1240^{0}C/8%→(10s)→1240^{0}C/8% →(10s)→ 1240^{0}C/8% →(10s)→ Air Cool (0.2°C/s to 300°C).

II. Treh = 1160^{0}C/5min,

G. Surface:1160^{0}C/15%→(10s)→1155^{0}C/15%-(10s) →1150^{0}C/15%→(10s)→0.2°C/s to 900°C→ DQ.
H. Surface:1160^{0}C/15%→(10s)→1155^{0}C/15%→(10s) →1150^{0}C/15%→(10s)→Air Cool(0.2°/s to 300°C).
I. Centre:1160°C/8%→(10s)→ 1160^{0}C/8% →(10s)→ 1160^{0}C/8%→(10s)→ 0.2°C/s to 900°C→ DQ (He).
J. Centre:1160C/8%→(10s)→1160^{0}C/8% →(10s)→ 1160^{0}C/8%→(10s)→Air Cool(0.2°/s till 300°C).

III. Hardening at 890° and 950^{0}C for 30min;

1.) Surface: 890^{0}C followed by cooling at 5, 15 and 25^{0}C/s to RT,
2.) Surface: 950^{0}C followed by cooling at 5, 15 and 25^{0}C/s to RT,
3.) Centre: 890^{0}C followed by cooling at 5, 15 and 25^{0}C/s to RT,
4.) Centre: 950^{0}C followed by cooling at 5, 15 and 25^{0}C/s to RT.

3.3 For Long Products Steel:

A1.) 1250°C/min→ (CR=3°C/s) →1150°C/20%→ 1050°C/25%→ 980°C/20%→900°C→CR=0.5, 1, 3 and 5°C/s → RT,
A2.) 1250°C/5min→ (CR=3°C/s) →1150°C/15%→ 1050°C/20%→1000°C/25%→950°/20%→870°C→ CR=0.5, 1, 3 and 5°C/s → RT,
B1.) 1180°C/5min→ (CR=3°C/s) →1100°C/20%→ 1000°C/25%→920°C/20%→850°C→CR=0.5, 1, 3 and 5°C/s → RT,
B2.) 1180°C/5min→ (CR=3°C/s) →1100°C/15%→ 1050°C/20%→1000°C/25%→950°/20%→870°C→ CR=0.5, 1, 3 and 5°C/s → RT,

The strain rate during experiments was nominally 2/s.

The yield stress (Rp$_{0.2}$ or Re) and hardness (HV1, HV0.5) were measured on fully transformed samples from the TMCP simulation experiments using compression tests performed at a strain rate of $5{\cdot}10^{-4}$ s^{-1}.

A hot solution of saturated aqueous picric acid, cupric chloride and wetting agent has been used for etching the austenite grain boundaries. Austenite grain sizes were determined by linear-intercepts along a circle.

The final microstructures of the TMCP processed steels have been studied using FEG SEM on OPS vibration polished specimens.

Transmission electron microscopy using carbon extraction replicas was used to examine precipitates in the present steels and analyses of the particle size and chemistry.

4. RESULTS AND DISCUSSION.

The austenite structure evolution and the final microstructure as well as properties of high strength microalloyed steels are usually dependent on the following TMCP parameters; reheating temperature, rolling schedules: reduction and finish rolling temperature together with the cooling parameters: accelerated cooling rate and finish accelerated cooling temperature or coiling temperature as well as, of course, steel composition.

The slab reheating temperature has a significant influence on the strength, toughness and microstructure of high strength microalloyed steels in the as TMCP condition [12-15]. A low reheating temperature usually gives finer austenite grains, refines the final microstructure of the steel and as a consequence improves the low temperature toughness. However, the yield stress at RT may decrease because a lower reheating temperature usually reduces the amount of dissolved niobium in the austenite and accordingly the potential for precipitation hardening after cooling.

The high and low finish rolling temperature practice affects not only the yield strength and toughness of the steel but also the productivity of the process for heavy plate production [1].

Accelerated cooling rates and finish accelerated cooling temperature or coiling temperatures (T$_{coil}$) are very important parameters which affect the final microstructure, yield strength and toughness of steel (4-10, 16-17).

In order to improve the properties of three groups of the present steels by optimising process parameters and to minimise production costs at the same time, various steps in the production of heavy plates, strips and long products have been examined.

The results obtained after hot rolling of strips, heavy plates and long products after simulations with reheating at different temperatures are presented in the following chapters.

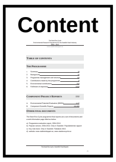
4.1 Hot rolling simulation of strips

The effect of slab reheating, finish rolling and coiling temperatures has been studied for various accelerated cooling rates in the range of 20-80°C/s regarding the yield strength, hardness and microstructure for three Nb-microalloyed high strength strip steels. One was 0.06%C-0.6%Mn steel (S1) microalloyed with 0.052% Nb, the second (S2) steel was with lower at 0.022%Nb, whereas the third was with 1.36%Mn and 0.055%Nb.

4.1.1 ThermoCalc predictions of equilibrium precipitation/dissolution.

For better understanding of the precipitate and microstructure evolution of the present steels during reheating and strip processing, ThermoCalc predictions of equilibrium precipitation / dissolution of M(C, N) were carried out for steel S1, S2 and S3, and the results are shown in Fig. 1. These calculations were used to predict possible low reheating temperatures that can be applied for the strip steels, as shown in Fig. 1. The acceptable temperature range for reheating of the present strip steels should be not lower than 1200°C if dissolution of the microalloying elements and precipitation strengthening during coiling is taken into consideration. Accordingly, it was decided to use the reheating temperatures of 1220° and 1280°C in this study.

Austenite grain sizes of the present steels were determined on the specimens in both the longitudinal and transverse directions, after reheating for 0.5h at lower (1220°C) and higher (1280°C) temperatures, as presented in Table 3.



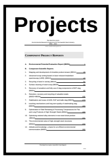


Table 3. Austenite grain sizes in strip steels S1, S2 and S3 (in longitudinal and transverse directions) reheated at 1220°C and 1280°C for 0.5h.

	Austenite grain size, µm		
	S1 steel	S2 steel	S3 steel
1220°C – L1	140	138	106
1220°C – T1	130	144	117
1280°C – L1	230	210	178
1280°C – T1	224	210	147

As shows in Table 3 the austenite grain size was in the range of 130-144µm for steels S1 and S2 (0.06C-0.6Mn with 0.02 & 0.05% Nb respectively) when reheated at 1220°C, whereas at the higher reheating temperature of 1280°C grain sizes were larger, 210 to 230µm.

It was observed that the steel S3 with a higher Mn content (1.35%) shows smaller grain size after reheating at the same temperatures, 106-117µm and 147-178µm, for 1220° and 1280°C, respectively. Differences in austenite grain sizes between the longitudinal and transverse directions were small or non-existent, as seen in Table 3.

4.1.2 Mechanical properties and final microstructure of simulated strips.

Example of the results obtained for strip rolling simulation after reheating at 1280°C and 1220°C are presented in the following figures. Rolling schedules with 3 deformations for strip simulation of the present steels are shown in §3.1 (A, B).

The results of yield stress, Rp0.2, and hardness, HV0.5, obtained after strip rolling simulation of S1 steel (0.06C-0.6Mn-0.5Nb) following reheating at 1280°C and 1220°C for the specimens in the longitudinal and transverse directions are shown in Fig. 2, whereas the final microstructures of the TMCP simulated steel for various cooling rates to coiling temperature of 600°C are shown in Fig. 3.

As seen in Fig. 2 a and 2 b, the yield strength of steel S1-L1 (specimens in longitudinal direction) was a little higher for specimens reheated at higher temperature, 1280°C, than for 1220°C, especially for higher applied cooling rate (>20°C/s) to coiling temperature. However, the lowest yield stress was obtained for steel S1_L1 (specimens in longitudinal direction), reheated at 1280°C, hot rolled followed by cooling at 20°C/s to RT or to coiling temperature of 600°C.

Generally can be pointed out that better results of yield stress (by 20-40MPa) were obtained for specimens in the transverse direction (T1) than in the longitudinal direction (L1) of steel S1, when processed in the same manner, as can be seen in Fig. 2 c and d in comparison with Fig. 2a and b .

As shown in Fig. 3 and 5 microstructure has changed from fine polygonal ferrite and high density ferrite / bainite in the specimen cooled at 20°C/s to 600°C to a bainitic structure after the higher cooling rates, (>40°C/s) for both applied reheating temperatures.

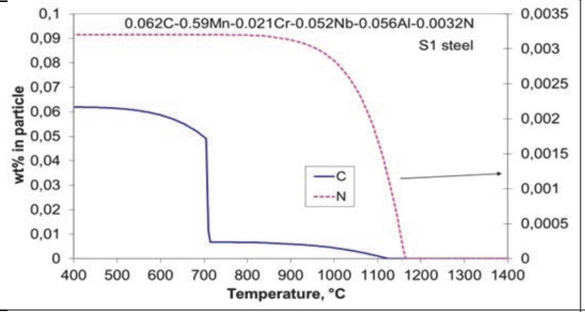
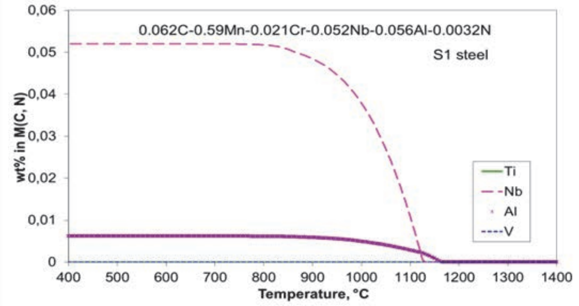
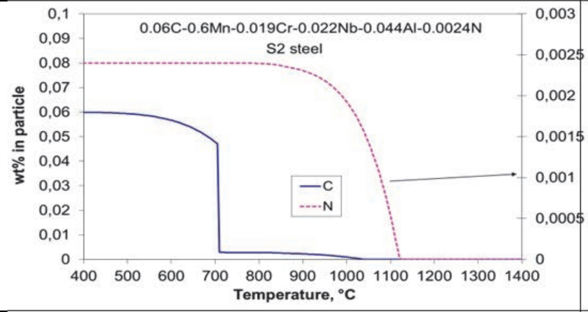
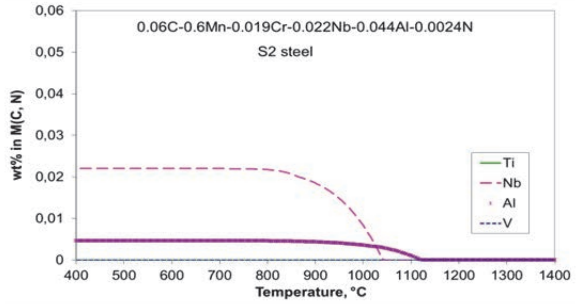
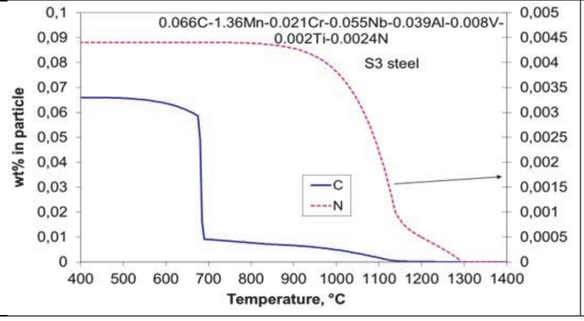
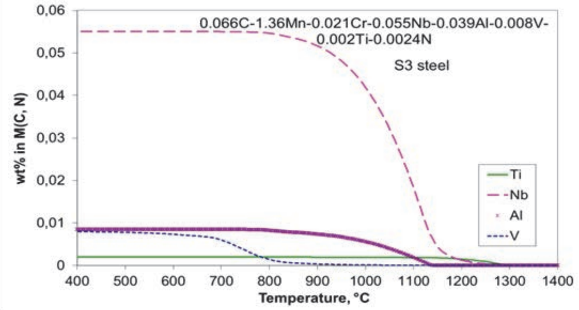
Steel	Carbon and nitrogen	Microalloyings
S1		
S2		
S3		

Fig. 1. *ThermoCalc predictions of equilibrium precipitation / dissolution of M(C, N) in steel S1, S2 and S3.*

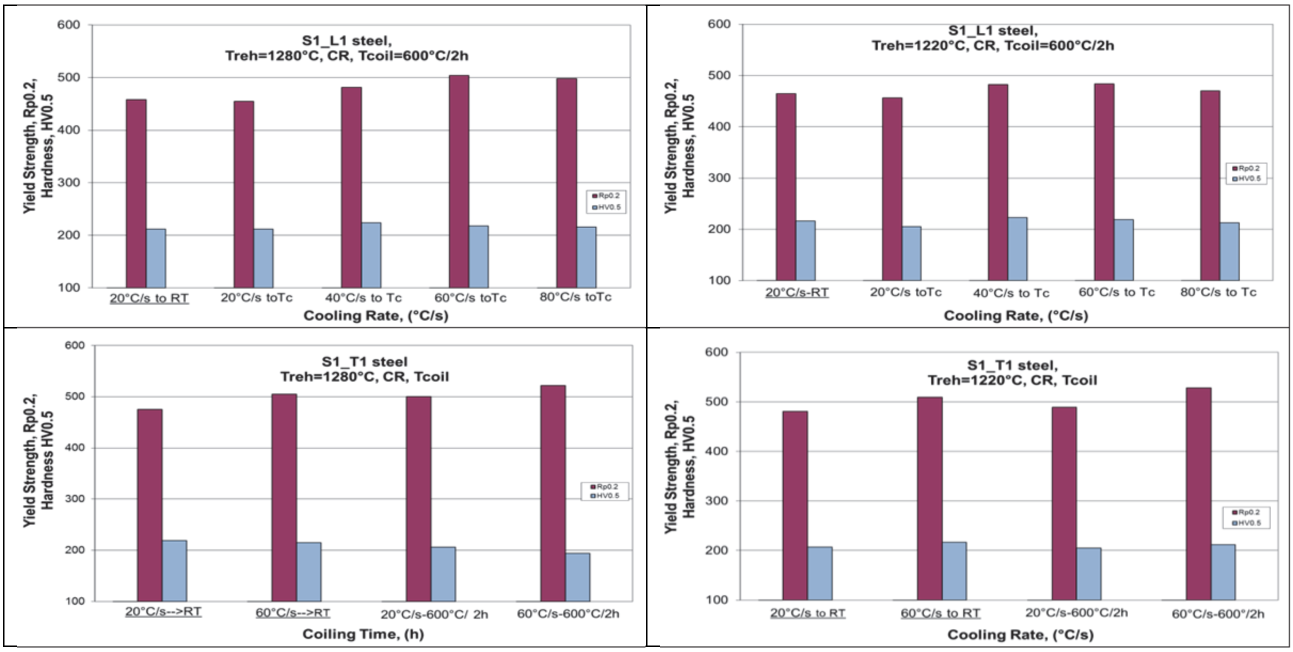


Fig. 2 Mechanical properties of simulated strip steel S1 after reheating at 1280°C and 1220°C, hot rolling followed by various cooling rates to RT or after coiling at 600°C; (a, b) for longitudinal and (c, d) for transverse direction.

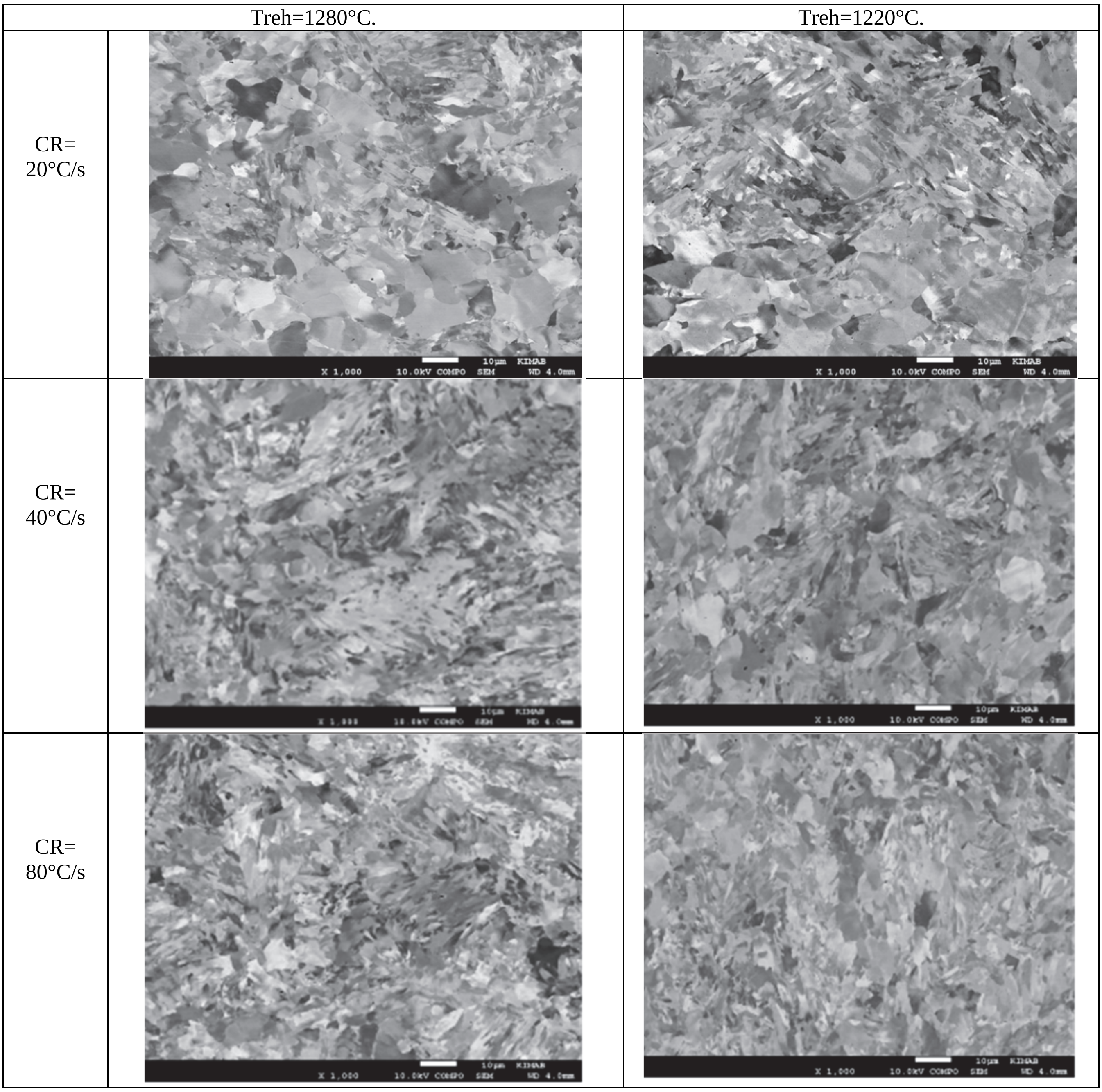


Fig. 3. Microstructure in simulated strip of steel S1 after reheating at 1280°C and 1220°C, then hot compression followed by various cooling rates to the coiling temperature of 600°C.

The effect of holding time at coiling temperature has also been studied and the results for steel S1_L1 and S1_T1 are presented in Fig. 4 with their respective microstructures in Fig. 5. Fig. 4a shows that the yield strength and hardness were quite equal (~460MPa) for both simulated specimens with Treh of 1280°Cand cooling rate of 20°C/s to RT or to coiling temperature of 600°C for 2h, whereas the highest Rp0.2 of ~490MPa and hardness ~220HV0.5 was obtained for 5 h holding time at 600°C for this steel. Higher yield strength and hardness in this specimen can be explained by a higher volume fraction of small precipitates that increases the precipitation strengthening effect of NbCN after the longer coiling time of 5h.

Fig. 4c and 4d show effect of Treh (1220° and 1280°C), cooling rate (20°C/s and 60°C/s) and holding time at lower coiling temperature of 550°C for steel S1_T1, in transverse specimens. The effect of cooling rate to 550°C on yield stress is greater than that of holding time in this case.

The yield stress, hardness and microstructure in **S2** steel with the lower Nb content (0.06C-0.6Mn-0.02Nb), reheated at 1280°C and 1220°C, strip rolling simulated with 3 deformations followed by various cooling rates to RT and to coiling temperature of 600°C are shown in Figs. 6, 7 and 8 for the specimens in the longitudinal and transverse directions.

As shown in Fig. 6 the yield stress Rp0.2 was in the range 350 to 400 MPa for both applied reheating temperatures and cooling rates. However, higher values of yield strength were obtained for lower Treh of 1220°C.

Results for transverse direction tests of steel S2_T1 presented in Fig. 7 show that the yield strength and hardness are higher (> 420 MPa) than for specimens in the longitudinal direction S2_L1 when processed in the same manner (Fig. 6).

The microstructure in these specimens changed from polygonal ferrite and high density ferrite / bainite to bainitic structure with variable substructure in the specimen cooled at 20°C/s to 600°C, as shown in Fig. 8. It was difficult to recognise very detailed variation of microstructure after high cooling rate (>40°C/s) that might affect the yield stress for either of the applied reheating temperatures and especially between specimens in the transverse and longitudinal directions. However, it was observed some precipitates and pearlitic microstructure in the transverse-T specimens that could increase the yield strength as shown in Fig. 7.

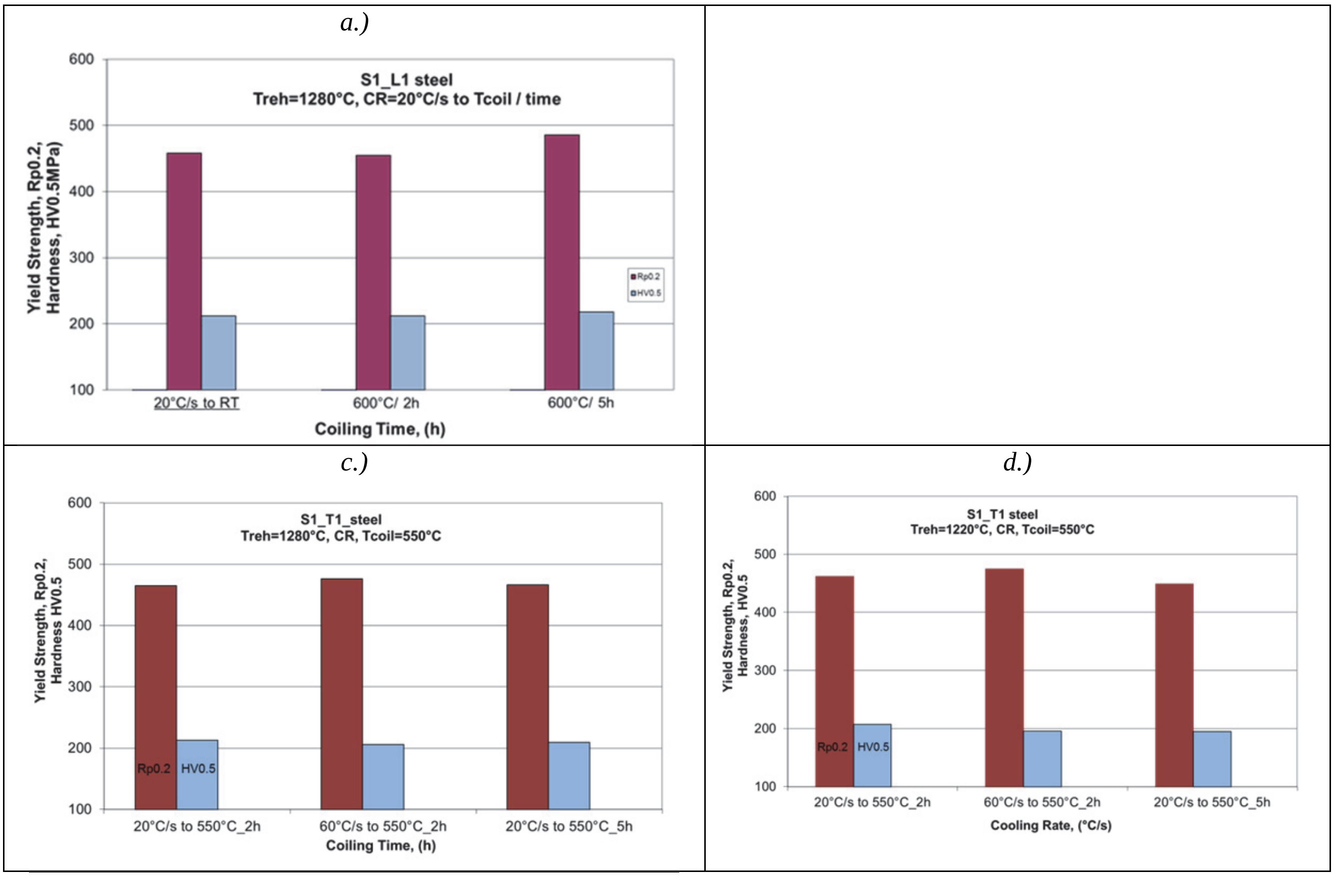


Fig. 4 Mechanical properties of simulated strip steel S1 after reheating at 1280°C and 1220°C, hot deformed, followed by cooling at 20°C/s to various coiling temperature (600°C or 550°C) and holding times (2h or 5h); (a) for longitudinal-L and (c, d) for transverse-T direction.

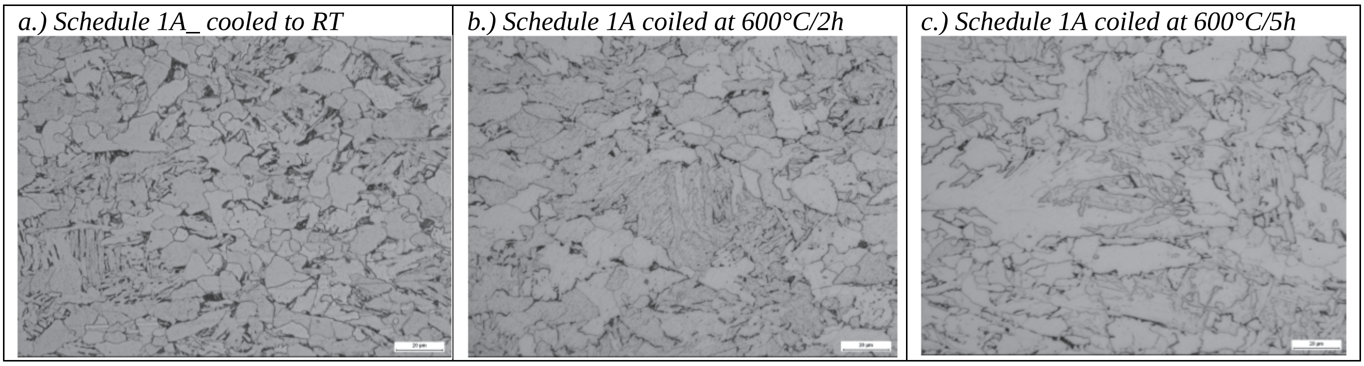

a.) Schedule 1A_ cooled to RT | *b.) Schedule 1A coiled at 600°C/2h* | *c.) Schedule 1A coiled at 600°C/5h*

Fig. 5 Optical microstructures in steel S1_L1 simulated with 3 deformations and cooled to RT (a), to Tcoil at 600°C for 2h (b) and to Tcoil at 600°C/5h (c). Magnification 500x
(Schedule:1280 ℃/3min →(CR=2 ℃/s) →1150 ℃/20% →1050 ℃/20% →890 ℃/20% →870°C(20 ℃/s) →RT or to Tcoil)

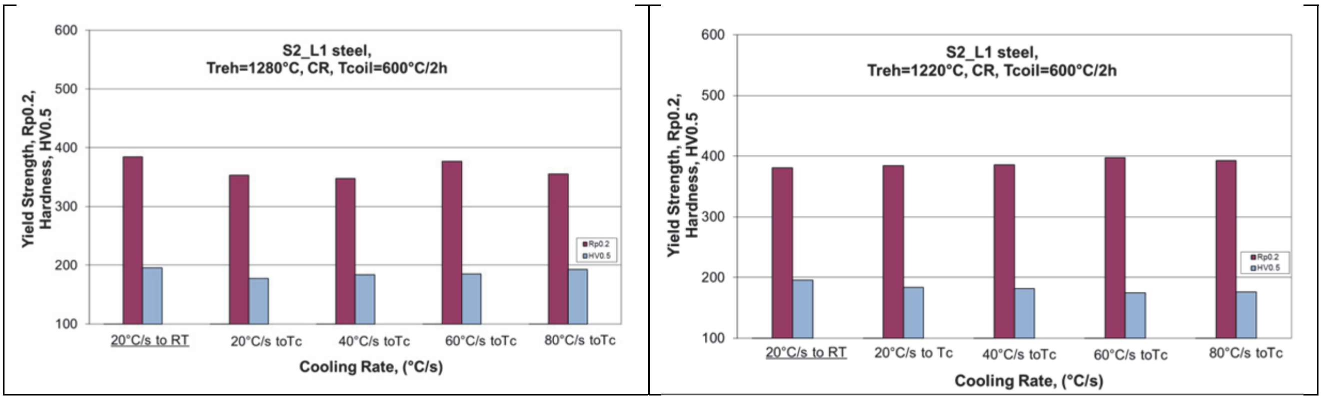


Fig. 6 Mechanical properties of simulated strip steel S2 after reheating at 1280°C and 1220°C, hot deformed, followed by various cooling rates to RT and to coiling temperature of 600°C for longitudinal-L direction.

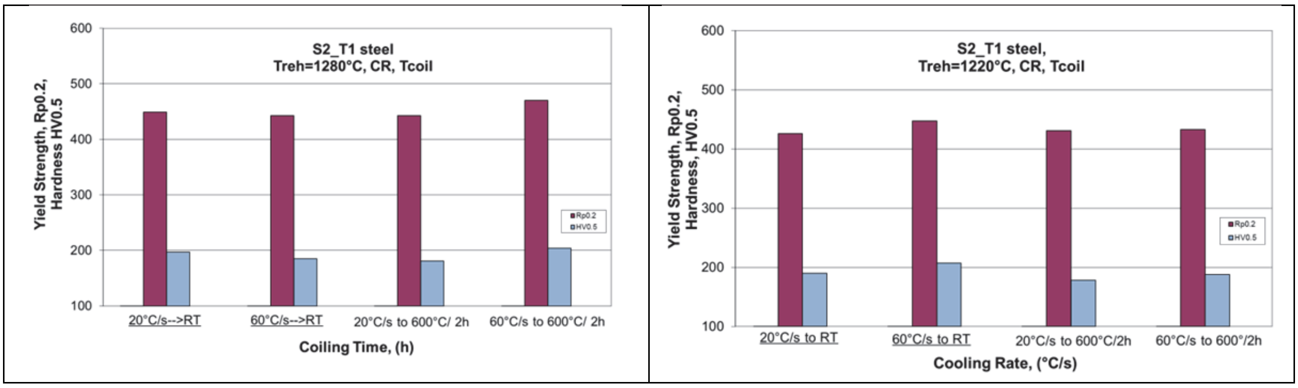


Fig. 7 Mechanical properties of simulated strip steel S2 after reheating at 1280°C and 1220°C, hot deformed, followed by cooling rates of 20°C/s and 60°C/s to RT and the coiling temperature of 600°C; for transverse-T direction.

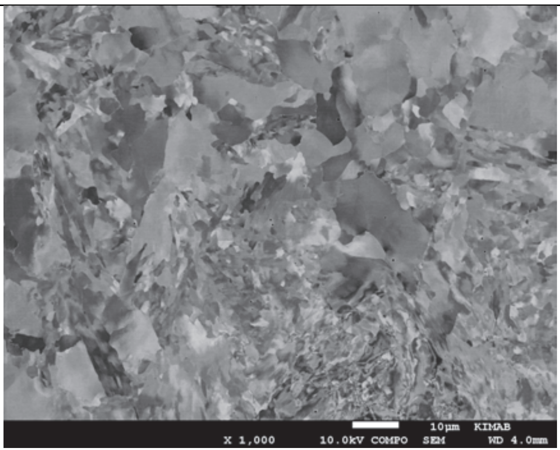
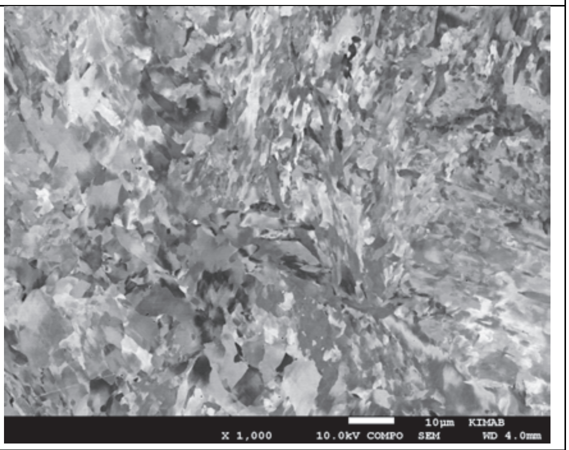
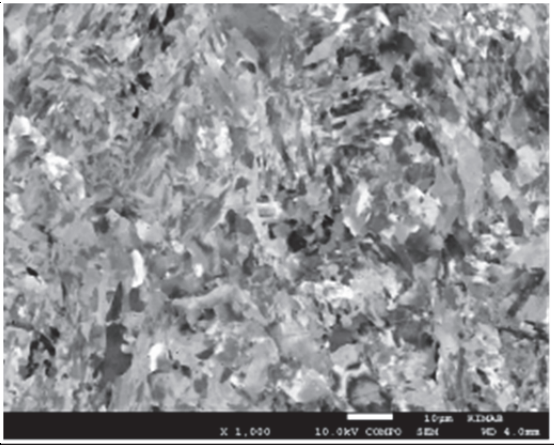
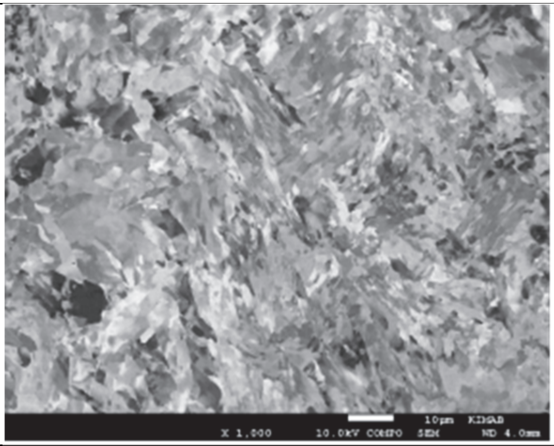
	Treh=1280°C	Treh=1220°C
CR= 20°C/s		
CR= 80°C/s		

Fig. 8. Microstructures in simulated strips of steel S2 after reheating at 1280°C and 1220°C, hot compression, followed by various cooling rates to the coiling temperature of 600°C.

The best results with yield stresses over 500 MPa and hardness over 230 HV0.5 were obtained for strip rolling simulated specimens of **S3** steel with the higher Mn and Nb contents (0.06C-1.36Mn-0.055Nb). The effect of reheating temperature, cooling rate, coiling temperature (600° and 550°C) and holding time on the yield strength, hardness and microstructure are shown in Figs. 9, 10, 11 and 12, for specimens in the longitudinal and transverse directions.

Figs 9 and 10 show that the yield strength and hardness are almost independent of reheating temperature, cooling rate and holding time at 600°C. Similarly, there is only a little effect of specimen position (longitudinal or transverse) on the strength and hardness of S3 steel.

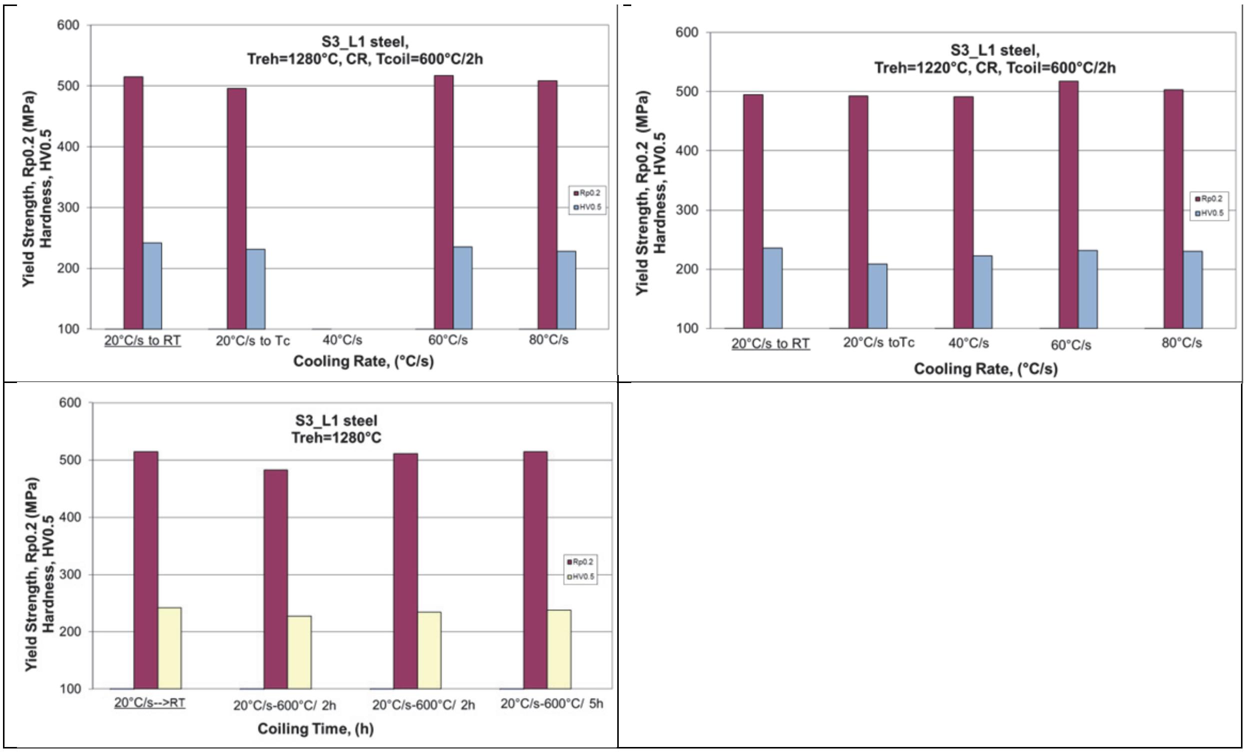


Fig. 9 Mechanical properties of simulated strip steel S3 after reheating at 1280°C and 1220°C, hot compression, followed by various cooling rates to RT and to the coiling temperature and time at 600°C for longitudinal-L direction.

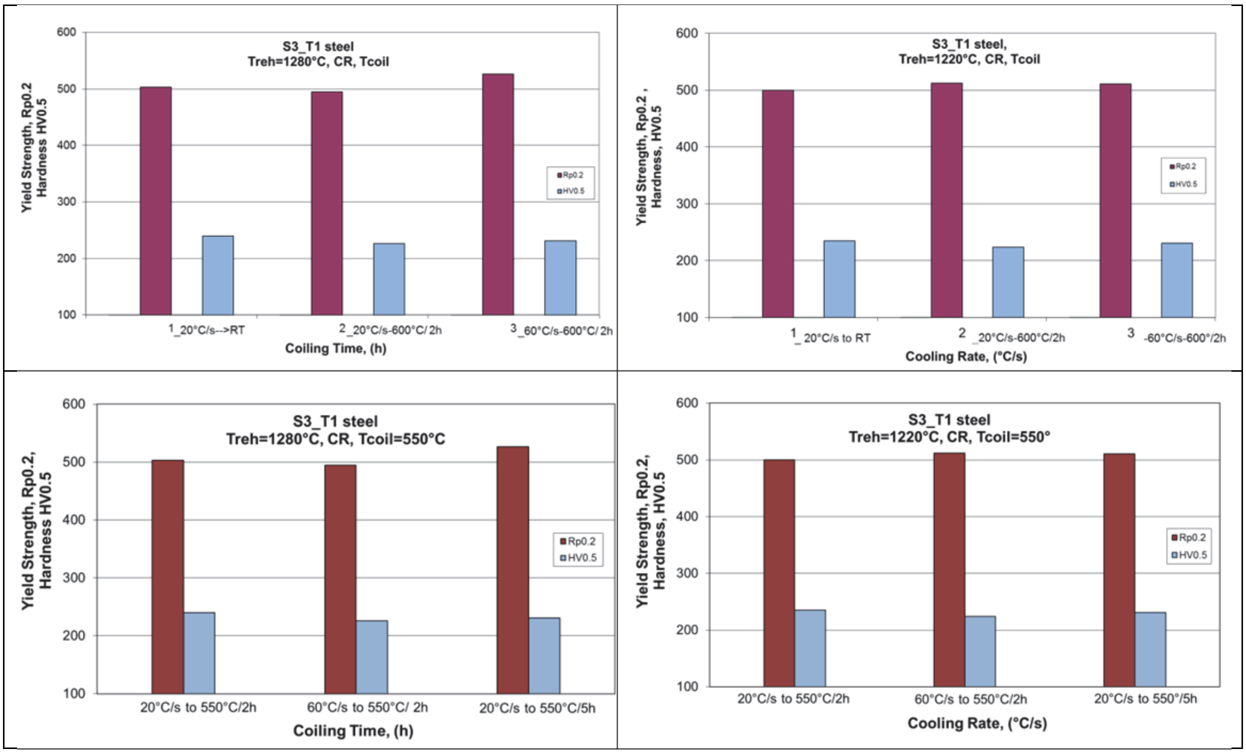


Fig. 10 Mechanical properties of simulated strip steel S3 for transverse-T direction after reheating at 1280°C and 1220°C, hot compression, followed by cooling rates of 20°C/s and 60°C/s to RT and to coiling temperatures of 600°C (a, b) and 550°C (c, d) with different holding times.

Microstructure in these specimens consisted mostly of high density ferrite / bainite and very fine polygonal ferrite. The grain size of ferrite and substructure density in the bainite changed with increasing cooling rate from 20°C/s to 80°C/s to coiling temperature of 600°C, see Fig. 11. As shown in Fig. 12, small ferrite grains and grain boundary carbides were sometime observed in the specimens after reheating at both 1220°C and 1280°C and for various cooling rates to Tcoil of 600°C. It was difficult to identified variations in the microstructure that affect yield strength and hardness after the applied cooling rates or between the transverse and longitudinal direction tests.

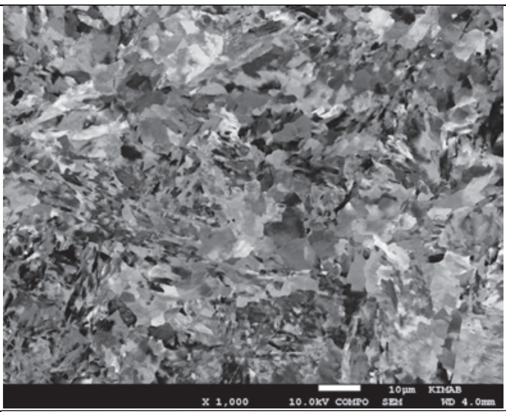
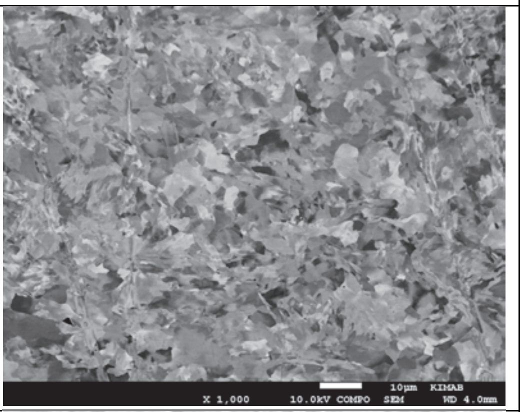
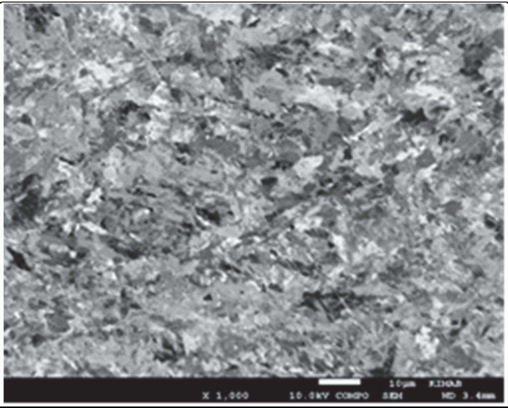
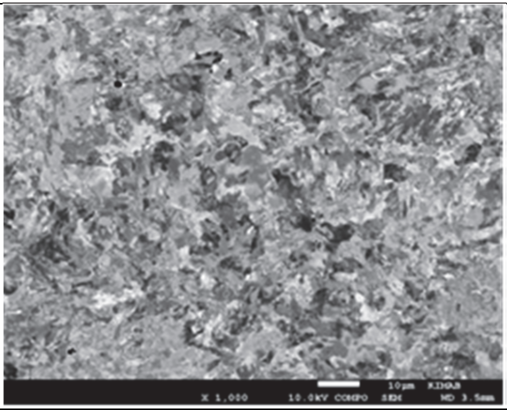
	Treh=1280°C	Treh=1220°C
CR= 20°C/s		
CR= 80°C/s		

Fig. 11 Microstructures in simulated strip of steel S3 after reheating at 1280°C and 1220°C, hot compression followed by various cooling rate to the coiling temperature of 600°C.

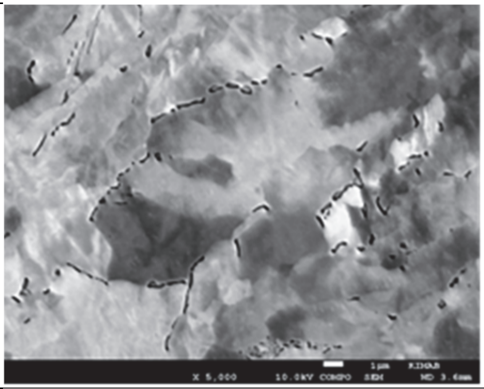
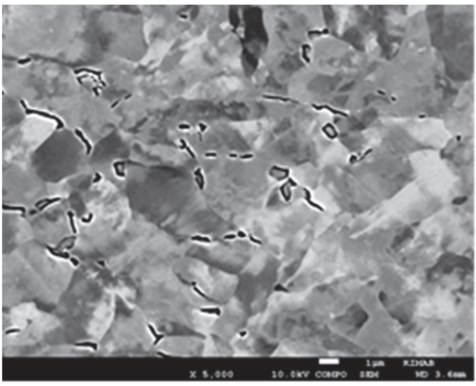
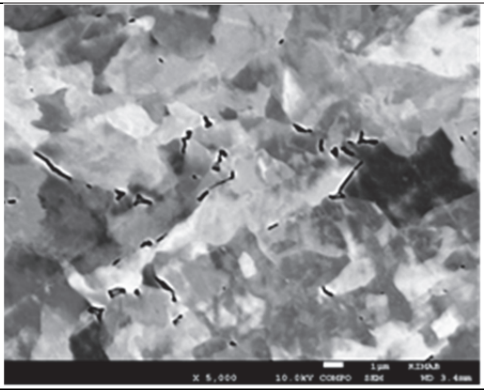
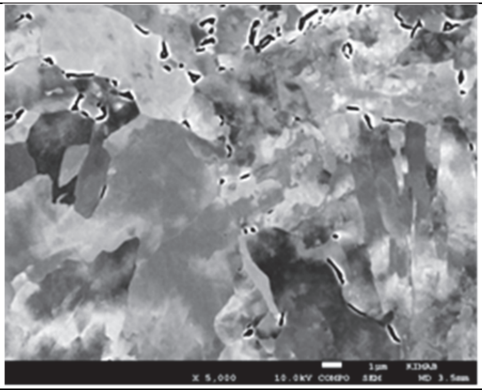
	Treh=1280°C/20% at 1150°C & Td →CR to 600°C.	*1220°C/20% at 1005°C & Td →CR to 600°C.*
CR= 20°C/s		
CR= 80°C/s		

Fig. 12 Microstructures in strip steels S3 simulated with 3 deformations after reheating at 1280°C or 1220°C, hot rolling and cooling at various rates to the coiling temperature of 600°C.

4.1.3 Transmission electron microscopy (TEM) analysis of precipitates in strips.

TEM examination of precipitates has been carried out on strip steel microalloyed with 0.05%Nb and various Mn content, 0.6% and 1.33%, in steels S1 and S3, respectively, using carbon extraction replicas. The particle size and composition of precipitates have been determined and the results for both steels are shown in Table 4 and Fig. 13. Some NbCN particles were observed at grain boundaries and probably some particles precipitated during hot rolling, but most of them have been precipitated during the coiling treatment. The size of particles determined in this study using TEM was in the range of 5 – 50nm.

Table 4. Particle size and composition of precipitates in steel S1_ L1(0.6Mn-0.052Nb) and S3_ L1(1.3Mn-0.05Nb) after Treh=1220°C→ (TMCP/60°C/s → 600°C/2h.

S1 steel		S3 steel	
type	size range (nm)	type	size range (nm)
Nb	30-50, cluster	Nb	10 - 30
Nb Ti	25-50	Nb Ti	50
Nb (Ti)	25-50		
Nb Al	20-30		

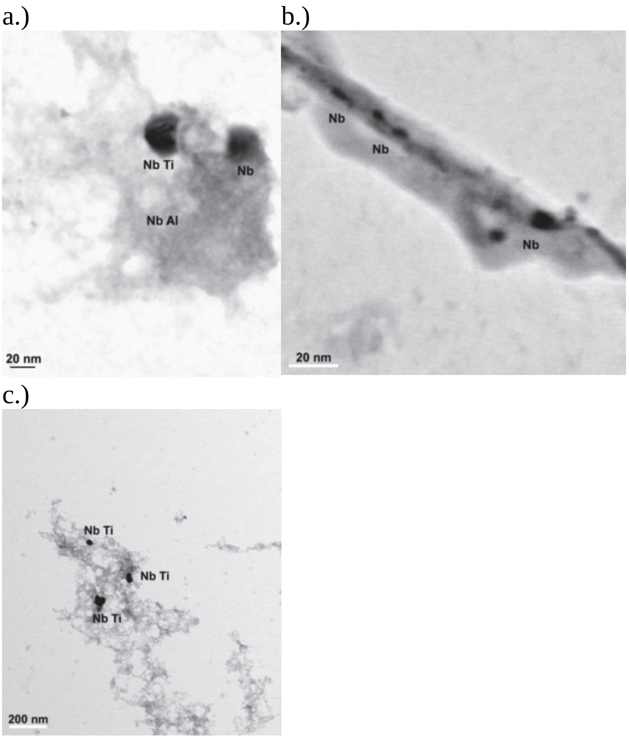


Fig. 13 Precipitates in the microstructure of simulated strip of steels S1 (a) and S3 (b, c) after reheating at 1220°C, hot compression, followed by cooling at 60°C/s to the coiling temperature of 600°C and holding 2h.

4.1.4 Mechanical properties and microstructures of fully scale processed strips.

The results of full scale processed steels S1_FS and S2_FS are presented in Fig. 14. A yield stress of 480MPa and hardness of 175HV0.5 were obtained for steel S1_FS reheated at 1270°C. The yield stresses were 400-410MPa and hardness values 154-156HV0.5 for steel S2_FS1 and S2_FS2, reheated at 1270° and 1220°C, respectively.

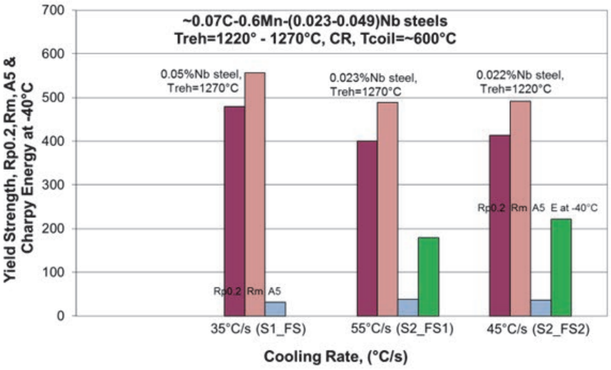
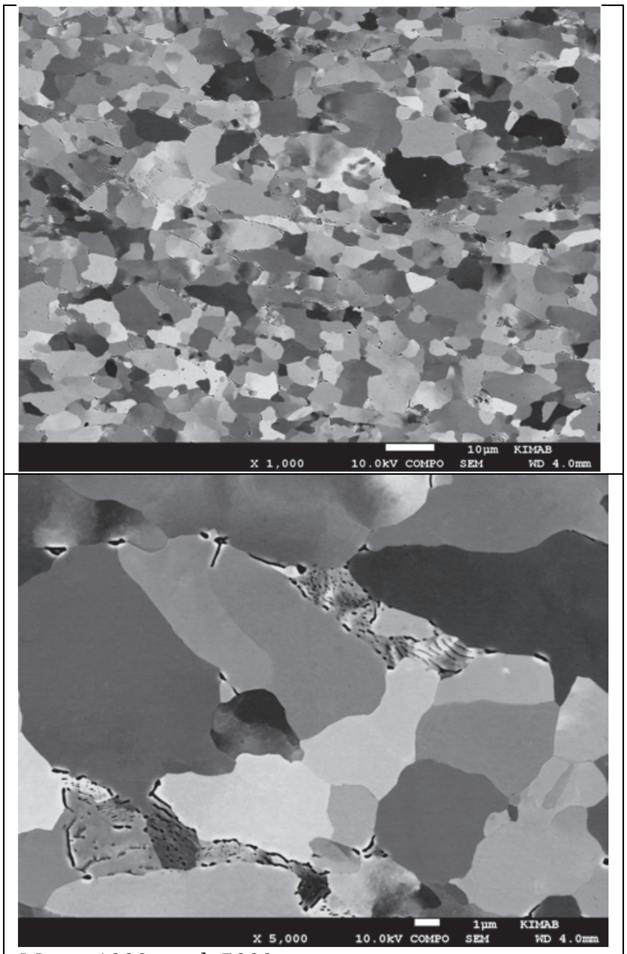


Fig. 14 Mechanical properties of full scale processed strip steel S1_FS and S2_FS for various Treh=1220-1270°C and cooling rates of 35-55°C/s to Tcoil of 600°C (specimens in longitudinal direction).

Examples of the microstructures observed in the specimen of steel S1_FS are shown in Fig. 15. Small and uniform ferrite/bainite structures are present with some grain boundary carbides as well as pearlite seen at the higher magnification, 5000x.

It is important to pointed out that the microstructure in full scale hot rolled strip was usually much more refined than the laboratory scale simulated strip rolling, and moreover, more cementite or grain boundary precipitates as well as more perlitic structure was observed in full scale processed strip steel.



Magn. 1000x and 5000x

Fig. 15 Microstructure of full scale strip steel S1_FS (longitudinal direction) for Treh=1270°C, rolling and cooling at 35°C/s to 600°C.

4.2 Hot rolling simulation of heavy plates.

Microstructure evolution and mechanical properties have been studied during hot rolling of plate steels P1 and P2 from the 280mm thick slab to heavy plate (>60mm) after reheating at low and high temperatures followed by three reductions by 8% or 15%, and cooling to RT at 0.2°C/s or DQ. The results of austenite grain size and the final microstructure as well as the yield strength and hardness for the present steels P1 and P2 are presented in this chapter.

4.2.1 ThermoCalc predictions for plate steels.

ThermoCalc calculations of equilibrium precipitation / dissolution of M(C, N) in the present steels, alloyed and microalloyed with Cr-Mo-Ti-V-Nb-B (P1) and Cr-Mo-Al-V-Nb-B (P2) are show in Fig. 16a and 16b, respectively. These were used for prediction of possible low reheating temperatures that may be applied for TMCP processing of heavy plate.

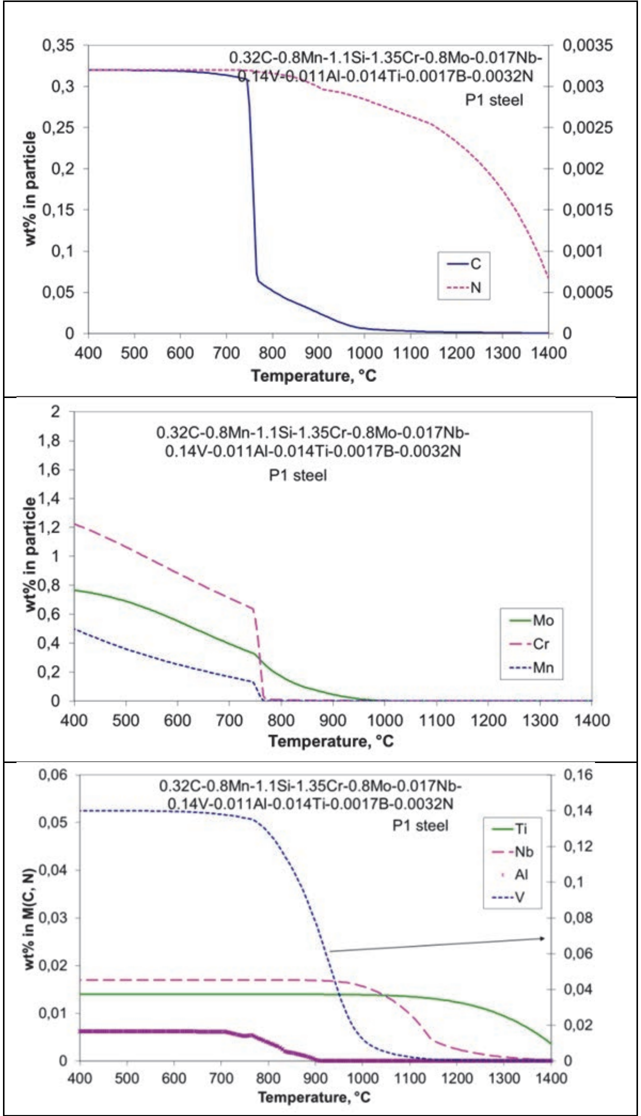


Fig. 16a. ThermoCalc predictions of equilibrium precipitation/dissolution of M(C, N) in steel P1.

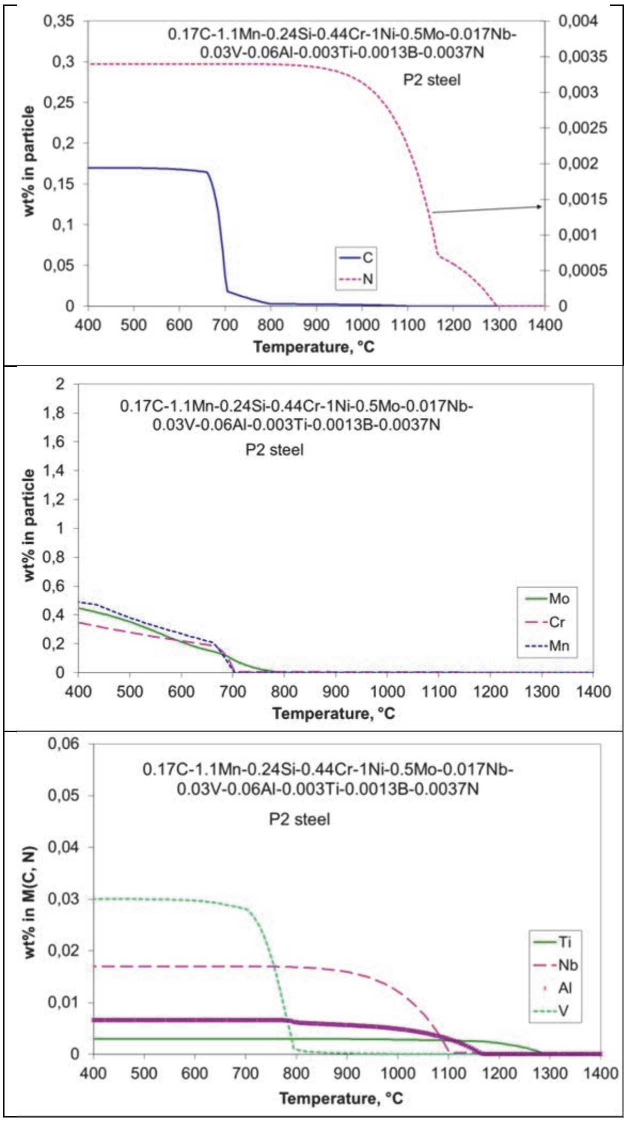


Fig. 16b. ThermoCalc predictions of equilibrium precipitation/dissolution of M(C, N) in steel P2.

4.2.2 Austenite grain size after reheating and TMCP simulations

Austenite grain sizes in steels P1 and P2 were determined after reheating at 1240°C or 1160°C and in connection with hot rolling simulation. Each step of TMCP simulation has been interrupted by gas quenching for analysis of the austenite evolution. The results of analyses are shown in Figs. 17 and 18 as well as in Tables 5, 6 and 7. Much smaller austenite grain sizes were observed in both study steels after reheating at 1160°C in comparison to 1240°C.

As shown in Fig. 17 and Table 5, higher reductions affect refinement of the austenite in steel P1 for both applied reheating temperatures. The smallest austenite grains (<40µm) were observed in the steel P1 reheated at 1160°C and deformed 15% three times, whereas the smallest austenite grains were about 85µm in this steel when reheated at 1240°C with similar 3 deformations of 15%. As shown in Fig. 17, there are only very small differences in the austenite grain sizes in the specimens machined from ¼ thickness and surface positions of the slab when heat treated and hot rolling simulated in the same manner. However, larger differences were observed between these results and results for the specimens through the thickness, especially when deformed 3 times by 15%.

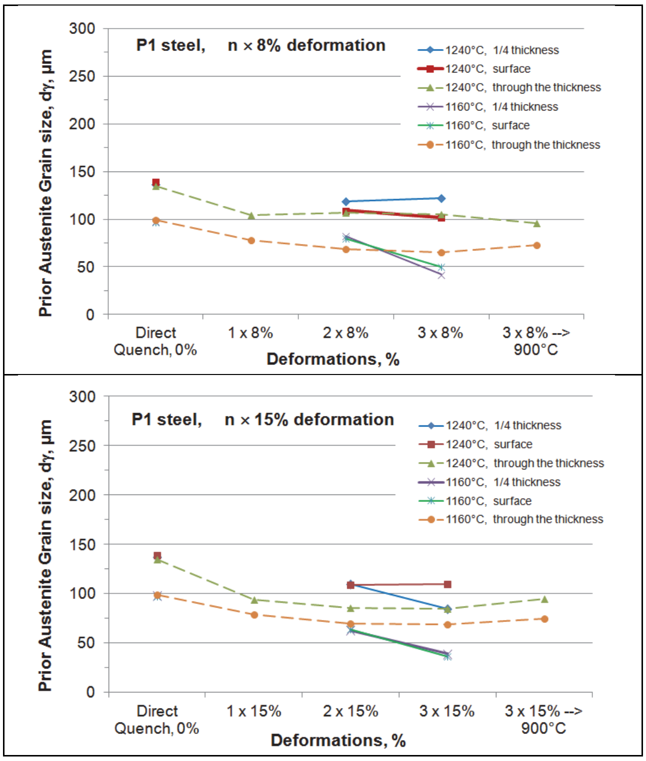


Fig.17. Measured austenite grain sizes at the surface and the ¼ thickness positions in steel P1 after reheating at 1240°C or 1160°C, followed by direct quenching and by hot rolling simulation with one, two or three deformations of 8% (a) and 15% (b), followed by gas quenching.

Table 5. Measured austenite grain sizes in steel P1 after reheating at 1240°C or 1160°C and hot rolling simulation with one, two or three deformations of 8% or 15%, followed by gas quenching.

P1 steel						
Processing from 1240°C	1240°C_dγ= 137 µm		1240°C_dγ= 139 µm		1240°C_dγ = 135 µm	
	specimen located at 1/4 thickness		specimen located at surface		through the thickness	
	8% deformed (centre condition)	15% deformed (surface condition)	8% deformed (centre condition)	15% deformed (surface condition)	8% deformed (centre condition)	15% deformed (surface condition)
	mean (µm)	mean (µm)	mean (µm)	mean (µm)	mean (µm)	mean (µm)
1 def--	-	-	-	-	104	94
2 def--	119	110	109	109	107	86
3def--	122	85	102	110	105	85
3def --> 900°C	-	-	-	-	96	95

P1 steel						
Processing from 1160°C	1160°C_dγ = 98 µm		1160°C_dγ = 97 µm		1160°C_dγ = 99 µm	
	specimen located at 1/4 thickness		specimen located at surface		through the thickness	
	8% deformed (centre condition)	15% deformed (surface condition)	8% deformed (centre condition)	15% deformed (surface condition)	8% deformed (centre condition)	15% deformed (surface condition)
	mean (µm)	mean (µm)	mean (µm)	mean (µm)	mean (µm)	mean (µm)
1 def--	-	-	-	-	78	79
2 def--	82	63	80	64	69	70
3def--	42	39	50	36	65	69
3def --> 900°C	-	-	-	-	73	75

Austenite grain sizes in steel P2 have also been determined after reheating at 1240°C or 1160°C in connection with hot rolling simulation for the specimens machined from the ¼ thickness and the surface positions of slab. Each step of TMCP simulation was interrupted by gas quenching for analyses of the austenite evolution.

The results of austenite grain size analyses are shown partly in Table 6 and Fig. 18. The smallest austenite grain ~50µm was observed in the specimens reheated at 1160°C and deformed 3 times by 15%. Some grain growth of the austenite grains was observed in the specimens reheated at 1160° and 1240°C following 3 deformations of 8% and then cooling down to 900°C (see Fig. 18a).

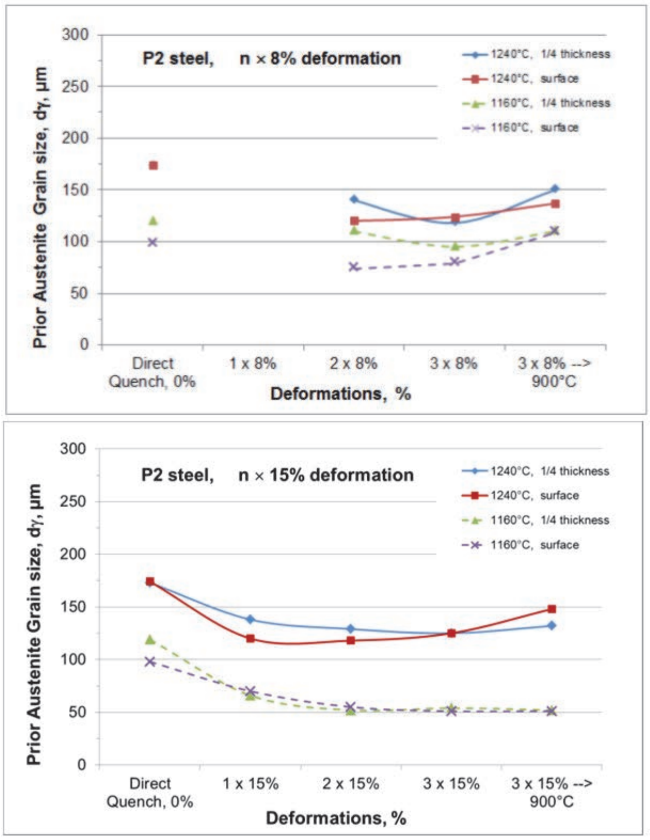


Fig.18. Measured austenite grain sizes at the surface and the ¼ thickness positions in steel P2 after reheating at 1240°C or 1160°C followed by direct quenching and by hot rolling simulation with one, two or three deformations of 8% (a) and 15% (b), followed by gas quenching.

Table 6. Measured austenite grain sizes in steel P2 after reheating at 1240°C or 1160°C and TMCP simulation with one, two or three deformations of 8% or 15%, followed by gas quenching.

P2 steel				
Processing from 1240°C	1240°C_dγ = 173 µm		1240°C_dγ = 174 µm	
	specimen located at 1/4 thickness		specimen located at surface	
	8% deformed (centre condition)	15% deformed (surface condition)	8% deformed (centre condition)	15% deformed (surface condition)
	mean (µm)	mean (µm)	mean (µm)	mean (µm)
1 def--	-	138	-	120
2 def--	140	129	120	118
3def--	118	125	124	125
3def --> 900°C	150	132	137	148

P2 steel				
Processing from 1160°C	1160°C_dγ = 119 µm		1160°C_dγ = 98 µm	
	specimen located at 1/4 thickness		specimen located at surface	
	8% deformed (centre condition)	15% deformed (surface condition)	8% deformed (centre condition)	15% deformed (surface condition)
	mean (µm)	mean (µm)	mean (µm)	mean (µm)
1 def--	-	66	-	70
2 def--	110	52	74	55
3def--	95	54	79	51
3def --> 900°C	110	52	109	51

It was important to compare the austenite grain sizes in steels P1 and P2 that has been determined after reheating at 1240°C or 1160°C and in connection with hot rolling simulation. Some variation was observed in the initial austenite grain sizes in specimens of steel P1 and P2, reheated at both temperatures. For Treh of 1160°C grain sizes were 98µm and 119µm, whereas for 1240°C these were 137µm and 173µm, for steel P1 and P2 respectively for specimens located at ¼ thicknesses,.

Detailed results of austenite grain sizes for both steels and from both positions (¼ thickness and at surface) are shown in Table 7 after hot rolling simulated in similar manners with 8% and 15% deformations.

Table 7. Measured austenite grain sizes in steels P1 and P2 after reheating at 1240°C or 1160°C and hot rolling simulation, followed by gas quenching.

Steel	1240°C				1240°C			
	specimen located at 1/4 thickness				specimen located at surface			
	8% deformed (centre condition)		15% deformed (surface condition)		8% deformed (centre condition)		15% deformed (surface condition)	
	mean (µm)	± *	mean (µm)	± *	mean (µm)	± *	mean (µm)	± *
P1	121,5	18,3	82,4	6,8	102,3	12,3	102,8	10,9
P2	117,7	6,7	125,1	8,0	123,9	7,2	124,7	6,9

Steel	1160°C				1160°C			
	specimen located at 1/4 thickness				specimen located at surface			
	8% deformed (centre condition)		15% deformed (surface condition)		8% deformed (centre condition)		15% deformed (surface condition)	
	mean (µm)	± *	mean (µm)	± *	mean (µm)	± *	mean (µm)	± *
P1	42,1	3,4	39,0	2,4	50,1	5,5	36,1	2,3
P2	95,3	5,3	104,2	3,7	79,0	3,2	95,6	3,0

* 95 % confidence interval for the mean austenite grain size, µm

As shown in Table 7 the austenite grain size of steel P1 after TMCP processing was usually smaller for both Treh temperatures (1160° and 1240°C) followed by deformation with different reductions, although after reheating at 1160°C the grain size for steel P1 was much smaller than for steel P2 after similar processing.

4.2.3 Mechanical properties and final microstructures after TMCP simulations

The results of yield stress, hardness and microstructure, obtained after heavy plate rolling simulation of P1 steel following reheating at 1240°C and 1160°C for the specimens at the surface and in the centre of the slab are shown in Fig. 19. As seen in Fig. 19a, the yield stress of steel P1 reheated at 1240°C and hot deformed 3 times with 15% strain was ≥ 1100MPa, whereas for specimens deformed by 8% the yield stresses were lower by ~100MPa. Much smaller differences were observed for specimens reheated at 1160° after similar processing. However, higher yield stresses and hardness were obtained in the steel P1 reheated at 1160°C and TMCP processed, as shown in Fig. 19 a and b.

Examples of the final microstructure in this steel reheated at both temperatures and simulated hot working with both applied deformations, followed by air cooling to RT are shown in Fig. 20. It is very difficult to distinguish differences in the final microstructure that consists of martensitic with hardness in the range 450-500HV1.

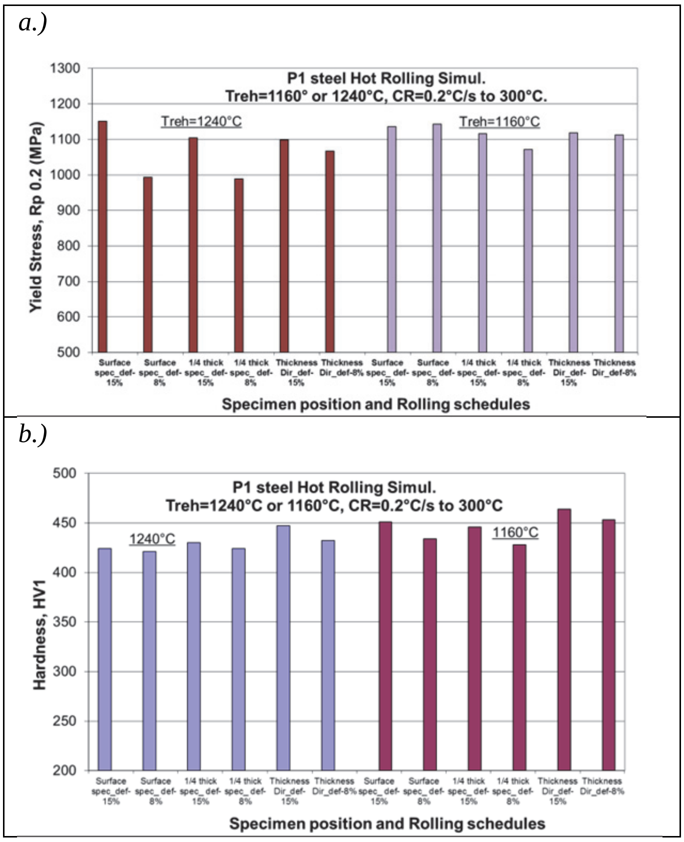


Fig.19 Yield stress (a) and hardness (b) of simulated heavy plate of steel P1 at the surface and ¼ thickness after TMCP simulation with Treh=1240°C and 1160°C followed by various deformations and then slowly cooled to RT.

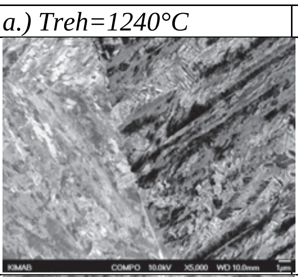
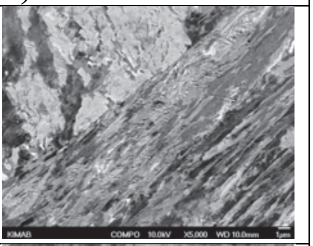
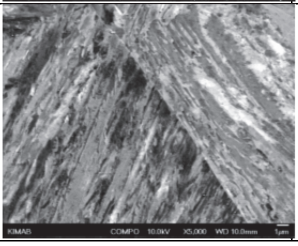
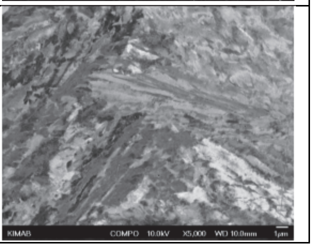
	a.) Treh=1240°C	*b.) Treh = 1160°C*
Red *8%*		
Red *15%*		

Fig. 20 Microstructures of simulated heavy plate rolling of steel P1 at ¼ thickness for Treh of 1240°C (a) and 1160°C (b) subsequently deformed by 8% or 15% several times followed by air cooling to RT.

The results of yield strength and hardness obtained for the steel P2 from specimens at the surface and the ¼ thickness of the slab after reheating at 1240°C and 1160°C with heavy plate rolling simulation are shown in Figs. 21 and 22, while microstructure in this steel simulated deformed as above with 8% and 15% followed by cooling at 0.2°C/s to RT are shown in Fig. 23.

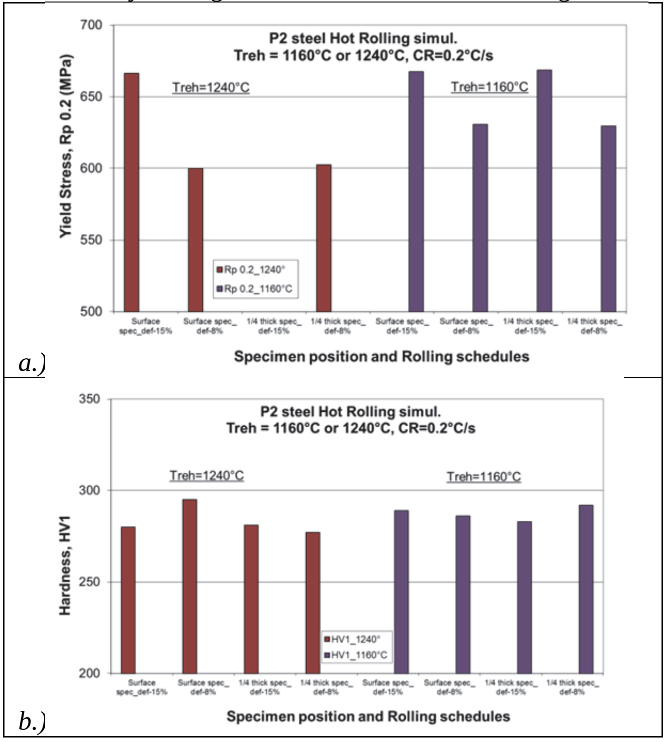


Fig.21 Yield stress (a) and hardness (b) of simulated heavy plate of steel P2 at the surface and ¼ thickness after TMCP simulation with Treh=1240°C or 1160°C, followed by various deformations (8% and 15%) and cooling at 0.2°C/s to RT.

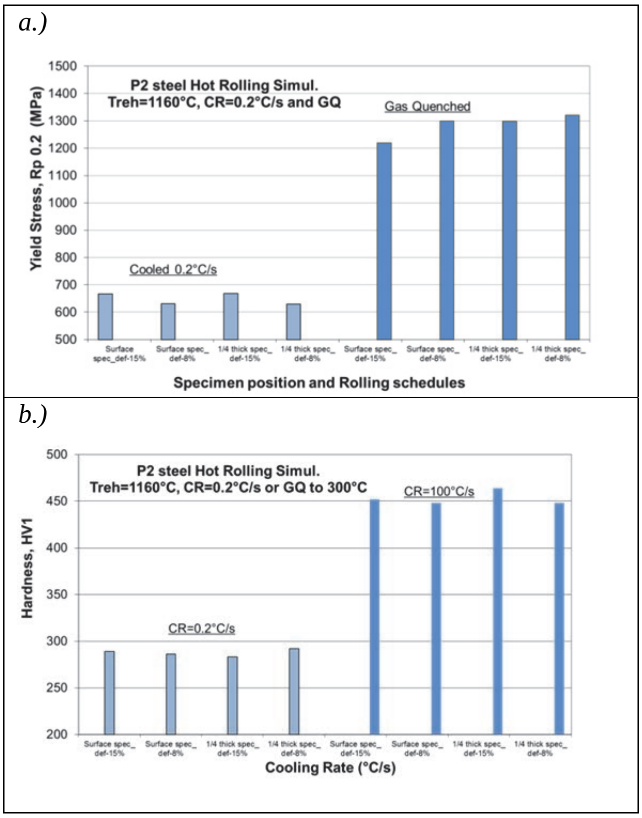
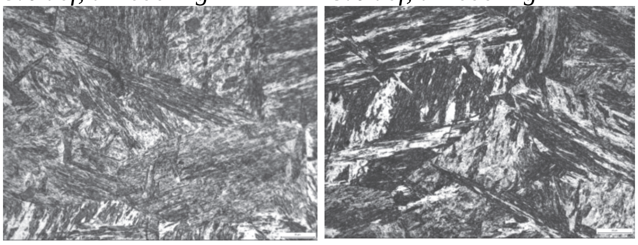


Fig.22 Yield stress (a) and hardness (b) of simulated heavy plate of steelP2 at the surface and ¼ thickness for TMCP simulation with Treh=1160°C, followed by various deformations (8% and 15%) and cooling (0.2°C/s or GQ) to RT.

The yield stress of specimens reheated at 1160° and 1240°C and hot deformed 3 times by 15% was over 670MPa whereas for specimens similarly heat treated but deformed by 8% they lay in the range of 600-630MPa. Hardness values of this steel for all processing conditions were in the interval 280 – 295HV1, as shown in Fig. 21.

Fig. 22 shows great variation of yield stress and hardness of steel P2 processed in the same manner but cooled in different ways. The yield stress and hardness after gas quenching following TMCP was much higher (1220-1300MPa, and ~450HV1) that for air cooling with 0.2°C/s (630-670MPa, and ~280HV1).

The microstructure of the P2 steel reheated at both temperatures with simulated TMCP with 8% and 15% deformations, followed by air cooling was usually bainitic, as shown in Fig. 23, whereas the microstructure of gas quenched specimens was martensitic with hardness about 450HV1.



a.) 1240°C-at ¼ thickness, 8% def, air cooling

b.)1160°C - ¼ thickness, 8% def, air cooling

c.) 1240°C at ¼ thickness, 15% def, air cooling

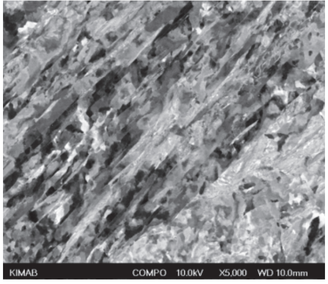


Fig. 23 Microstructure of heavy plate rolling simulated P2 steel at the ¼ thickness for Treh of 1240°C or 1160°) and deformations of 8% (a, b) and 15% (c).

4.2.4 Comparison of the mechanical properties and final microstructure after TMCP simulations

The examples of the results obtained after heavy plate rolling simulation of steels P1 and P2 with different reheating temperatures (1240°C and 1160^{0}C) and the respectively similar hot rolling and cooling schedules (see §3.2) are presented in the following figures 24-25.
As seen in Fig. 24, steel P1 shows much better yield strength (by 40-600MPa) and hardness (by 150-200HV1) properties than steel P2 after reheating, hot processing and gas quenching in the same manner.

Larger differences in the yield stress and hardness were observed for the steels P1 and P2 reheated at 1240°C and followed by air cooling, Rp0.2 by 400-500MPa and HV1 by ~150HV1, than for gas quenching, Rp0.2 by 100-200MPa and HV1 by ~20, respectively.

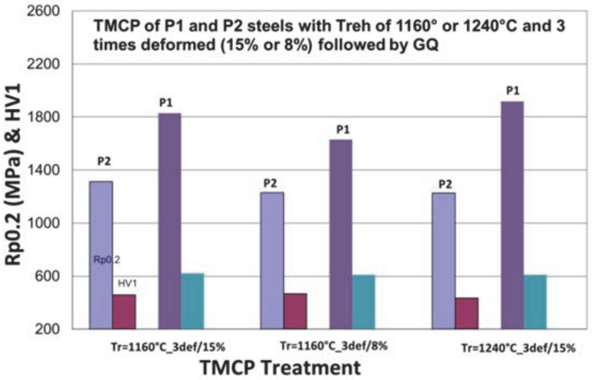
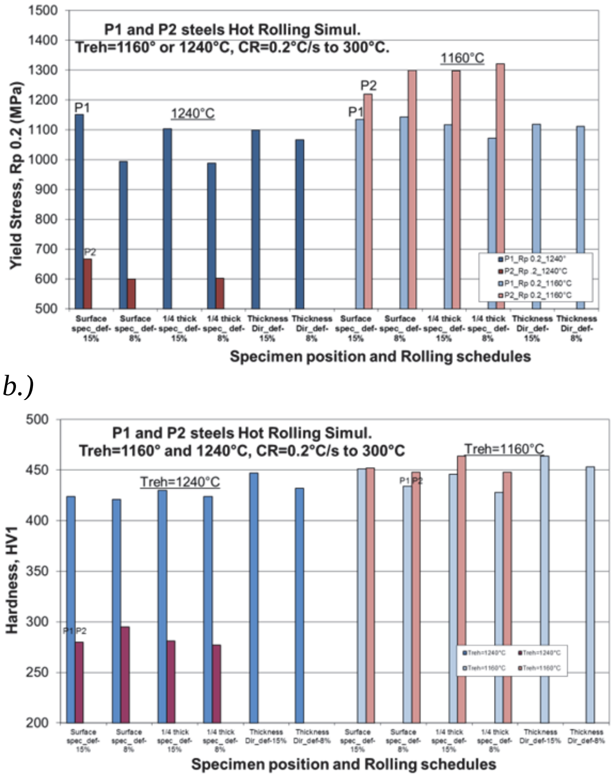


Fig.24 Yield stress and hardness of simulated heavy plates of steels P1 and P2 after TMCP simulation with Treh=1160°Cand 1240°C, followed by deformations of 8% and 15% and gas quenching(GQ) to RT. (-1160°C/5min_3def/1150°C/15%_10s-GQ; -1160°C/5min_3def_1160°C/8%_10s-GQ; -1240°C/5min_3def/1230°C/15%-10s_GQ)


a.)

b.)

Fig.25 Comparison of yield stress (a) and hardness (b) of simulated heavy plates of steels P1and P2(at surface and ¼ thickness) for TMCP simulation with Treh=1240°C and 1160°C followed by various deformations and slowly cooled to RT.

4.2.5 TEM analyses of precipitates in microstructures of TMCP plates.

Particle size distribution in the microstructure of steels P1 and P2 processed in the same manner were studied using the transmission electron microscope and carbon extraction replica technique.

The steels P1 and P2 were treated as follows; Treh=1160°C/TMCP-15%→CR=0.2°C/s→300°C and the results of particle size distributions and chemical compositions of precipitates are shown in Fig. 26 and Table 8.

Small NbC, (Nb,Ti)(C,N), (Ti,Nb,V)(C,N)particles and similar with Cr, Ni and Mo were observed in both steels. It was very difficult to distinguish any differences in chemistry between precipitates in steels P1 and P2. It would be necessary to make much more detailed TEM studies to clarify any differences but the financing of this project did not allow it.

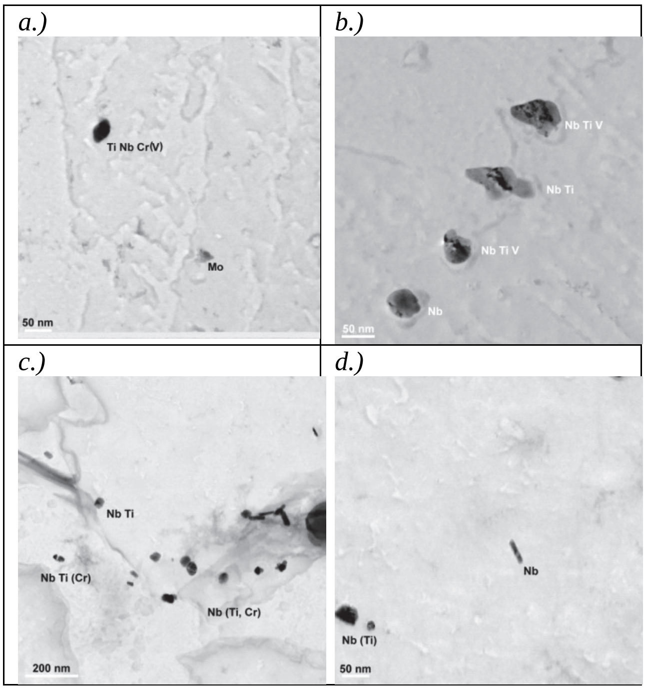


Fig. 26 Precipitates in the microstructure of simulated plates of steel P1 (a, b) and P2 (c, d) after reheating at 1160°C, TMCP processing with 15% reductions→ CR=0.2°C/s → 300°C→RT.

Table 8. Particle sizes and compositions of precipitates in steel P1 (0.32C-1.1Si-0.8Mn-1.35Cr-0.8Mo-Ti-0.14V-Nb-B) and P2 (0.172C-1.1Mn-1Ni-0.4Cr-0.5Mo-Al-V-Nb-B) after Treh= 1220°C → (TMCP/ 60°C/s → 600°C/2h.

P1 steel		**P2 steel**	
Type of precipitate	size range (nm)	Type of precipitate	size range (nm)
Nb	25	Nb Ti	50
Nb Ti	25	Nb (Ti)	50
Nb Ti V	25	Nb Ti (Cr)	50
Ti Nb Cr (V)	50	Nb (Ti,Cr)	50
low Cr	5-10	low Cr	5 -10
Mo	5-10	Mo	5-10
Mo Cr	10	Nb	25

4.2.6 Microstructure and mechanical properties after hardening treatment simulations

Quenching and tempering processes are important in the production of heavy plates of high strength steels. It has been shown in a previous study (7, 9, 15) that reheating temperature and a sufficiently high cooling rate are the most important factors of quenching process, which controls the transformation during quenching.

The effect of reheating temperature and cooling rate, on the yield stress and hardness has been studied for both steels P1 and P2, on the specimens from the ¼ thickness and at the surface of the slab. The results for reheating temperature in the range of 890° to 950°C and cooling rate during quenching in the interval 5°C/s – 25°C/s are show in Fig. 27 for both steels.

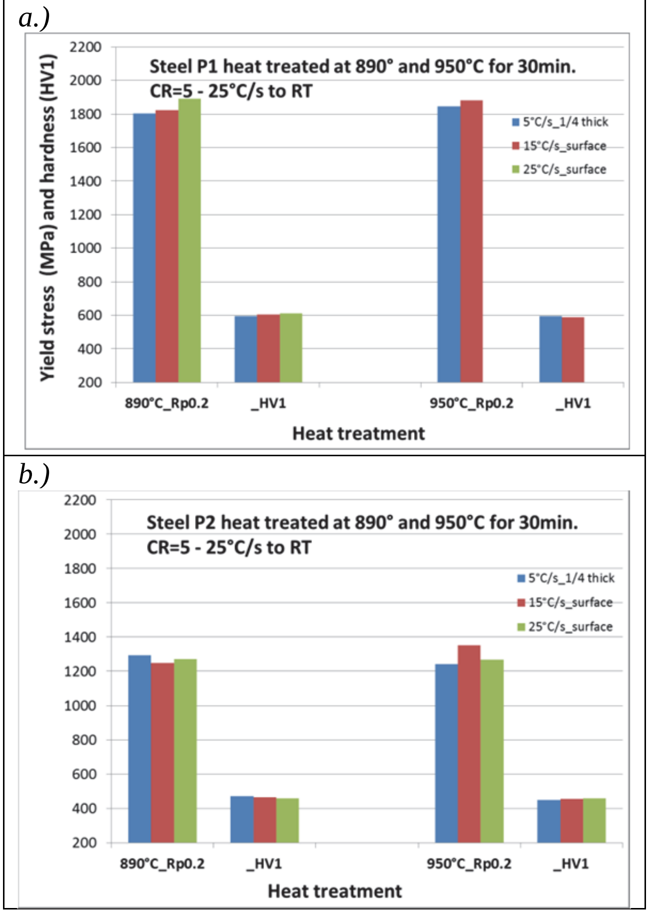


Fig. 27 Yield stress and hardness properties of simulated heavy plate hardening treatment for steels P1 (a) and P2 (b) at surface and ¼ thickness of slabs after 30min at Treh=890°C and 950°C followed by various cooling rates to RT.

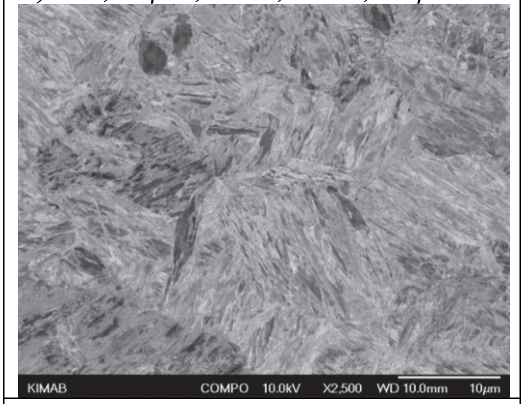
Table 9. Austenite grain sizes in steels P1 and P2(at surface and at ¼ thicknesses after heat treatment at various temperatures and for various cooling rates.

Cool Rate	Austenite grain size (µm) in **P1** steel			
	surface		1/4 thickness	
	Treh=890°C	950°C	890°C	950°C
5°C/s	-	-	13	18
25°C/s	15	17	-	-
	Austenite grain size (µm) in **P2** steel			
	surface		1/4 thickness	
	Treh=890°C	950°C	890°C	950°C
5°C/s	-	-	22	28
25°C/s	20	27	-	-

Yield stresses over 1800 MPa and hardness values of about 600HV1 were obtained for steel P1 (for ¼ thickness and surface specimens) quenched from both applied temperatures and quenching rates, whereas yield stresses in the range of 1250 – 1350MPa and hardness about 450HV1 were obtained for all specimens of steel P2 heat treated in the same manner.

The austenite grain sizes after some variants of reheat quenching and for both present steels are shown in Table 9. Some examples of the final microstructure of reheat quenched specimens are shown in Figs. 28 & 29.

a.) P1, surface, 890°C, 25°C/s, 15 µm



b.) P1, surface, 950°C, 15°C/s, 17 µm

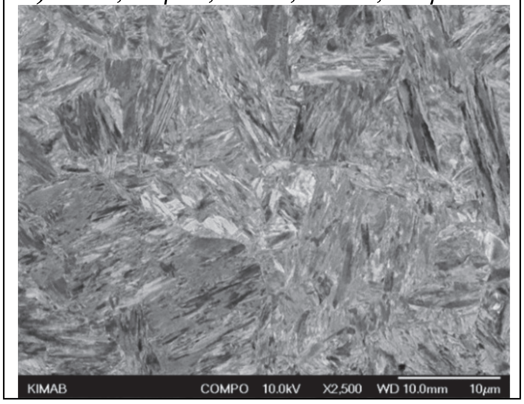
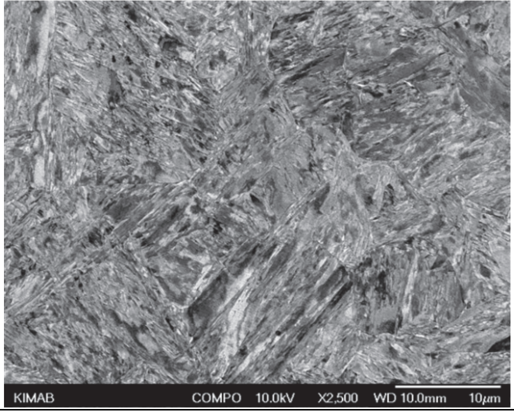


Fig. 28 Microstructure after simulated hardening of heavy plate P1 steel for 0.5h at Treh=890°C and 950°C followed by various cooling rates to RT. SEM, 2500x.

a.) P2, surface, 890°C, 25°C/s, 20 µm



b.) P2, surface, 950°C, 25°C/s, 27 µm

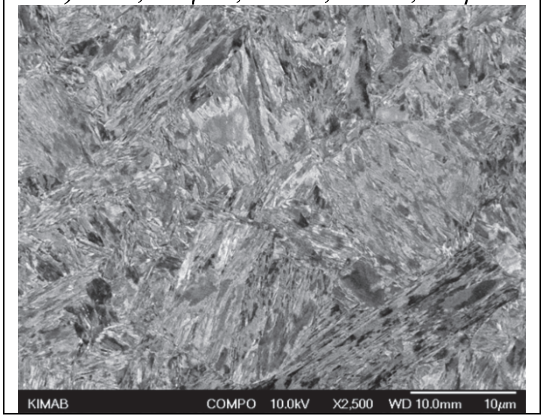


Fig. 29 Microstructure after simulated hardening of heavy plate steel P2 after 0.5h at Treh=890°C and 950°C followed by cooling at 25°C/s to RT. SEM, 2500x.

4.3 Hot rolling simulation of long products

High strength low carbon steel (0.05%C-1%Mn-4%Cr-0.06%Nb) type IMACRO EL700 with the yield stress of ~700MPa are very important long products. It was decided to carry out the investigation of the effect reheating, finish rolling temperature and cooling rate on the yield stress, hardness and microstructure of steel **L1**.

4.3.1 ThermoCalc calculations of equilibrium precipitation

ThermoCalc calculations of equilibrium precipitation / dissolution of M(C, N) in the present steels, (micro)alloyed with Cr-(Mo)-Al-Nb (L1), are shown in Fig. 30, and these have been used for prediction of possible low reheating temperatures that can be applied.

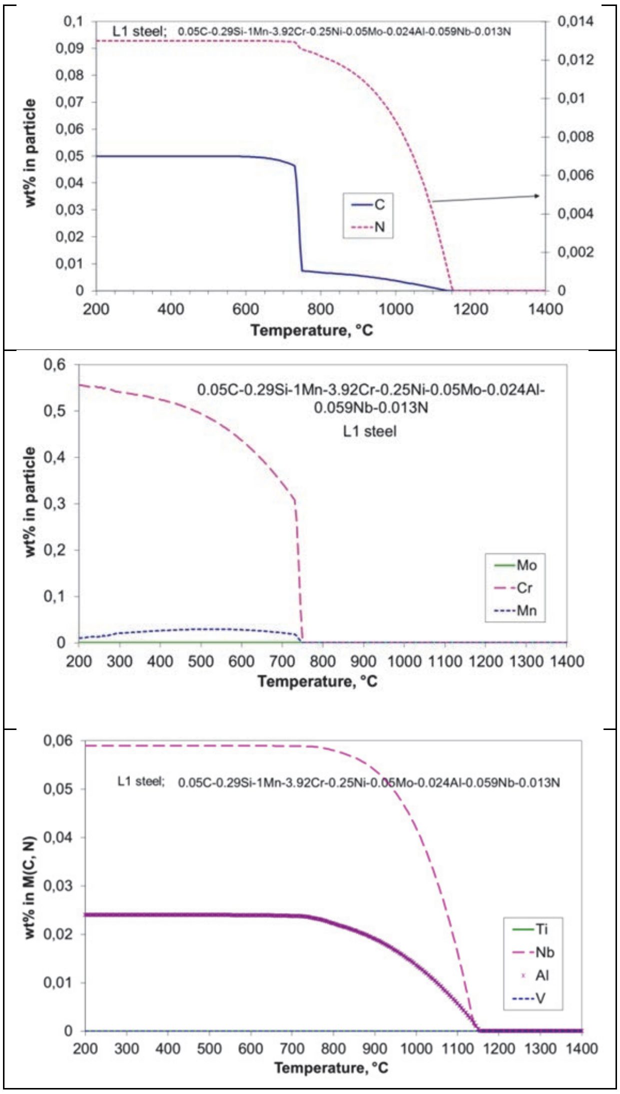


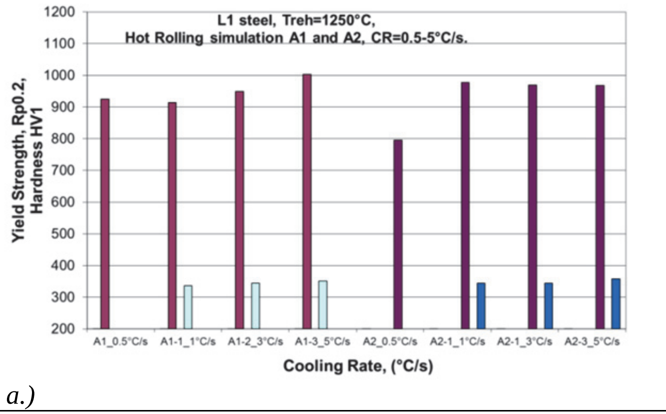
Fig. 30 ThermoCalc predictions of equilibrium precipitation / dissolution of M(C, N) in L1 steel.

4.3.2 Mechanical properties and final microstructure of long product after TMCP simulations

On the basis of the ThermoCalc predictions presented in Fig. 30 for steel L1 it has been decided to apply a reheating temperature of 1250°C and 1180° C for long product rolling simulation in laboratory scale.

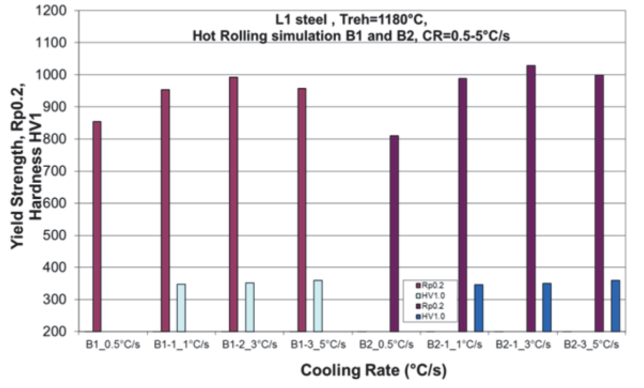
The mechanical properties results obtained after rolling simulation for both reheating temperatures, followed by sequences of deformations and cooling rates are presented in Fig. 31. As seen in this figure for Treh=1250°C, the yield strength (Rp0.2) increases from 920 to 1000MPa with increasing cooling rate up to 5°C/s for rolling schedule A1 with higher FRT of 980°C, whereas somewhat lower values of Rp0.2 in the range of 800 to 970 MPa were obtained for rolling schedule A2 with the lower FRT of 950°C.

In the case of lower reheating temperature of 1180°C for hot rolling simulation for steel L1 the yield stress was in the range of 820 to 1030MPa for rolling schedule B2 with higher FRT of 950°C, and 860-995MPa for schedule B1 with FRT of 920°C.



a.)

A1.) *1250°C/5min→(CR=3°C/s)→1150°C/20%→1050°C/25% →980°C/20% →900°C→CR=(1, 3 & 5°C/s) → RT,*
A2.) *1250°C/5min→(CR=3°C/s)→1150°C/15%→1050°C/20%→ 1000°C/25%→950°/20%→870°C→CR=(1,3& 5°C/s)→ RT,*



b.)

B1.) *1180°C/5min→(CR=3°C/s)→1100°C/20%→1000°C/25% →920°C/20% →850°C→CR=(1, 3 & 5°C/s) → RT,*
B2.) *1180°C/5min→(CR=3°C/s)→1100°C/15%→1050°C/20%→ 1000°C/25%→950°C/20%→870°C→CR=(1,3&5°C/s→ RT*

Fig. 31 Yield stress and hardness properties of simulated long product steel L1 for Treh=1250°C (a) and 1180°C (b) followed by various deformations and cooling parameters.

Thus, some increase of yield strength by 20-30 MPa has been observed after long product rolling simulation with the lower reheating temperature of 1180°C for both applied rolling schedules and especially for higher cooling rates over 0.5°C/s.

The austenite grain sizes of the steel L1 reheated at these temperatures were in the range 120 and 90µm, respectively. Examples of the microstructure obtained after long product rolling simulation for reheating at 1250°C and 1180°C, followed by sequences of deformations and cooling rates are presented in Fig. 32. Bainitic microstructures with variations in the length and thickness of the laths were observed depending on the Treh, FRT and cooling rate.

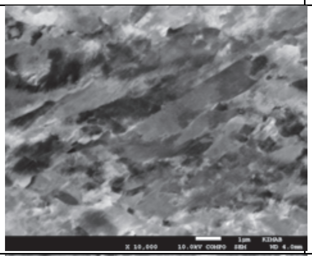
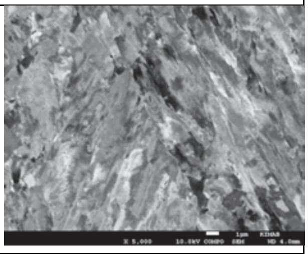
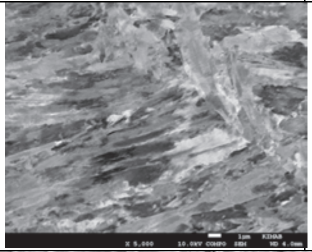
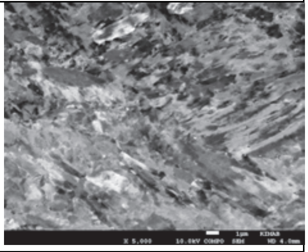
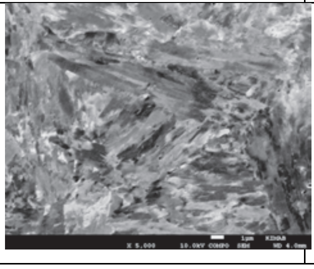
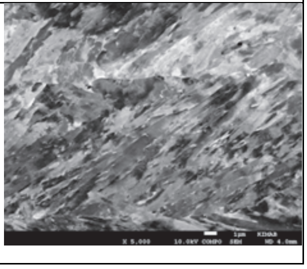
	Treh = 1250°C	Treh = 1180°C
A		
B		
C		

Fig. 32 Microstructure of long product hot rolling simulation of steel L1 for Treh=1250°C and 1180°C followed by various rolling schedules and cooling rates of 1, 3 and 5°C/s.

A.) Treh/5min→ (3°C/s) →Tstart °C/20%→1050°C/25% →980°C/20%→ 900°C→CR=1°C/s→ RT
B.) Treh/5min→ (CR=3°C/s)→Tstart/20%→ 1050°C/25% →980°C/20%→900°C→CR=3°C/s→ RT
C.) Treh/5min→ (CR=3°C /s)→Tstart / 20%→ 1050°C/25%→ 980°C/20%→900°C→ CR=5°C/s→RT.

These full scale results for L1-FS steel (Table 10) can be compared with the lab-scale simulation results (Table 11) obtained for steel L1 after reheating at 1180°C and 1250°C followed by cooling at rate of 0.5°C/s. A somewhat higher yield stress Rp0.2 was obtained for steel simulated with Treh of 1180°C than for full scale processing with Treh at 1205°C. The lowest Rp0.2 result of 750 MPa was obtained for full scale processing steel L1_FS-2 with the lowest applied Treh of 1130°C.

Table. 10 Mechanical properties of L1_FS steel after full scale TMCP rolling.

	Treh °C	Re, MPa	R_m, MPa	A5 %	Charpy-V (J)	Hardness HB
L1_FS-1	1205	780	896	13.1	65-27-51	286-298
L1_FS-2	1130	750	861	12.7	45-61-31	277-283

Table. 11. Yield stress at 0.2% & 1% plastic deformation for L1 steel TMCP simulated in lab-scale.

	Treh °C	$R_{p0.2}$, MPa	$R_{p1.0}$, MPa	HV1
A1	1250	925	1050	336
A2	1250	795	975	338
B1	1180	855	1015	342
B2	1180	810	964	337

5. CONCLUSIONS _ Industrial Benefits

* The effect of TMCP-parameters; reheating temperature, finish rolling temperature and cooling rate to RT or to the coiling temperature have been investigated in laboratory scale as regards the mechanical properties and microstructures of high strength steels for strips, heavy plates and long products.
* Modelling using ThermoCalc has been applied to calculate the equilibrium dissolution of M(C, N) in the present steels and the results have been used to predict suitable low reheating temperatures for these steels.
* Mechanical properties of the steels after simulated strip rolling show that the lower Treh of ~1220°C together with a cooling rate > 40°C/s to a coiling temperature at 550°-600°C results in a favourable effect on the properties of strips.
* Relationships between TMCP simulation process parameters and development of microstructures as well as the mechanical properties have been determined for two heavy plate steels. The processing parameters have an important influence on the final grain size during thick plate rolling. This can be used for choosing optimum parameters when rolling continuously cast slabs to thicker gauges.
* Optimisation of thermo-mechanical / direct quench processing of high-strength products permits elimination of a reheat hardening treatment and improve productivity aspects.
* Mechanical properties of long product have been improved by applying a lower Treh of 1180°C together with a cooling rate over 1°C/s to RT.
* Recommendations have been given to the strip, heavy plate and long products producers about the most promising processing parameters (reheating temperatures, TMCP and cooling parameters) for obtaining the best mechanical properties of the present steels after full-scale production.
* IVLs life cycle calculations show that a lower temperature reduces the oxide scale loss during heating the slabs with 200 tonnes / year.

CONCLUSIONS _ Environmental Benefits

* Low slab reheating temperature and proper rolling parameters reduce energy consumption and in this way release less CO_2 into the atmosphere during the thermo-mechanical processing.
* IVLs life cycle calculations show that lowering the reheating temperature by 60-80°C reduces energy consumption by up to 14000 MWh per year and reduces CO_2 emissions by 3 600 tonnes/year.
* Conversion to a direct quenching process reduces coke gas consumption by $70 m^3$/tonne plate and reduces CO_2 release by up to 50kg/tonne plate.
* High strength steels with their increased load-bearing capacity allow less steel to be used to achieve the same function will reduced environmental impact.

CONCLUSIONS _ Scientific

* Research on project 88041 has shown scientific value in terms of knowledge of precipitation and microstructure development in connection with optimization of the thermo-mechanical processes of high strength steel,
* This knowledge provides the possibility to eliminate a hardening process and improve the productivity during hot rolling of heavy plate and strip.
* Good agreement was found between observed austenite grain sizes and the ThermoCalc predictions as well as TEM analyses of the chemistry of precipitates.

Further research is needed to increase knowledge as to how these can be exploited in practice with respect to:
- the role of precipitates and different hardening mechanisms,
- methods of optimization of energy-efficient processing to improve high strength steel.

6. FURTHER UTILIZATION

The project utilization includes deliverables for steels producer;
- to certify processing conditions for providing maximum strength and toughness properties of strips, heavy plates and long products to the steel industry,
- to give information about the effect of various slab reheating treatments during processing on;
  i.) improving the environment aspects,
  ii.) energy reduction during processing,
  iii.) optimisation of production security, rescue treatments and surface quality during hot rolling and for final product,
  iv.) productivity aspects for strip, heavy plate and long product hot rolling.

Pre-heating is very energy-intensive and these developments place further technological demands such as new concept for modification of high strength steels chemical compositions for application of the lower reheating temperatures.
Only a few steel grades were studied in this project. For full utilization of the findings the implementation on more commercial steel grades will be needed.

Planned scientific deliverables;
- to describe the methods for optimisation of energy efficient processing routes for improving high strength steels with different alloying- and microadditions,
- to improve the knowledge about the role of precipitates and different strengthening mechanism and how these can be utilised in practice.

ACKNOWLEDGMENTS

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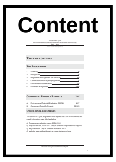
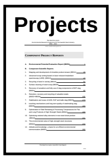
It is a pleasure to acknowledge the stimulating cooperation with engineers from SSAB EMEA and from OVAKO Bar. Special thanks to Professor W.B. Hutchinson for comments to the content of the report.





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OPTIMIZING RETAINED ALLOY ELEMENTS IN NEW STEEL SHEET PRODUCT (88042)

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Abstract

This work, which is a part of the "Steel Eco-Cycle" program is aimed at finding ways of obtaining the maximum benefit out of the accompanying alloy elements that arise from ores or recycled iron so that these can be retained and used to their best advantage, both ecologically and economically. This was done by a wide literature survey and discussions with different Swedish steel producers about the effect of residual elements on down-stream processes and end properties of low-carbon low-alloyed steel. Two application examples were then laboratory tested to demonstrate the relevance of this work.

The most remarkable trend that was identified is the dominance in literature of Cu, which is extensively studied and whose concentrations in the recirculated steel *need to be held at a low level. Problems arise often during processing at high temperature, so called hot shortness. If these problems can be avoided, a higher Cu content may be accepted without disadvantage for the final product.*

Laboratory testing of the effects of copper and nickel on low alloyed steel intended for thin sheet applications showed that Cu and Ni up to 0.3% may be tolerated without deteriorating the final properties, and with some advantage regarding cold formability. Consequently, the accepted level of Cu in scrap intended for production of thin steel sheets may be increased, which could lead to a higher flexibility in production and the possibility of using cheaper raw material. This would however imply costly adaptation of production and changes of routines. A motor for change may be if the saving on raw materials is high enough.

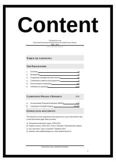
The possible use of vanadium retained from LD slag (work from MEFOS "Recovery of vanadium and full use of slag components in BOF-slag"(88031) in the "Steel Eco-Cycle" program) was examined by testing vanadium micro-alloyed steels with higher contents of phosphor. The results are promising, showing no deterioration of the properties with increasing P content. This may allow the use of the semi product from MEFOS for alloying in the ladle without prior V-P separation, leading to an important environmental and economic profit.

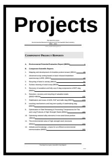
1 INTRODUCTION

It is now well established that good environmental practice necessitates the recycling and re-use of all materials as well as the optimal use of raw materials. In this perspective, the growing recirculation of steel scrap coming mainly from the collection of obsolete products may result in a substantial increase of residual elements in steel, which is often considered a problem. However, residual elements in scrap can be used as effective micro-alloying elements if the appropriate production is used. The current restrictions on levels of residual elements have often been set from a cautious viewpoint. With a deeper understanding of the dynamics behind the interactions of different elements, it is reasonable to believe that the level of residual elements can be increased in some high quality steel products.

Interviews with technical representatives of Sweden's major steel producers showed that the re-use of alloying elements present in the scrap is standard practice in the stainless steel industry (Cr and Ni). Serious efforts are also being made by producers of low alloy steels to sort scrap with the aim of making use of existing alloy content (Ni,Cr,Mo,Mn,V) although a significant amount of these may be lost during steelmaking. It is also recognized, at least in some cases, that the less expensive mixed scrap may be extra valuable because of the alloy elements that it contains.

However, it appears that little or no intentional use is made of these concepts among the manu-





facturers of structural steels. Mixed scrap as well as accompanying elements from ore are rather viewed as a threat to the smooth operation and achievement of close tolerances in chemical composition. Nevertheless, it must be a natural development to make use of the value of accompanying elements rather than to refine these away and then make new alloy additions.

By means of newly developed analysis and classification techniques as well as modified production methods, a larger part of these valuable elements may be used. This is shown by the green production method of figure 1. This so called self-alloying results in reduced costs for raw material and most of all a better use of resources.

In industrial terms, the aims of the present project can be said to be both well-accepted and pioneering. Much of the work will be concerned with analysis of material in the literature and in data-banks

A major task will be to identify and evaluate other products that could be developed by utilizing retained elements from ore or scrap.

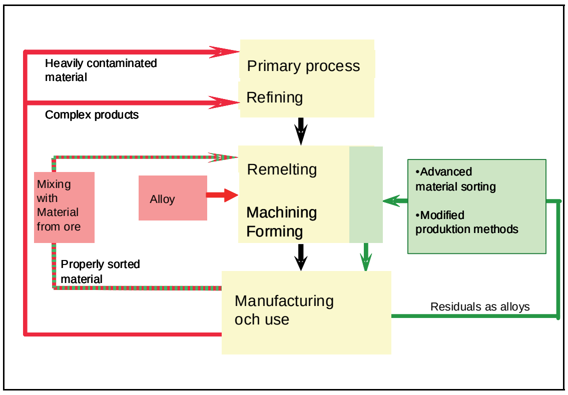


Fig. 1. ”Green” thinking and production way allow a more effective use of resources and save energy.

Swedish iron ores contain significant levels of both vanadium (V) and phosphor (P) while scrap often contains copper (Cu), manganese (Mn), nickel (Ni), chromium (Cr) or molybdenum (Mo), All these elements can be valuable alloys as well as the cause of different types of problems. This implies that in current practice, many alloy elements are lost or intentionally removed by way of precaution during steel-making which represents a loss of value and may even result in further environmental problems in disposing of the contaminated by-products.

The high vanadium content of ores means that there is a good potential for recovering this micro-alloy element. Vanadium is a powerful strengthening agent, especially in combination with nitrogen. MEFOS is working, in the frame of the “Steel Eco-Cycle” project, on a new method for recovering of V from LD slag (Recovery of vanadium and full use of slag components in BOF-slag (88031)). The material obtained has a high P content together with V, and a ratio V/P of around 15-20, see figure 2. Increasing the V/P ratio to 50-100, in order to match today’s specifications in steel sheet production may be difficult and costly. However, P is widely used as an addition to certain sheet steels where it improves strength with minimum detriment to formability Thus it is very important to study the effect of (and the possibility of tolerating) a higher P content in steel sheets micro-alloyed with V. Such a study will probably make the use of the product obtained at MEFOS possible without prior V-P separation.

It is unlikely that this type of product could form a major part of steel production in a foreseeable future but on the basis of it becoming a significant niche product with a volume of 100ktons/year, the value, in V-alloy cost alone, would amount to 20MSEK.

The effect of copper on steel processing is extensively studied in the literature. Concentrations of copper in the recirculated steel need to be kept at a low level. Problems arise often during processing at high temperatures, so called hot shortness. If these problems can be avoided, a higher Cu content may be accepted without disadvantage for the final product and may even lead to improvement of the final properties. In order to demonstrate the interest of tolerating elevated Cu contents in recycled steel, low carbon steel sheets containing Cu and Ni were produced in the laboratory and evaluated.

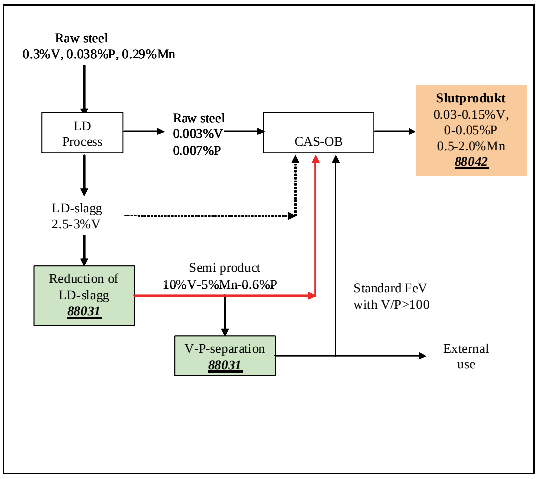


Fig. 2. Semi product from MEFOS

2 OBJECTIVES

The aim of this work, which is a part of the steel eco-cycle program, is to emphasize the green vision from fig 1 and to find ways of obtaining the maximum benefit out of the accompanying alloy elements that arise from ores or recycled iron so that these can be retained and used to their best advantage, both ecologically and economically. To allow this, it is necessary not only to seek advantages from 'self-alloying' but also to identify and avoid the problems that can arise from the mixed feed-stock. An alloy element in one material can be a contaminant in another (and vice versa). Often, the problems caused by contaminants in steel do not concern the final product properties but rather the down-stream processing (e.g. hot working) or the economic cost/value of by-products. .These aspects must also be investigated.

The first stage of the work was to investigate how the alloy elements that can be retained in steels after re-melting with today's or feasible future processes can be utilized to obtain special user properties. Steel compositions that are not standard today may still provide interesting properties in a cost-effective manner. In effect, the aim is to convert elements that are perceived as impurities in the scrap into useful alloy elements. Together with process modification where necessary, this will enable special new high performance products to be developed.

Based on the results from the first stage and preliminary studies conducted at KIMAB, low carbon steel sheets containing Cu and Ni were evaluated in cooperation with SSAB tunnplåt. The aim was to demonstrate the possibility of tolerating higher Cu and Ni content than in the actual production without deterioration of formability and mechanical properties.

Finally, steel compositions with various V and P contents, that can be achieved metallurgically by alloying in the ladle with the product from LD slag recovery (Recovery of vanadium and full use of slag components in BOF-slag), were laboratory processed by simulated hot rolling and coiling and tested. The aim was to evaluate the possibility of using the semi-product obtained at MEFOS in steel production.

3 METHODS

This work was divided into three different tasks presented below. The literature survey and experience mapping (3.1) provided a basis for the choice of materials for laboratory testing of the effect of Cu and Ni in low alloyed sheet steel (3.2). Finally, the effect of V and P on the properties of micro-alloyed high strength steel sheets was investigated. The latest is a collaboration with another work of the "Steel Eco-Cycle" program conducted at MEFOS.

3.1 EFFECT OF RESIDUAL ELEMENTS ON STEEL PROPERTIES – A LITERATURE SURVEY

The focus of this part of the work is so called self-alloying from scrap, which means the possibility of using residuals as alloying element when recycling.

A literature survey about the effects of different residual elements on steel production and final properties was published under the title of "”Opportunities and dangers of using residual elements in steel: a literature survey".

This study is aimed at giving an overview of the situation and state of the art concerning residual elements in low-alloy low-carbon steels, their effects on processing and final properties of the steels and the way they are used today.

The study is a summary of around 60 publications and reports from the literature.

3.2 EFFECT OF COPPER AND NICKEL IN LOW-ALLOYED SHEET STEEL

In this task, the effects of copper and nickel on low-alloyed (LA) steel intended for thin sheet applications are studied through laboratory production and evaluation, including tension tests, light-optical microscopy, texture measurements and chemical analysis. The choice of material is based on a previous study done at KIMAB and a literature study in combination with company visits. This work was done in close cooperation with SSAB Tunnplåt i Borlänge as a master thesis work in 2006.

Thin sheets with increased levels of Cu and Ni were tested, see composition in table 1.

Table 1 Chemical analysis (%w)

Cu	Ni	C	P	S	Si	Al	Mn
0 – 0.3	0 – 0.3	0,010	0,0072	0,0091	0,0073	0,070	0,310

Laboratory testing simulating the production of cold rolled thin sheet were performed. Batch annealing and continuous annealing treatments were used to compare the behavior of the sheets obtained and the differences in the evolved microstructure. The process simulation included following steps:

- Casting
- Hot rolling 1200ºC
- Coiling: 530ºC and 740ºC / 30 min,.
- Cold rolling
- Continuous and batch annealing

The temperature curves for continuous annealing are given in figure 3 and the one for batch annealing in figure 4.

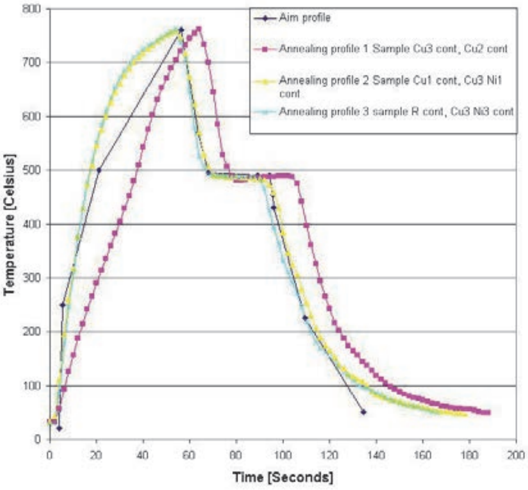


Figure 3 : Temperature curve for continuous annealing.

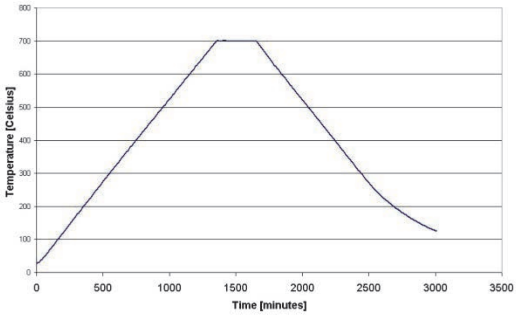


Figure 4 : Temperature curve for batch annealing.

The mechanical properties such as yield strength and Lüders strain are measured with tensile testing. The microstructure is also investigated and correlated with mechanical properties. The microstructure is examined with conventional optical microscopy and electron microscopy, enabling texture measurements with Electron Back Scatter Diffraction (EBSD) and imaging of the fracture surface.

3.3 HIGH STRENGTH STEEL SHEET USING V RECOVERED FROM LD SLAG

This work was done in collaboration with MEFOS in Luleå (projekt "Recovery of vanadium and full use of slag components in BOF-slag").

Six different vanadium micro-alloyed steels with higher contents of phosphor were tested, see compositions in table 2.

Table 2 Chemical analysis (%w)

	C	Mn	Si	N	Al	V	P	V/P
1	0.11	1.1	0.25	0.01	0.05	0.10	0.008	12.5
2							0.020	5
3							0.035	2.9
4						0.15	0.008	18.8
5							0.035	4.3
6	0.20					0.10	0.008	12.5

Laboratory testing simulating the production of hot-rolled micro-alloyed sheet was performed using cylindrical samples and high speed compression equipment. The process simulation included the following steps:

- Casting
- Pre-heating 20min at 1200ºC
- Hot rolling (see figure 5)
- Coiling: 500ºC to 650ºC, 60 hour /5 hours, simulation in a furnace.

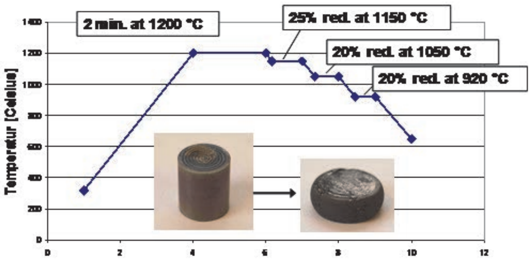


Fig. 5. Hot rolling simulation

The sample with the lowest V/P ratio (sample 3) was tested with 4 different coiling temperatures. The temperature giving the best mechanical properties (500ºC) was thereafter used for testing the other samples. However, as this temperature is low, the coiling time was modified

Tensile testing was performed to determine yield strength, tensile strength and elongation. The samples were also etched and observed with the light optical microscope, and the composition was analyzed with GDOES.

4 RESULTS AND DISCUSSION

4.1 EFFECT OF RESIDUAL ELEMENTS ON STEEL PROPERTIES – A LITERATURE STUDY

An overview of the possible effects of residuals elements on down-stream process and end properties of steels, classified by their nature in the steel, is proposed through a summarising figure (figure 6).

The effect of residual elements on down-stream processes and end properties of low-carbon low-alloyed steels is a wide topic, which is consequently difficult to summarize briefly. Some general trends and features could however be found, which are presented here. The most remarkable trend is the dominance of Cu in the elements studied: most of the studies are concerned with the influence of copper, alone or in combination with other elements.

Hot working

- Most studies are related to the effect of Cu, which can cause hot-shortness during hot working, even for contents as low as 0.1% in some cases. The critical temperature for hot shortness is between 1100°C and 1200°C. Modifying the process can allow higher Cu contents, at least up to 0.8%.
- Several studies are concerned with the influence of other elements in combination with Cu on hot-shortness, $Cu_{equivalents}$ being presented in some cases. Mainly Sn, but even Mn, Cr, As and V are reported to increase hot-shortness whereas mainly Ni, but even Co, Al and Si are reported to decrease it.
- Grain boundary segregation, which is a non-equilibrium segregation at grain boundaries of mainly Sn, leads to a low hot ductility in the temperature range 600°C to 950°C. Cooling rates between 5 and 20 °C/s were shown to increase risk for grain boundary segregation.
- DSC (direct strip casting) allows a higher content of Cu and Sn in the material without hot-shortness problems, by combining short oxidation time with rapid cooling and direct rolling. Processing windows to avoid hot-shortness were studied at KIMAB.

Cold working

- Elongation and drawability are the main properties used to define cold workability. Residual elements mainly contribute to harden the matrix, which has a negative effect on cold workability. Ni, Cr, Cu, Mo, Sn and As were reported to decrease the ability to deep drawing and formability of LC steels whereas Ti and Nb showed the contrary effect.
- Copper was shown in some cases to have positive effects on formability when processing and heat-treating the material properly.

Hardenability

- Most residual elements, with the exception of Co, Ti and S, increase the hardenability by slowing down the ferrite and pearlite reactions. Mn is reported to be very effective for this purpose, as well as Mo, Cr and P, whereas Ni and Cu are less effective.
- Several studies are concerned with copper, which is shown to increase hardenability by decreasing the transformation to ferrite.

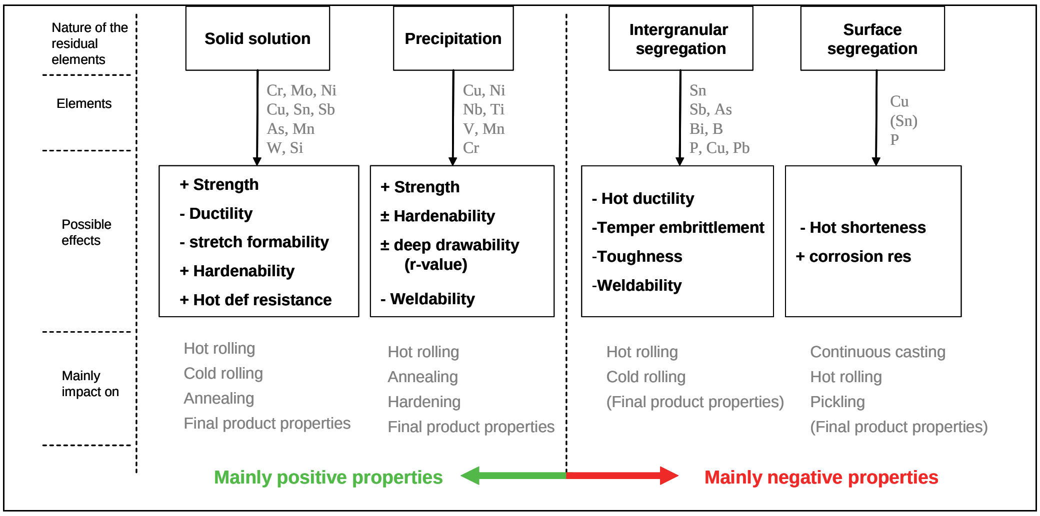


Fig. 6. Overview of the possible effects of residuals elements on down-stream processes and end properties of steels, classified by their nature in the steel

End properties

- Most residual elements increase the strength and decrease the ductility, which is mainly due to solid solution hardening and also to precipitation.
- Copper leads to a weak solid solution hardening. However, a high strength was obtained due to the fine dispersion of ε-Cu particles after ageing at low temperatures (450°C to 500°C).
- Cu, Cr and Ni in low C – TRIP aided cold rolled sheets were reported to increase tensile strength and elongation by increasing the content of retained austenite.
- Reduction of the grain boundary cohesion, so called grain boundary embrittlement, is due to the segregation of elements at the grain boundaries during cooling, coiling and final annealing. Sn, Sb, As and P are reported to segregate to surfaces.
- Copper can act as a protection against corrosion in certain steels.

Welding

- Most residual elements contribute to the hardenability in the HAZ in a more or less negative way.
- Steel that contains up to 0.85 w% copper has not been reported to be a problem. In fact the forming of precipitates is reported to be beneficial in regards to the toughness of the weldment.
- The combination of tin and copper is a problem both in hot rolling and welding, causing similar problems. The presence of a copper phase that has a low melting point compared to the base material can cause surface cracking during hot rolling and hot tearing during welding as the material solidifies.

An experience mapping was even done through discussions and meetings with different Swedish steel producers. Cu appeared to be a recurrent element for which concentrations want to be held low in the recirculated steel. Problems arise often during processing at high temperatures, so called hot shortness. If working problems in the hot state can be avoided, a higher Cu content can usually be accepted without disadvantage for the final product.

A common fear also concerns the need for adaptation of production and changes of routines which hinder tolerating a higher Cu content. The companies and their customers have built up standards and routines over a long period of time which are difficult to change. A motor for change may be a sufficiently high saving on raw materials.

4.2 EFFECT OF COPPER AND NICKEL IN LOW ALLOYED SHEET STEEL

The effects of higher Cu and Ni on final properties of sheet products were investigated. Demonstrating that an increased Cu and Ni content do not decrease final properties is the first step towards use of scrap with higher residuals contents. Production methods will need thereafter to be adapted.

Results of this study show that there is no major effect of copper on the tensile strength in either batch or continuously annealed sheets (see figure 7 and figure 8). Copper in combination with the highest nickel content in this study show an increase in tensile strength in the batch annealed materials, but no significant effect in the continuously annealed material.

Elongation remains essentially constant with copper level and in combination with lower nickel levels in the continuously annealed materials. Finally the Lüders elongation decreases slightly with increasing copper content and with the addition of nickel in the continuously annealed material.

The continuously annealed material shows a finer microstructure than the batch annealed, that has a more pronounced elongation of grains in the rolling direction (figure 9).

There is no discernible influence from copper or nickel on the average grain size in the continuously annealed materials at the composition levels within this study

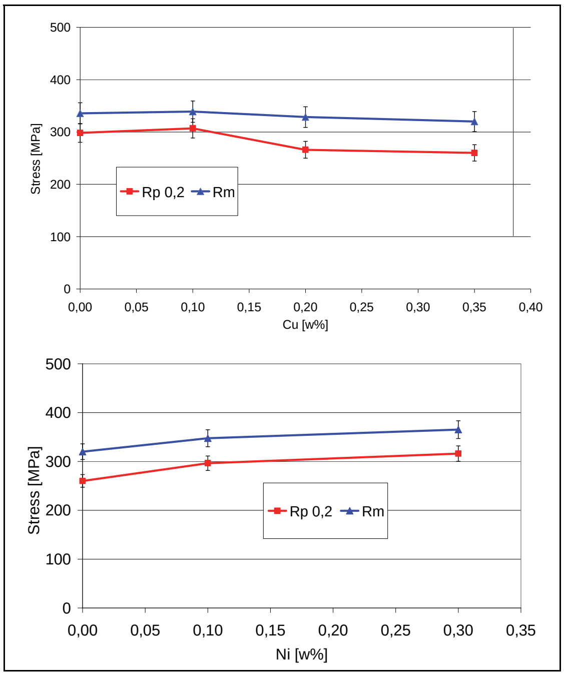


Fig. 7. Yield strength and tensile strength for continuosly annealed samples with different Cu and Ni content

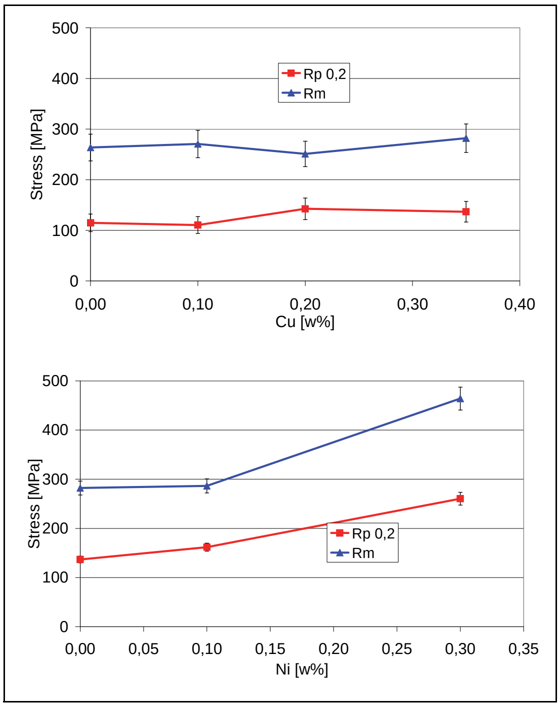
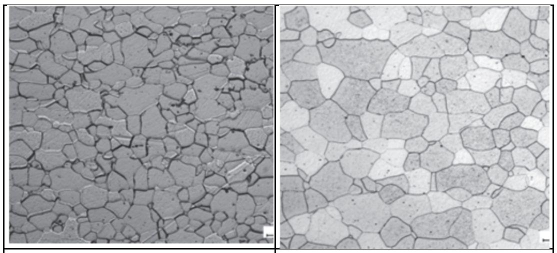
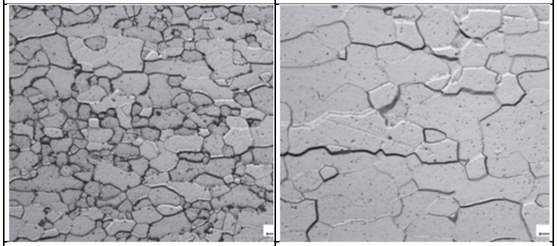


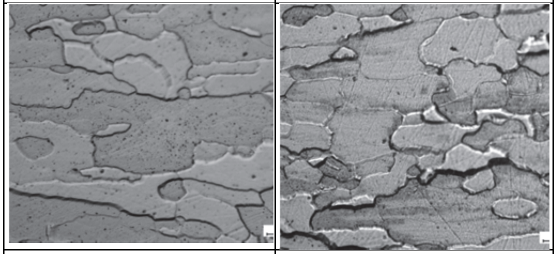
Fig. 8. Yield strength and tensile strength for batch annealed samples with different Cu and Ni content



R Cont.-1 at x500 Cu3 Cont.-1 at x500



Cu3 Ni3 Cont.-1 at x500 R Batch.-4 at x500

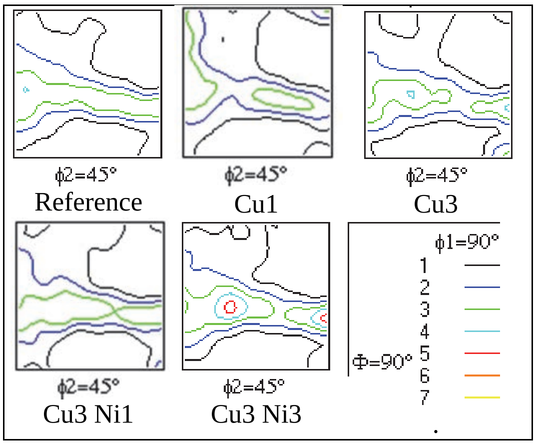


Cu3 Batch.-3 at x500 Cu3 Ni3 Batch.-3 at x500

Fig. 9. Microstructure of continuously annealed and batch annealed samples with different Cu and Ni contents.

The so-called gamma-fiber texture is more pronounced in the batch annealed material, and has a higher intensity with increasing copper and nickel content in both annealing types (figure 10).

The addition of copper and nickel increases the strength of the gamma fiber texture that is favorable for deep drawing abilities of low-alloyed steel.



Figur 10 Gamma fibre intensity from EBSD measurements r for different Cu and Ni contents.

This study showed that Cu and Ni up to 0.3% may be tolerated in these sheet products without deteriorating their final properties, and with some advantage regarding cold formability. Consequently, the accepted level of Cu in scrap intended for production of thin steel sheets may be increased, and by that a higher flexibility in production and the possibility of using cheaper raw materials could be reached.

4.3 HIGH STRENGTH STEEL SHEET USING V RECOVERED FROM LD SLAG

Steel compositions with various V and P contents, that can be achieved metallurgically by alloying in the ladle with the product from LD slag recovery (Recovery of vanadium and full use of slag components in BOF-slag), were laboratory processed by simulated hot rolling and coiling and tested. The aim was to evaluated the possibility of using the semi-product obtained at MEFOS in steel production.

The first step of this work was to produce one of the alloys studied (sample 3, see table 3) using different coiling temperatures and to analyse the material obtained. The results of tensile testing are shown in Fig 11 and the microstructures of the corresponding samples are given in figure 12.

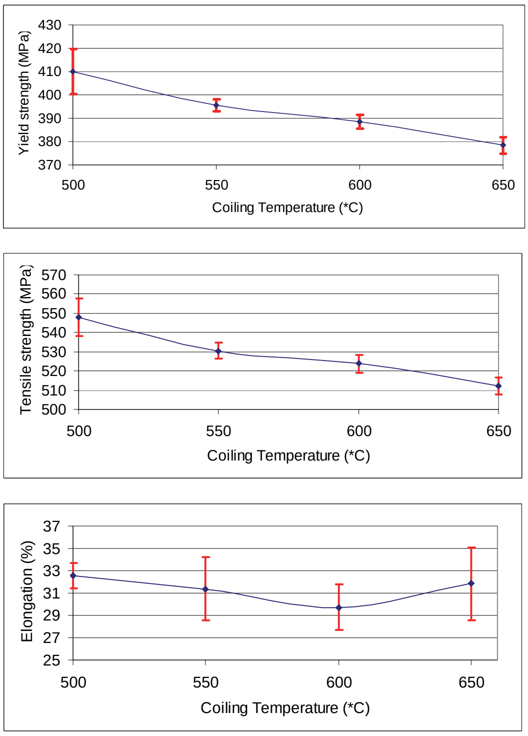
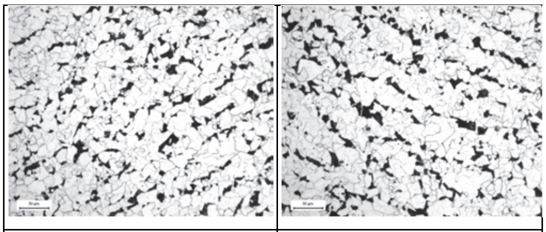


Fig. 11. Tensile testing for sample 3 with different coiling temperatures

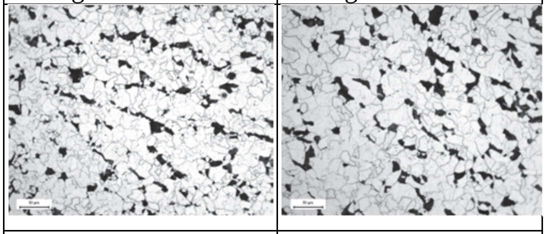
As can be seen, coiling at 500ºC gives the highest yield strength, tensile strength and elongation. Thus, this temperature was chosen for testing all materials. However, in order to allow a better precipitation hardening effect through vanadium, the coiling time at 500ºC was increased from 1 hour to 5 hours.

The second step of this work was to produce all samples using a coiling temperature of 500ºC and to analyse the material obtained.

The analysed composition of the different samples as well as the results from the tensile testing and hardness measurement are given in table 3. Mn, Si, N and Al content was close to the specified content for all samples and is not given here. Moreover, the stress strain curves for material 4 and 5 are shown as examples in Fig 13 and the microstructures of the corresponding are given in figure 14.



Coiling at 500ºC | Coiling at 550ºC



Coiling at 600ºC | Coiling at 650ºC

Fig. 12. . Microstructure of sample 3 tested at different coiling temperatures, LOM of etched samples, magnification 200x.

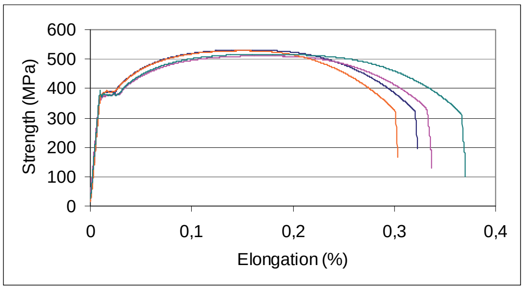
Table 3 Chemical analysis (%w)and results from mechanical testing and hardness measurement

	C	P	V	V/P	Rp0,2 (MPa)	Rm (MPa)	strain	HV 0.5
1	0,096	0,0098	0,080	8,2	400	534	33%	181
2	0,095	0,026	0,093	3,6	402	536	32%	185
3	0,113	0,036	0,109	3	397	534	30%	175
4	0,127	0,008	0,124	15,5	378	522	33%	169
5	0,095	0,034	0,145	4,2	393	536	32%	180
6	0,189	0,011	0,095	8,6	398	585	30%	189

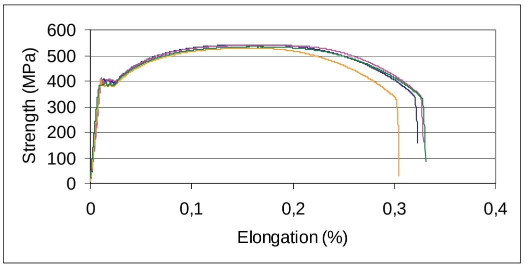
As can be seen, there is no deterioration of the mechanical properties when increasing P content (or decreasing V/P). The microstructures in the light optical microscope are very similar in the different samples. One concern may be that there is no increase in mechanical properties when increasing V content; thus, there has possibly not been an ideal precipitation hardening effect in the samples, which may be due to the fact that the chosen temperature was too low. More investigations are needed to clarify this point.

Finally, sample 3 is compared with different coiling times. The mechanical properties are lower when increasing the coiling time (Table 4 and figure 15), which is possibly also an indication that another phenomena than precipitation hardening gave higher mechanical properties at 500ºC. Once again, this point needs to be clarified in further research.

In conclusion, the results are promising, showing no deterioration of the properties with increasing P content. However, the production parameters, mainly the coiling temperature, need to be optimised to obtain a good precipitation hardening effect.



A



B

Fig. 13. Stress strain curves for samples 4 (A) and 5(B).

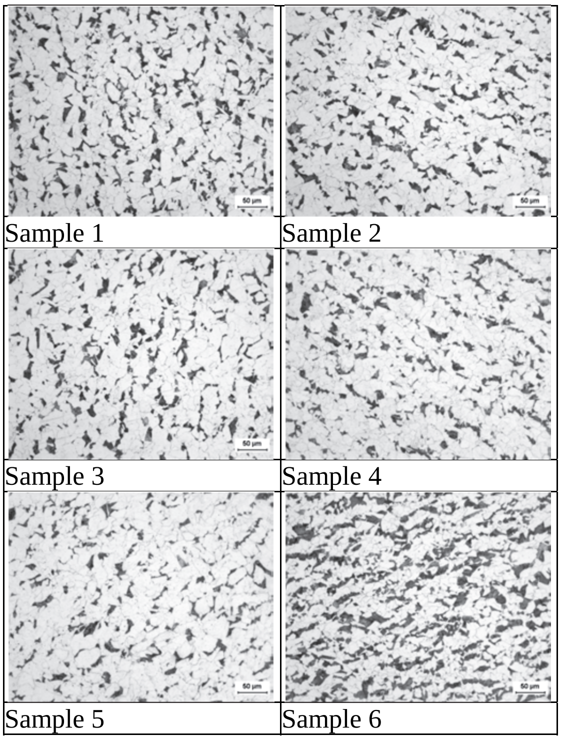

Sample 1 Sample 2
Sample 3 Sample 4
Sample 5 Sample 6

Fig. 14. Microstructure of the six samples tested, LOM of etched samples, magnification 200x

Coiling timeat 500ºC	Rp 0,2 (MPa)	Rm (MPa)	Elong.	HV 0.5
1 hour	410	548	33%	178
5 hours	397	534	30%	175

Table 4. Comparison of the mechanical properties for sample 3 with different coiling times at 500 ºC.

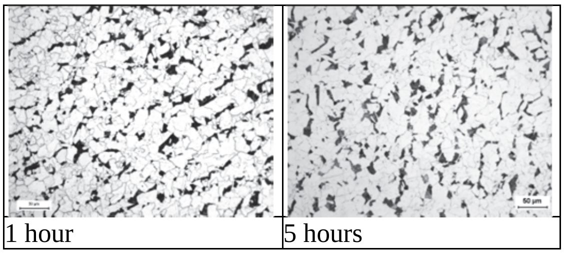

1 hour 5 hours

Fig. 15. . Microstructure of sample 3 with different coiling times at 500 ºC, LOM of etched samples, magnification 200x.

5 CONCLUSIONS

The effect of residual elements on down-stream processes and end properties of low-carbon low-alloyed steels is a wide topic, which is consequently difficult to summarize briefly. Some general trends and features could however be found through a literature survey. The most remarkable trend is the dominance of Cu in the elements studied: most of the studies are concerned with the influence of copper, alone or in combination with other elements.

Discussions and meetings with different Swedish steel producers showed even that Cu is a recurrent element whose concentrations in the recirculated steel need to be kept at a low level. Problems arise often during processing at high temperature, so called hot shortness. If working problems in the hot state can be avoided, a higher Cu content can usually be accepted without disadvantage to the final product.

A common fear also concerns the need for adaptation of production and changes of routines which hinder tolerating a higher Cu content. A motor for change may be a sufficiently high saving on raw materials.

The study of the effects of copper and nickel on low alloyed steel intended for thin sheet applications showed that Cu and Ni up to 0.3% may be tolerated in these sheet products without deteriorating their final properties, and with some advantage regarding cold formability. Consequently, the accepted level of Cu in scrap intended for production of thin steel sheets may be increased, and by that a higher flexibility in production and the possibility of using cheaper raw material could be reached. Adaptation of production to avoid problems like hot-shortness will be needed.

Finally, the possible use of vanadium retained from LD slag (work from MEFOS in the “Steel Eco-Cycle” program, “Recovery of vanadium and full use of slag components in BOF-slag”(88031)) was examined by producing on laboratory scale and testing different vanadium micro-alloyed steels with higher phosphor content The results are promising, showing no deterioration of the properties with increasing P content. This may allow the use of the semi-product from MEFOS for alloying in the ladle without prior V-P separation, leading to important environmental and economic gains.

6 FURTHER RESEARCH

The most immediate field for further research is to find and evaluate possible industrial applications and uses for the high vanadium content products obtained by MEFOS through reduction of LD slag (Recovery of vanadium and full use of slag components in BOF-slag). Two main areas of interest may be investigated:

- Possibility of using a Fe-V product with V/P < 100 (use of the product from LD slag reduction before VP separation - selective oxidation - for producing hot rolled steel sheets micro-alloyed with V). Such a study will probably make the use of the product obtained at MEFOS for alloying in the ladle without prior V-P separation possible.
- Replacing part of the Nb and Ti which is used today in micro-alloyed steels in the 300-500 MPa range with V, see figure 16. This is of particular economic interest because of the large quantity of vanadium expected from the LD slag reduction.

Steel compositions for hot rolled steel sheets micro-alloyed with V having different V/P ratios are to be laboratory processed by simulated hot rolling and coiling. These steels shall have relatively high P contents corresponding to what is expected when using the product from LD slag reduction before V/P separation (selective oxidation) as an alloy in the ladle. Different strengthening mechanisms are to be investigated including precipitation hardening with VN, dual–phase and back-annealing. In this way the down-stream processing can be optimised with respect to the chemical composition of the steel. The properties of the steels obtained (mechanical properties, microstructure, weldability) shall be extensively evaluated. Based on the results obtained, industrials tests may be conducted.

Strength	280 MPa →	450 MPa →	550 MPa →	700 MPa
Micro alloying Elements used	Nb	Nb + V	Nb + Ti	
Interesting with an Increased "V field"	Nb	Nb + V	Nb + Ti	

Fig. 16. . Replacement of Nb and Ti with V

7 DISSEMINATION AND PUBLICATIONS WITHIN THE CURRENT PROJECT

Reports

[1] Opportunities and dangers of using residual elements in steel: a literature survey, Olivier Rod, Christian Becker, Margareta Nylén, KIMAB-2006-124

[2] Effective use of residual elements in steels produced from scrap, Master Thesis Work, Christian Becker, KIMAB-367023

Conference publications, non-refereed

[3] Självlegering – ta vara på resurserna, Olivier Rod, Margareta Nylén, Stål 2007.

8 REFERENCES

As an important part of this work was a literature survey, a large number of references were consulted. Only few of them, which give a broad overview of the topics studied, are given here.

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THE ENVIRONMENTAL VALUE OF HIGH STRENGTH STEEL STRUCTURES (88044)

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Abstract

This paper covers the development and validation of methods for life cycle assessment of the environmental impact when advanced high strength steel is used for weight optimization of structures.

As expected, a Life Cycle Assessment (LCA) of increased strength for carbon steel and stainless steel structures shows that the environmental impact will be considerably reduced since increased strength makes it possible to reduce weight of constructions.

Models have been developed for life cycle assessment of structures of advanced high strength steel. They have been validated by ten different case studies on active structures like road and rail transport vehicles and on passive structures like a storage tank and a steel construction, Friends Arena.

Analysis of existing real life upgrading cases and the case studies show that achieving 20 % weight reduction for parts in which conventional steel is replaced by high strength steel is realistic. It also indicates that there is an even greater potential, especially for passive structures.

Calculations show that every million tonne of advanced high strength steel that replaces conventional steel in a road vehicle fleet would result in an improvement of 8 million tonne CO_2 emissions and 31 TWh non-renewable energy recourses in a life cycle assessment, including a use phase. Over 90 % of these savings are related to the use of the vehicles.

The above results emphasise the importance of including the use phase in the life cycle assessment in order to recognize the environmental potential of advanced high strength steel.

Key Words: *high strength steel/weight reduction/ /LCA/LCC/environmental benefit*

1. INTRODUCTION

Recent statements by researchers on the connection between global warming and CO_2 emissions have emphasised the need for more aggressive measures to be taken to limit this impact on the environment.

Application examples have demonstrated that there is a great potential for considerable weight savings and decreased environmental impact by using advanced high strength steels. These examples can be found in many industrial sectors, including the transport sector that contributes to about 20 % of the global CO_2 emissions. Especially in this sector, in which at least 90 % of the environmental impact is related to the use of the vehicle, there is a large potential for reducing these emissions by developing lighter structures. In order to benefit fully from high strength steel, the structural design and production processes must be adjusted to the properties of the steel. The technology for doing so needs to be more widely known, and it is important for designers to take a holistic view in optimizing product performance in technical, environmental and economic terms at the same time.

The main obstacles to increased use of advanced high strength steel are lack of experience in using such steel, lack of simultaneous engineering, standards that have not been updated with new steels and conservatism among designers and production engineers.

The introduction of these steels on the market has therefore taken a rather long time and has largely been in the nature of a technology push [1:1]. Many measures have been taken at the interface between the steel manufacturer and the steel user to increase knowledge and technology transfer [1:2, 1:3, 1:4, 1:5, 1:6]. Some common efforts by the world steel industry have also been made, such as in the ULSAB (Ultra-Light Steel Auto Body) and ULSAB-AVC (Advanced Vehicle Concepts) projects [1:7, 1:8, 1:9].

Research in this area has been initiated and performed largely by steel producers, in cooperation with steel users and research institutes. The research areas cover mainly joining and forming of advanced high strength steel, static load-bearing capacity, including stability and buckling, energy absorption as well as fatigue performance. General research in specific fields, including life cycle assessment methods, is being pursued at universities. However, few projects are directly related to high strength steel and no holistic and systematic research is identified in which the connection between the properties of these steels, weight reduction and environmental impact is covered.

In order to speed up and broaden the knowledge transfer process, relevant tools for judging the potential for reducing the environmental impact and cost by using advanced high strength steel, need to be developed and validated. The Swedish steel industry has the technical knowledge on how to design and manufacture structures of advanced high strength steel, why it is important for the steel industry to take an active role in the technology transfer to close the existing knowledge gaps.

This report covers work performed in project 88044 “The environmental value of high strength steel structures” since the start in January 2007. The project is part of the “Steel Eco-Cycle” program funded by MISTRA. The first chapters of this report deal with life cycle assessment of high strength steel production and the use of structures made of these steels. The outcome in terms of weight reduction of using advanced high strength steel is presented by a summary of real life upgrading cases. Design philosophy as well as design issues to be considered when using advanced high strength steel in structures is also briefly discussed. The environmental improvement of using high strength steel is demonstrated by ten different case studies. It includes the use of developed models for the analysis of environmental impact and an estimate of the potential for reducing CO_2 emissions in different segments.

The research work has been carried out with active input from SSAB EMEA, Outokumpu Stainless, Sandvik Materials Technology, IKEA and IVL, who have contributed by collecting steel upgrading cases and in the Life Cycle Inventory (LCI) of steel production. A great deal of information has been collected within the network of steel using companies consisting of Bombardier, Cargotec HIAB, Green Cargo, Metso Minerals, MST (Mjölby Trailer and Tractor), Scania, Saab, Sweco, Volvo Car Corporation, Volvo AB and Volvo Construction Equipment.

2. OBJECTIVES

This project has focused on the use of steel in structures and especially how to value the environmental impact of lightweight design solutions of advanced high strength steel. The goal of the project can be divided as follows.

2.1 General

Develop and validate life cycle assessment methods identifying the environmental impact of using advanced high strength steel for weight optimization.

2.2 Industrial

Deliver methods and rules of thumb for the evaluation of the environmental product value of advanced high strength steels - methods that for example can be introduced in handbooks and design guidelines. Develop a practical software tool for calculating the environmental value of different applications.

2.3 Environmental

Reduce the environmental impact by showing the potential for weight reduction by using advanced high strength steel. A quantitative goal of 20 % weight reduction is set for parts of the structure in which conventional steel is replaced by advanced high strength steel. The corresponding improvement in environmental impact is assessed by using LCA.

3. METHODS AND MATERIALS

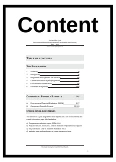
3.1 Project structure and activities

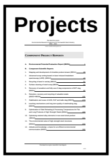
The project has been performed in four phases*:*

1. Collection of data and information
2. Analysis and system development
3. Case studies - validation
4. Communication

LCA on the production of different steel grades has been performed and relationships between environmental impact, steel type, steel strength and chemical composition have been evaluated.

Methods for LCA of high strength steel structures have been developed and the potential for reducing environmental impact has been exemplified.





Real life upgrading cases have been evaluated, and reductions in weight related to increases in steel strength have been established.

Information is collected on critical design issues that need to be handled when designing for weight reduction in advanced high strength steel.

3.2 Steel grades

The steel grades included in this investigation are carbon steel and stainless steel as hot rolled and cold reduced sheet material. The high strength carbon steels are micro-alloyed cold forming steels, dual phase steels and martensitic steels. Some grades of micro alloyed and dual phase steels are hot dip galvanized. The high strength stainless steels are austenitic-ferritic duplex steels, including those which are temper rolled or high chromium and molybdenum steels. Three of these steels are especially developed for tubes to urea production. Furthermore, structural steel and abrasion resistant steel as heavy plate are included. These steel grades are quenched and tempered steels with fairly low alloying element contents. The yield strength of the investigated steels varied between 220 to 1400 MPa. A total of fifty-three steel grades are analysed. The actual grades, their chemical composition and mechanical properties are given in detail in [3: 1].

3.3 Life cycle assessment

Considering the environmental value of high strength steel, it is important to analyse the whole life cycle, Figure 3.3.1.

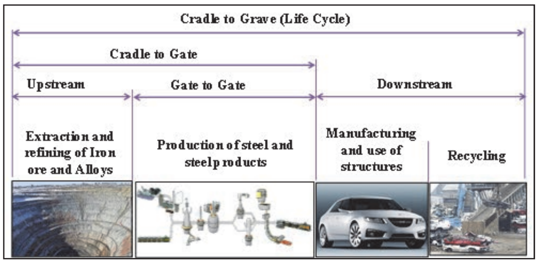


Figure 3.3.1. Schematic of life cycle of steel material

Different phases in the life cycle assessment are normally designated as shown in figure 3.3.1 and the expressions mostly used in this report are “cradle to gate” and “cradle to grave”. The life cycle assessment has normally been performed as a differential analysis, in which structures of advanced high strength steel are compared with structures of conventional steel. The analysis is then possible to relate to particular steel sheet components of the structure, where conventional steel has been replaced by advanced high strength steel.

3.3.1 LCA of steel production

The life cycle inventory (LCI) of steel production has been performed in co-operation with the Swedish Environmental Research Institute, IVL. The details concerning system boundaries, methodology and data are presented in [3:1]. Below the most important conditions are described. The LCI-study covers raw material extraction, steel production, heating of slabs, rolling, annealing, quench and tempering as well as related transportation. All raw material upstream contributions to the environmental impact are included.

The study has been based on a weight reference unit (kg) of steel. This is, of course, not the relevant figure to use for assessing the environmental impact from structures of high strength steel, since a smaller amount of such steel than of conventional steel is used for a specific function. The reason for doing so is that the total LCA is built up as a modular system, and this unit is the most appropriate to use as input data in the module analysis. In the total life cycle assessment, the end result is converted into environmental impact per functional unit.

The life cycle for production of steel starts with the extraction of natural resources used for the production of iron ore, alloy materials and other raw material inputs.

Most of these raw materials, as well as fuels and electricity, have been traced back from the cradle. The input of external steel scrap has been considered as “free” from environmental burden in the cradle to gate analysis. However, when the whole life cycle for a steel structure is considered, this steel scrap will have a burden at the same time as the recycled scrap is given a credit.

General data, sourced mainly from the GaBi database [3:2], has been used for the production of raw materials, alloying elements, generation of electricity, and transportation.

This analysis has been performed as an absolute analysis and the result is expressed as environmental equivalent parameters of Global Warming Potential (GWP, CO_{2e}), Acidification Potential (AP), Eutrophication Potential (EP), Photochem Ozone Creation Potential (POCP) as well as the use of non-renewable energy resources.

3.3.2 LCA of structures of high strength steel

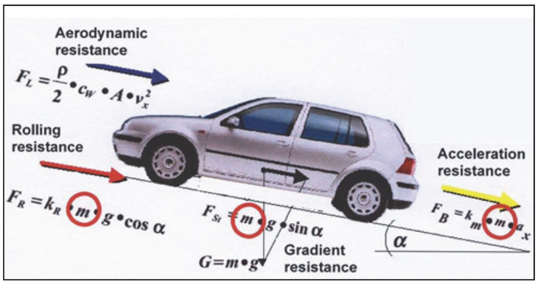
When assessing the environmental value of high strength steel in structural applications, it is appropriate to differentiate between passive and active structures. For passive structures, it is the environmental impact during the production of steels, manufacture of structures and related transport, together with the service life and end of life features that normally contributes most in the life cycle assessment. However, there are examples when the use phase can have a considerable influence also for passive applications, se the case study on the pipe system reported in chapter 6.10. For active structures, the environmental impact during the use phase has a substantial influence on the result of the life cycle assessment. One main issue for both passive and active structures is to evaluate how well the higher yield strength of the high strength steel can be transformed into lower weight.

It is also important to know whether some part of the increased yield strength of the high strength steel is used to increase performance in terms of higher payload, improved crash resistance, longer life, improved dent resistance or improved abrasion resistance, corrosion resistance, etc.

Especially for active structures, it is important to know how much of the weight reduction can be transformed into lower energy use during the use phase. It is then important to know, especially for vehicles in the transport sector, whether the transport is weight critical or volume critical.

If the transport is weight critical, a weight reduction could be directly converted into an increased payload, with corresponding decreases in environmental impact and a lower cost for a certain amount of load transported. Some examples of such structures are different types of vehicles for construction work, such as wheel loaders, heavy trucks and dumpers as well as timber transport vehicles, tanker trucks and cranes.

If the transport is volume critical, the lower weight is used to lower the energy needed for propulsion and thereby lower the environmental impact. However, it is normally not possible in this case to convert all weight reduction into reduction in energy used, since some of the energy supplied is utilized to overcome air resistance (drag) and losses in transmissions, and to operate auxiliary systems. The forces acting on a vehicle is schematically illustrated in Figure 3.3.2 and the distribution of energy flows in Figure 3.3.3 [3:3].



The energy flows related to weight are kinetic energy during acceleration and braking, potential energy losses in uphill and downhill travel and rolling resistance.

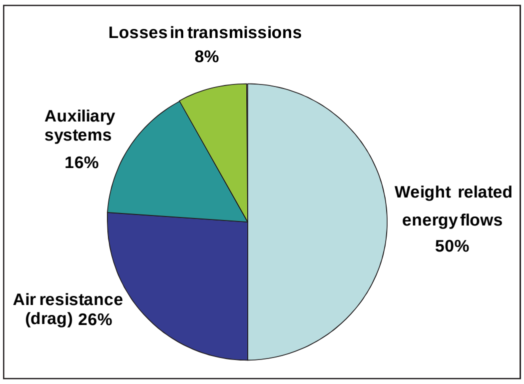


Figure 3.3.3. Example of flows of energy for a passenger car, average values [3:3]

The use of advanced high strength steel structures can also improve crash energy absorption, dent resistance and wear resistance, as well as the working environment due to lower weight of structural parts during production and transport.

It can also result in easier and less costly production due to smaller welds with less filler material and reductions in process steps such as heat treatment, thus reducing both environmental impact and cost. These factors are not always easy to quantify, but improved wear resistance and corrosion resistance, for example, can be accompanied by an increase in service life and reduced maintenance. Increased crash energy absorption can be considered by performing an alternative calculation of the increase in environmental impact that would have been the result if conventional steel were not replaced by high strength steel with higher energy absorption.

3.4 Model for the LCA and LCC analysis

The model for the analysis in this project is shown in Figure 3.4.1. The different steps in the life cycle will be regarded as separate modules and the total environmental and cost impact will be the sum of the contributions from each module.

Figure 3.3.2. Forces acting on a car, schematic

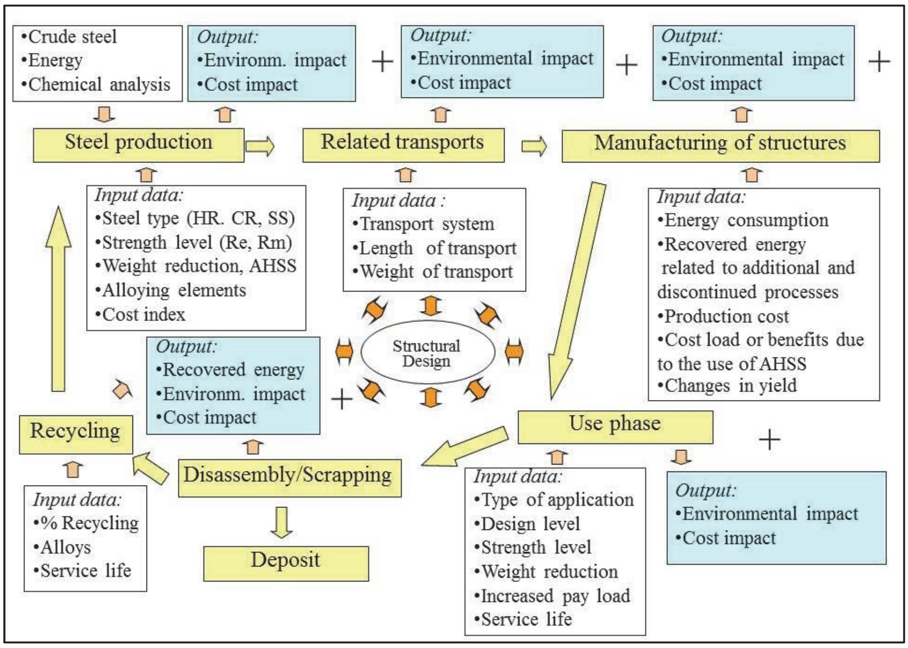


Figure 3.4.1. Structure of the life cycle analysis

4. RESULTS AND MODELS FOR LCA OF STEEL AND STEEL STRUCTURES

4.1 LCA of raw material and steel production, cradle to gate

The analysis of environmental impact from steel production is reported in detail in [3:1].

Figures 4.1.1- 4.1.4 shows the summarized results for steel production including production of raw materials and alloys as a function of yield strength (cradle to gate according to figure 3.3.1). The results are presented in terms of Global warming potentials (GWP) as kg CO_2-equivalents (CO_{2e}) and as a function of the yield strength. This value mainly consists of CO_2-emissions, which is why it is referred to as such in discussing the results, but emissions such as methane and nitrous oxide also contributes. More detailed results are reported in [3:1].

For carbon steel grades, the type of steel influences more than the yield strength.

In general the values for cold reduced steel are somewhat higher than for hot rolled steels, since the process also includes cold rolling and annealing. The values for hot dip galvanized steel are higher than for cold reduced steel since more alloying is needed to reach certain strength in the hot deep galvanizing process.

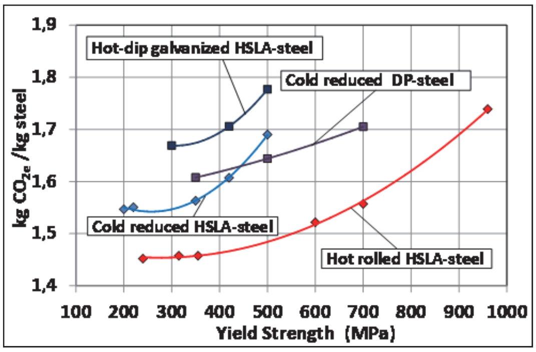


Figure 4.1.1. CO_{2e} emissions, cradle to gate for strip products of carbon steel

The influence of yield strength is comparatively small for all these steels, Figure 4.1.1. The value for steel S960 (1.74 kg CO_{2e}/kg steel) is given for a production route which is based on a future production at the metallurgy in the SSAB Luleå plant. However, today the slabs are delivered from SSAB Oxelösund, and as long as this is the case, the value will be 2.23 kg CO_{2e}/kg steel.

In general the carbon dioxide emissions for strip products, figure 4.1.1, are lower than values found for such products at continental steel works. They are therefore also lower than average data published by worldsteel. When calculating potential improvements in environmental impact on the European level when using advanced high strength steel is the values published by worldsteel used. The basic level used for hot rolled coils of conventional steel is then 2.0 ton CO_{2e}/ton steel, cradle to gate. The influence of yield strength is evaluated based of data from this project.

Figures for carbon dioxide emissions of carbon steel plate, stainless strips and tubes are shown in Figures 4.1.2. to 4.1.4.

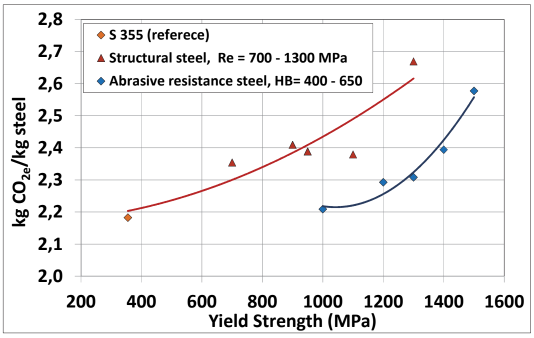


Figure 4.1.2. CO_{2e} emissions, cradle to gate, for plate products of carbon steel

For the carbon steel plate grades there is a clear tendency of increasing CO_{2e} emissions with increasing strength. The explanation to the fact that steel type S1100 has lower CO_{2e} values than S900 type steel is due to differences in production yield in this case.

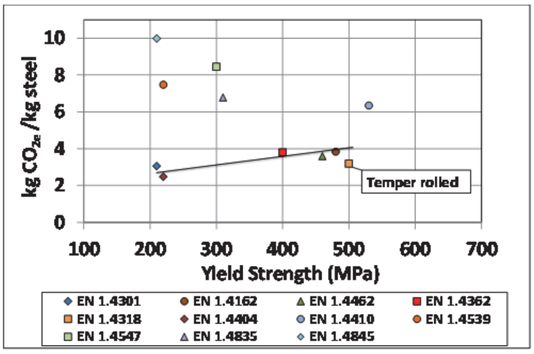


Figure 4.1.3. CO_{2e} emissions, cradle to gate for stainless steel from steel strip products

The process metallurgy for producing high strength steel is continuously being optimized. This has an effect on the environmental cradle to gate data and it is especially evident for the stainless steels. Those are highly alloyed and the share of alloying element of virgin raw material compared to alloys in scrap can vary quite a lot. A newly developed grade which normally have a large share of virgin alloys show high values of CO_{2e} in a cradle to gate analysis, values that will decrease with time when the grade is more established. This issue which contributes to a large overall scatter in cradle to gate data will be the adjusted by burden and credits for scrap in a cradle to grave analysis.

This is also shown in the cradle to grave analysis which is performed in the case studies on stainless steel applications in chapter 6.2, 6.9 and 6.10. If the stainless steels with similar corrosion properties, reported in figure 4.1.3, are regarded, that is for example steels with cradle to gate CO_{2e}-emissions below 4 kg/kg steel, the increase in CO_{2e} with increasing strength seems reasonable. The steel with higher CO_{2e}-emissions contain higher amount of alloys since other properties than increased strength is given precedence to.

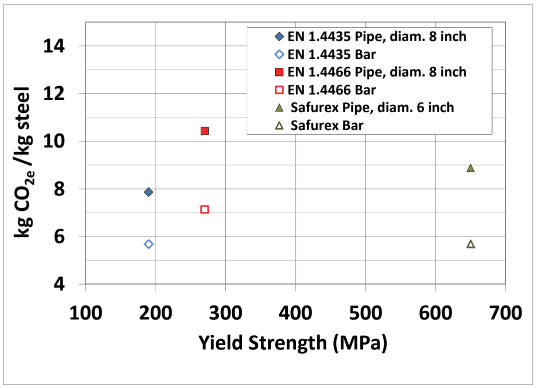


Figure 4.1.4. CO_{2e} emissions, cradle to gate, for stainless steel bars and tubes used for Urea production plants

For the stainless tube steels there is neither a systematic increase in environmental impact with increasing strength, and the differences between bar and tube shown in figure 4.1.4 is mainly related to differences in yield in the manufacturing process.

In order to evaluate relations between environmental impact and chemical composition, a multiple regression analysis with different alloying elements as independent variables has been performed for all investigated steels. Regression constants for Equation 4.1 have been evaluated based on the CO_{2e}-values shown in figures 4.1.1-4.1.4 and the typical chemical composition of the steels, Table 4.1.1. Note that this is a result of a pure mathematic regression which is valid only for the type steels analysed and for the range of alloying content that is the basis for the analysis.

$$CO_{2e}=m_C*C+m_{Si}*Si+m_{Mn}*Mn+m_S*S+m_N*N+m_{Cr}*Cr+m_{Ni}*Ni+m_{Cu}*Cu+m_{Mo}*Mo+m_{Al}*Al+m_{Nb}*Nb+m_V*V+m_{Ti}*Ti+m_0 \qquad (4:1)$$

The elements in the chemical composition are expressed in per cent and the CO_{2e} in kg/kg steel.

Table 4.1.1. Regression coefficients (m) for different chemical elements and types of steel

Type of steel	Number of data points	m_C	m_{Si}	m_{Mn}	m_S	m_N	m_{Cr}	m_{Ni}	m_{Cu}	m_{Mo}	m_{Al}	m_{Nb}	m_V	m_{Ti}	m_0	r2	Std dev
Carbon steel																	
Hot rolled strip, all	11	-1,070	0,590	-0,269	-3,298	2,057	0,850	0,234	-2,042	0,000	0,000	0,217	0,000	2,192	1,682	1,000	0,0000
Optimized 1	11	-3,098	0,006	0,012	0,000	0,000	1,622	0,867	-1,427	0,000	0,000	0,615	-17,90	1,663	1,664	1,000	0,0027
Optimized 2	11	0,000	0,638	-0,242	0,000	0,000	-0,115	-0,570	0,000	0,000	0,000	0,000	18,070	1,601	1,563	0,795	0,0879
Cold redused strip, all	12	0,270	0,194	0,047	2,238	0,000	0,510	-0,134	-0,413	0,000	1,069	0,377	-0,186	0,000	1,449	0,999	0,0080
Optimized	12	0,000	0,205	0,048	0,000	0,000	0,501	0,000	-0,413	0,000	0,000	0,000	0,000	0,000	1,534	0,997	0,0217
Hot dip galvanised, all	7	0,000	0,499	0,070	0,000	0,000	0,381	12,554	0,000	-0,434	0,000	1,251	0,000	0,000	1,125	1,000	0,0000
Hot rolled structural plate, all	5	0,000	0,000	-0,728	0,000	0,000	1,771	-0,434	0,000	-0,338	0,000	0,000	0,000	0,000	3,137	1,000	0,0000
Hot rolled wear plate, all	5	0,000	0,000	-0,228	0,000	0,000	-0,040	0,041	0,000	0,282	0,000	0,000	0,000	-3,095	2,584	1,000	0,0000
Stainless steel																	
Hot rollrd strip, scrap and virgin alloys	11	0,000	0,000	0,030	0,000	0,000	0,487	0,269	0,000	-0,004	0,000	0,000	0,000	0,000	-7,771	0,855	1,2479
Hot rollrd strip,virgin alloys only	11	0,000	0,000	-0,116	0,000	0,000	0,237	0,253	0,000	0,093	0,000	0,000	0,000	0,000	1,374	0,992	0,2988
Pipe, scrap and vrigin alloys	3	0,000	0,000	0,000	0,000	0,000	1,408	-0,073	0,000	0,000	0,000	0,000	0,000	0,000	-14,765	1,000	0,0000
Pipe,vigin alloys only	3	0,000	0,000	0,000	0,000	0,000	3,642	-0,144	0,000	0,000	0,000	0,000	0,000	0,000	-32,219	1,000	0,0000

In order to reduce the number of independent variables (chemical elements) in the regression an optimizing has been performed. The determination coefficient, r2, decreases somewhat and the standard deviation increases. However, the accuracy of the prediction is still very good. For stainless strip steels the determination coefficient, r2, increases and the scatter decreases a lot if only the amount of virgin Cr and Ni is included in the regression, Figure 4.1.5. However, for pipe and bars the number of data is too few to make such an analysis.

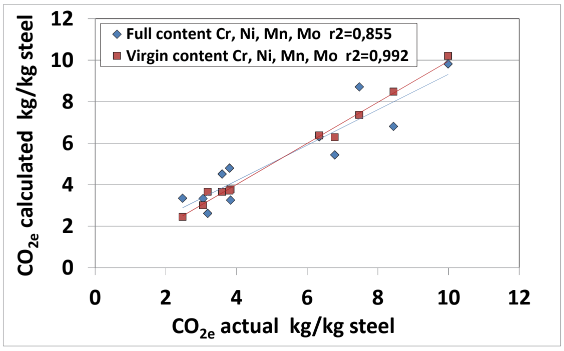


Figure 4.1.5. Comparison between actual and calculated CO_{2e}-values for stainless steel sheet

The life cycle assessment of steel production [3:1] shows that results for other impact categories are closely related to the CO_{2e}-emissions and that this relationship is almost independent of steel grade at a specific production site.

With a few exceptions this also holds for the use of non-renewable energy resources in steel production.

If these resources are expressed in kWh per kg CO_{2e}, this relation is 4.0-4.4 kWh/kg CO_{2e} for iron ore based production of carbon steel and 3.3-3.8 kWh/kg CO_{2e} for stainless steel manufactured from scrap.

In order to show a more adequate relationship between environmental impacts of different steel grades used in *products and structures* where conventional steel has been replaced by high strength steel, an example is shown in Figure 4.1.6. This graph is valid for hot rolled strip steel with data according to figure 4.1.1, and assuming that the relationship between weight reduction and yield strength follows the square root formula* for upgraded parts. The slight increase in environmental load per tonne steel with increasing yield strength, which is seen in figures 4.1.1- 4.1.4 is more than outweighed by the light weighting benefits.

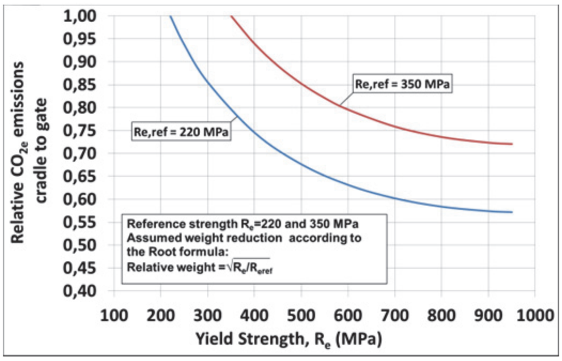


Figure 4.1.6. Relative CO_{2e}-emissions, cradle to gate, as a function of yield strength when hot rolled strip is used in structures

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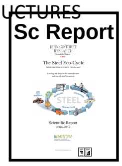
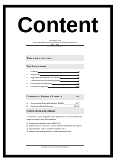
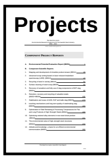
* See chapter 5.2 "Design in advanced high strength steel"







4.2 The applicability of the LCA-results

In the previous section, cradle-to-gate results for carbon and stainless steel grades were presented. These results should be used as a “database” when performing a full cradle-to-grave LCA on steel applications. The cradle-to-gate results should not be used for comparing the steel grades with each other (per tonne of steel) and there are several reasons for this:

- One steel grade can require less material to fulfil a specific function in a steel application.
- The input of steel scrap has been considered as free of environmental burden, which is in line with the methodology recommended by World Steel Association (WSA). This means that no burden for scrap is given in the cradle-to-gate phase but the burden given in the cradle-to-grave analysis.
- For stainless steel grades, it is furthermore a fact that different steel grades receive different shares of alloy elements from steel scrap and from virgin raw materials. Since scrap is considered as free from environmental burden in the cradle-to-gate phase, a steel grade with a large share from scrap comes out better.

It is the results for the stainless steel grades that are mostly affected by the fact that the input of steel scrap has been considered as free of environmental burden. This is illustrated by an example below:

The cradle-to-gate results shown in figure 4.1.3 are presented in a bar diagram in Figure 4.2.1.

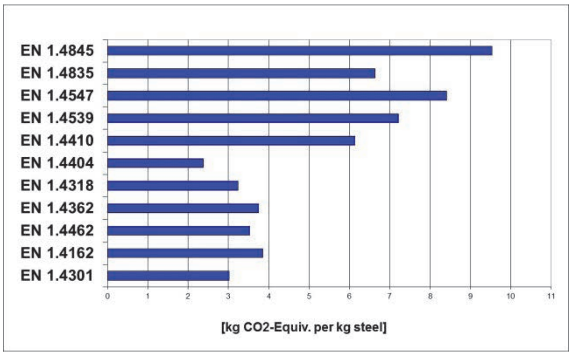


Figure 4.2.1. CO$_{2e}$ emissions per kg steel, cradle to gate for stainless steel from steel strip products

Figure 4.2.2 shows the cradle-to-gate results when the burdens for the scrap inputs have been added.

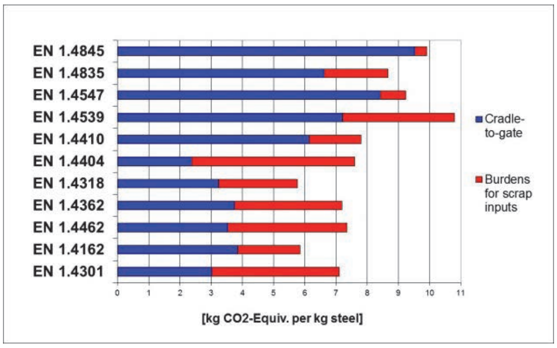


Figure 4.2.2. CO$_{2e}$ emissions, for stainless steel strip products - when burdens for the scrap inputs have been added (red bars) to the cradle-to-gate (blue bars)

When the cradle-to-grave LCA is performed on a steel application, a credit for the amount of recycled steel will be taken into account and the actual environmental burden is shown in Figure 4.2.3.

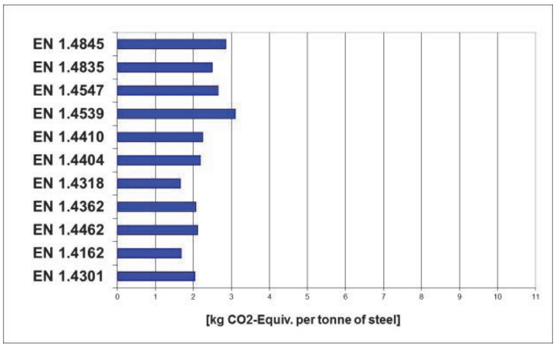
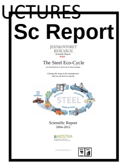


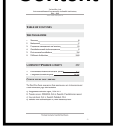
Figure 4.2.3. CO$_{2e}$ emissions, for stainless steel strip products - total results cradle-to-grave when a credit for the recycled steel after use in a steel application has been considered (95 % recycling rate assumed)

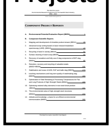
The conclusion is that when taking the whole picture (cradle-to-grave) into account, the comparison of the steel grades is substantially affected. When also taking into account that certain steel grades can require less material to fulfil a specific function in a steel application, the conclusion might be that the steel grade appearing to be the worst according to the cradle-to-gate results (figure 4.2.1) might in fact be the best from a total life-cycle perspective.

4.3 LCA for structures of advanced high strength steel

The division of the LCA into modules means that the total environmental impact is achieved by adding the results from each module. The following designations are used for different LCA modules.







M1 = Steel production
M2 = Transport of steel and structures
M3 = Manufacture of structures
M4 = Use of structures
M5 = Dismantling/Recycling

The equations shown below only refer to the calculation of carbon dioxide emissions (CO_{2e}). However, the way the calculation is performed for different impact categories is basically the same, regardless of which category that is considered [3:1].

4.3.1 Steel production, cradle to gate (M1)

The total environmental value for steel and raw material production is calculated by Equation 4:2.

$$M_{steel} = \Sigma(M_{steel,x} * W_{steel,x})_n \qquad (4:2)$$

where

M_{steel} = Total environmental value of the upgraded parts of the structure

$M_{steel,x}$ = Environmental value (cradle to gate) for grade x [per kg steel]

$W_{steel,x}$ = Weight of steel x [kg]

n = Number of steel grades

The environmental value $M_{steel,x}$ is found in figure 4.1.1-4.1.4. The total environmental *saving* is calculated by applying equation 4:2 before and after upgrading and calculate the difference (ΔM_{steel}). If the parts in the structure have shorter lifetime before than after upgrading the environmental value before upgrading can be multiplied by the lifetime ratio after and before upgrading. See also $M4_{wear}$ section 4.3.5 below.

4.3.2 Transport (M2)

The total environmental value of the transports is calculated by Equation 4:3:

$$M_{trsp} = \Sigma(M_{trsp,y} * W_{steel,y} * TDy)_n \qquad (4:3)$$

where

M_{trsp} = Total environmental value for transport of upgraded parts of the structure

$M_{trsp,y}$ = Environmental value for y-type of transport vehicle [per tonnekm]

$W_{steel,}$ = Total amount of steel transported with y-type of transport vehicle [tonne]

TD_y = Transport distance with carrier y [km]

n = Number of types of carriers

The environmental value $M_{trsp,y}$ for some transport vehicles is found in figure 4.3.1. The total environmental *saving* is calculated by applying equation 4.3 after and before upgrading and calculate the difference (ΔM_{trsp}).

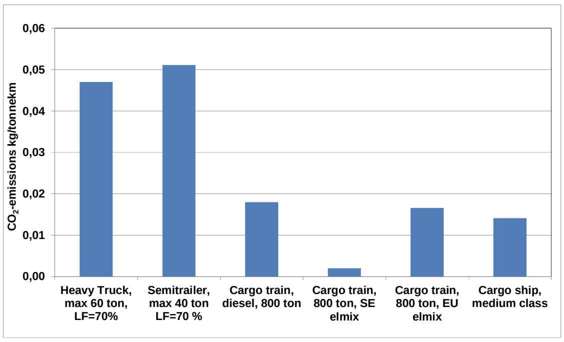


Figure 4.3.1. Environmental value for some transport vehicles, kg CO_{2e} per tonkm

4.3.3 Manufacture of structures (M3)

This module deals with the differences in production of structures made of advanced high strength steel compared to conventional steel. There could be less environmental impact due to smaller welds and reduction in process steps, such as heat treatment. For ease of assessment, these factors could normally be expressed in terms of energy.

The net environmental value related to manufacture with high strength steel instead of conventional steel is calculated according to Equation 4.4:

$$\Delta M_{manuf} = M_3 * (EC) \qquad (4:4)$$

where

EC = Gained - lost electrical energy due to the use of AHSS for upgrading (kWh)

M3 = For electrical energy: M3 = 0.082 (kg CO_{2e}/kWh) for »Swedish average« electrical energy mix (IEA 2007); corresponding figures for »Nordic average« is 0.1, Swedish marginal electricity produced from natural gas is 0.35, for European average (EU 27) where a lot of electricity is generated by coal, the figure is 0.52 kg CO_{2e} /kWh (IEA 2005).

4.3.4 Use of structures (M4)

When assessing the environmental value of high strength steel in structural applications, it is appropriate to differentiate between passive and active structures. For most passive structures, it is the environmental impact during the production of steels, manufacture of structures and related transport, together with the service life and end of life features that contributes in the life cycle assessment. For active structures, the environmental impact during the use phase also has a substantial influence on the result of the life cycle assessment.

Passive structures

Passive steel structures often give little or no environmental impact during the use phase. The environmental benefits of passive structures are therefore mainly related to the consumption of less steel, and to a smaller amount of steel to be transported.

Note the exception in the case study reported in chapter 6.10.

If the use phase would be of significance, it is only interesting to know if there is a difference before and after upgrading.

One can, for example, imagine that the structure or parts of it have different life time. Repair, maintenance and replacement of various wear parts in the structure may differ before and after the upgrading of the steel, and this will influence the life time and the environmental impact.

The service life can be extended by using more corrosive resistant steel. Heat resistance steel can also increase the efficiency of energy generation and give significant environmental benefits during the design life. If the life time of a structural component is shorter than the service life after upgrading. This can be taken into account by multiplying the environmental value of steel component before upgrading with life time ratio L2/L1. L1 is then the life time after and L2 the life time before upgrading. Note that when doing such a calculating the influence on the amount of recycled steel should be considered.

Active structures

Active structures that are mostly structures in the transport segment normally have their main environmental impact in the use phase. The whole service life expressed as life time distance is considered. The assessment in this module is somewhat different if the transport is weight or volume critical.

Weight critical transports

If the transport is weight critical, a weight reduction could be directly converted into increased payload, with corresponding decreases in environmental impact for a certain amount of load transported.

An increased payload means fewer trips to transport a certain amount of goods with corresponding savings in environmental impact.

For the weight critical (wc) transports the environmental savings is calculated according to Equation 4:5:

$$\Delta M_{use,wc} = FC_{full} * WR/MPL * M_{fuel} * LTD_{wc} \quad (4:5)$$

where:

$\Delta M_{use,wc}$ = Total environmental saving due to weight reduction [kg CO_{2e}/vehicle]
FC_{full} = Fuel consumtion fully loaded [litre/km]
M_{fuel} = Environmental value for production and burning of fuel [kg CO_{2e} per litre of diesel fuel = 3 kg CO_{2e}/litre including production of the fuel]
WR = Weight reduction [kg]
MPL = Maximum pay load [kg]
LTD = Life time driving distance [km]

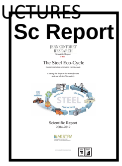
Volume critical transport

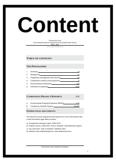
If the transport is volume critical (vc) which include empty trips it is, as mentioned, not possible to convert all weight reduction in weight into reduction in energy used, since some resistance factors are not mass dependent, see figure 3.3.2. The part of the energy which is related to the mass is usually about 25 to 80 percent of the total energy, depending on driving style, terrain, speed, acceleration, rolling resistance and aerodynamic drag. At operating conditions, with many starts and stops, much acceleration, hilly terrain and at low to moderate speeds, the energy savings are greatest for a given weight reduction.

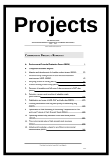
There are two alternative ways to assess the effectiveness of a weight reduction. One way, which is often used for brief calculations, is to use an energy efficiency, η, for expressing the relative benefit, in terms of energy saving in %, of a certain weight reduction expressed in % of the actual gross weight. This efficiency η is defined by Equation 4:6.

$$\text{Saving in energy consumption [\%]} = \eta * \text{weight reduction [\%]} \quad (4:6)$$

The efficiency η for some typical vehicles is given in Figure 4.3.2.







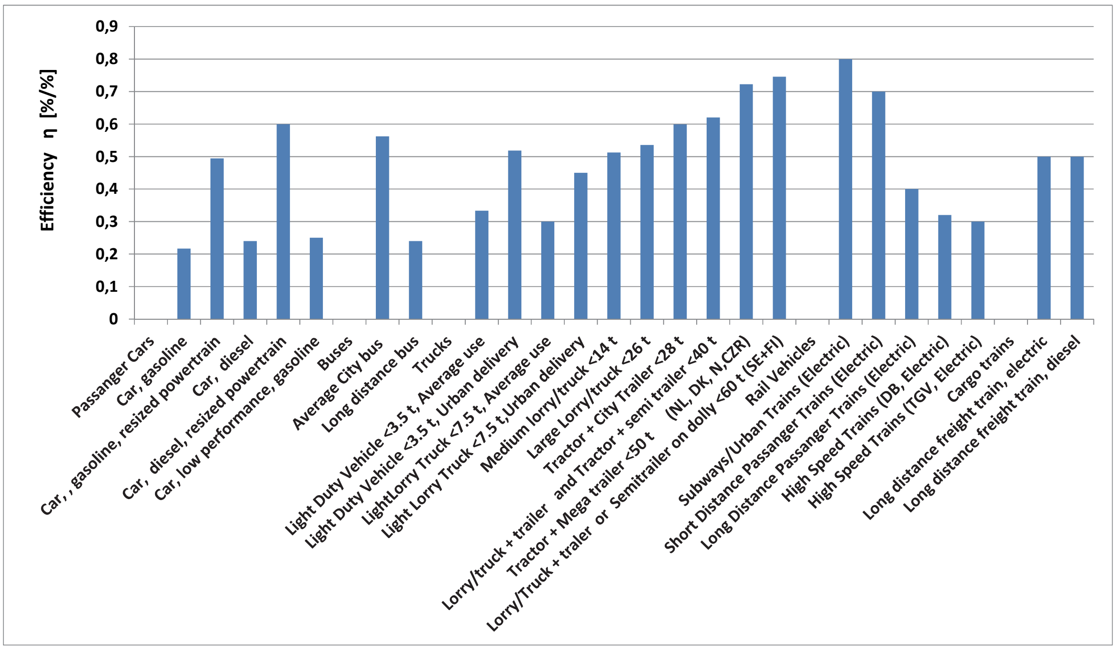


Figure 4.3.2 Examples for the energy efficiency η for different vehicles when light weighting

The environmental savings is calculated by multiplying the efficiency η with the environmental value for manufacturing and consumption of fuel, or the production and consumption of electricity if the "fuel" is electricity, with the weight reduction and with the total lifetime distance, Equation 4:7.

$$\Delta M_{use,vc} = \eta * M_{fuel} * FC(EC) * VM * LTD \qquad (4.7)$$

where

$\Delta M_{use,vc}$ = Environmental savings due the weight reduction WR [kg]

η = Energy efficiency

M_{fuel} = Environmental value in the production and use of "fuel" [litre of fuel or kWh of electricity,]

FC(EC) = Energy consumption litres/km or kWh/km at the current load

WR = Weight reduction at upgrading as a percentage of current gross weight

LTD = Total life time mileage [km]

The second way to analyse the fuel savings resulting from a weight reduction for volume critical and empty transportation, is to calculate the specific energy savings for a given weight reduction SFC [litres/km and kg weight loss] or SEC [kWh/km kg weight reduction]. The reason for this is that under the same driving conditions the correlation between energy consumption and vehicle weight is linear [4:1]. When doing so data on energy consumption for the entire vehicle, empty and fully loaded and the maximum load capacity of the vehicle is needed. SFC is then calculated according to Equation 4:8.

$$SFC = (FC_{full} - FC_{empty})/MPL \qquad (4:8)$$

where

SFC = Specific saving in fuel comsumption [litre/(km and kg weight reduction)]

FC_{full} = Fuel consumtion fully loaded [litre/km]

FC_{empty} = Fuel consumtion empty loaded [litre/km]

MPL = Maximum pay load [kg]

For volume critical transports the energy consumption is related to the resistance forces on the vehicles which mainly are rolling resistance, gradient (hilly or flat), inertia, internal friction and air resistance, Equation 4:9.

$$F_{tot} = mg * C_{rr} + mg * \sin\alpha + (e_i m_{veh} + m_{load}) * a + F_{if} + 0,5 * C_d * A * \rho_{air} V^2 \qquad (4:9)$$

where

m = Vehicle gross weight ($m = m_{veh} + m_{load}$)

g = Acceleration of gravity

C_{rr} = Road resistance factor

α = Gradient angle

e_i = Mass correction factor

a = Vehicle acceleration

F_{if} = Sum of internal friction forces

C_d = Air drag coefficient

A = Vehicle face surface

ρ_{air} = Density of air

V = Vehicle speed

All resistance forces except internal friction and aerodynamic resistance are linearly dependent on the vehicle mass. The aerodynamic resistance depends on the vehicle dimensions and the square of the vehicle speed. If one particular kind of vehicle and driving situation is considered, i.e. with a certain average speed, start and stop pattern, acceleration and gradients, the absolute energy savings for a certain mass reduction is independent of the vehicle gross weight [4:1].

If the energy consumption for the actual vehicle empty and fully loaded is not available, literature data could give guidance for estimating SFC. Figures 4.3.3 and 4.3.4 show such data for cars and trucks and buses as a function of average speed.

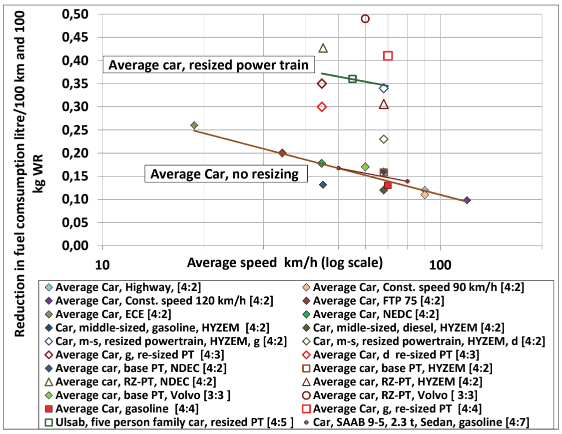


Figure 4.3.3. Absolute saving in fuel consumption for cars, litre/(100 km and 100kg weight reduction)

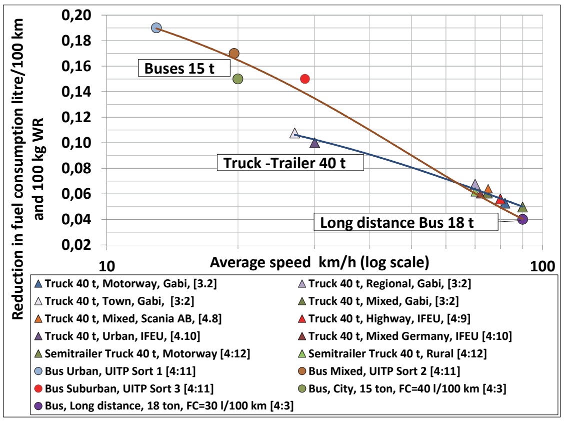


Figure 4.3.4. Absolute saving in fuel consumption for trucks and buses, litre/(100 km and 100kg weight reduction)

The average speed is a variable which at least approximately should be able to catch the influence of different driving cycles.

Data and background on absolute energy savings, SFC/SEC, as well as the weight efficiency values, η, is given in [4:2-4:11] and summarised in Table 4.2.1. Since η varies somewhat with the load factor (LF), common defaults according to [4:12] have been chosen when calculating values given in Table 4.3.1. This table also includes an estimate of life time performance of the vehicles [4:3 and 4:4]. Except for the rather extreme situations like a truck on a flat motorway or underground trains, η does not vary that much for a certain type of vehicle, but there is of cause a small influence of type of operation and average speed. SFC and SEC do not normally vary with the load factor.

Table 4.3.1. Summary of specific and absolute environmental savings together with estimated life time performance for different vehicles

Road Vehicles	**η [%R-FC/%WR]**	**SFC^1 [litre/(100 km *100 kg WR^2)]**	**Life time [million km]**
Passanger Cars			
Car, gasoline	0,22	0,150	0,20
Car, , gasoline, resized powertrain	0,49	0,350	0,20
Car, diesel	0,24	0,120	0,20
Car, diesel, resized powertrain	0,60	0,300	0,20
Car, low performance, gasoline	0,25	0,150	0,10
Buses			
Average City bus	0,56	0,150	1,00
Long distance bus	0,24	0,040	1,20
Trucks			
Light Duty Vehicle <3.5 t, Average use	0,33	0,200	0,30
Light Duty Vehicle <3.5 t, Urban delivery	0,52	0,350	0,36
LightLorry Truck <7.5 t, Average use	0,30	0,120	0,38
Light Lorry Truck <7.5 t,Urban delivery	0,45	0,200	0,46
Medium lorry/truck <14 t	0,51	0,076	1,00
Large Lorry/truck <26 t	0,54	0,061	1,00
Tractor + City Trailer <28 t	0,60	0,068	1,00
Lorry/truck + trailer and Tractor + semi	0,62	0,061	1,20
Tractor + Mega trailer <50 t (NL, DK, N,CZR)	0,72	0,071	1,20
Lorry/Truck + traler, Semitrailer on dolly <60 t	0,75	0,086	1,20
Rail Vehicles	**η [%R-EC/%WR]**	**SEC^3 [kWh/(100 km *100 kg WR^2)]**	**Life time [million km]**
Passanger trains, electric			
Subways/Urban Trains	0,80	0,640	3
Short Distance Passanger Trains	0,70	0,460	4
Long Distance Passanger Trains	0,40	0,140	8
High Speed Trains (DB)	0,32	0,096	15
High Speed Trains (TGV, Electric)	0,30	0,129	15
Cargo trains			
Long distance freight train, electric	0,50	0,110	8
Long distance freight train, diesel	0,50	0,250	8
1) SFC=Saving in Fuel Consumption			
2) WR=Weght Reduction			
3) SEC=Saving in Energy Consumption			

4.3.5 Environmental savings with abrasive resistance steel

Wear resistance steels normally have a hardness varying from 360 to 700 HB. If an application is upgraded from conventional steel to a wear resistance steel the service life could be considerably increased in a wear application. If such an upgrading is made it also means that the environmental impact of the application can be reduced due to the fact that less steel need to be used in order to fulfil the function for a certain product life.

The theory behind the relation between hardness of the worn steel, wearing material and relative wear is well described in [4:13], Figure 4.3.5. Note the substantial reduction in wear which is a result of changing the mechanism of wear from abrasive wear to plastic deformation wear.

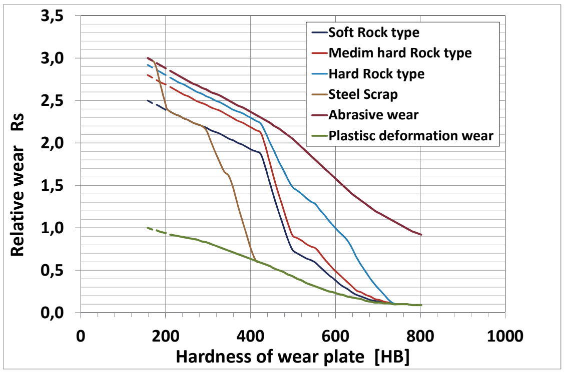


Figure 4.3.5. Relation between relative wear, hardness of worn steel and wearing material

The relative improvement in wear life could be described by Equation 4:10.

$$L_2/L_1 = Rs_1/Rs_2 * t_2/t_1 \qquad (4:10)$$

where

L = Wear life
Rs = Relative wear
t = Thickness of worn plate
Index 1 = Before upgrading
Index 2 = After upgrading

The environmental improvement of the upgrading can be calculated by applying equation 4:2 and multiplying it with the relative wear ratio for each wear part according to equation 4:10, Equation 4:11.

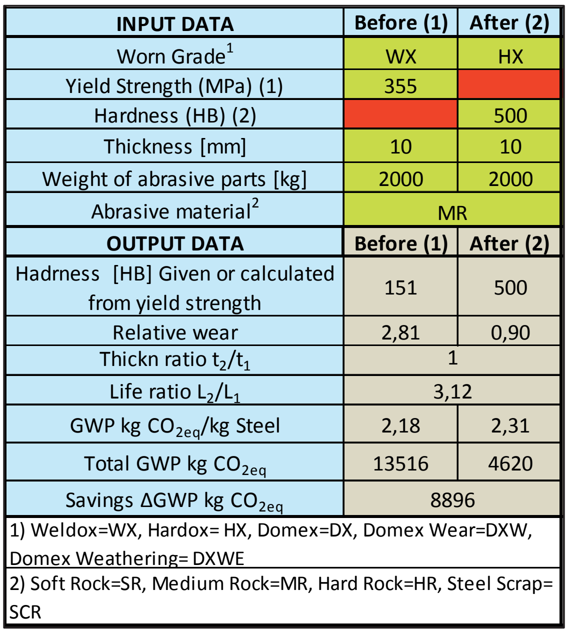
$$\Delta M_{wear} = \Sigma((M_{steel,y1} * W_{steel,x,y1} * L_{2x}/L_{1x}) - (M_{steel,y2} * W_{steel,x,z2}))_n \qquad (4:11)$$

where

ΔM_{steel} = Total environmental improvement of the wear upgraded parts of the structure
$M_{steel,y}$ = Environmental value for grade y [per kg steel], used before upgrading
$M_{steel,z}$ = Environmental value for grade y [per kg steel], used after upgrading
$W_{steel,x,y1}$ = Weight of part x of steel y before upgrading [kg]
$W_{steel,x,z2}$ = Weight of part x of steel z after upgrading [kg]
n = Number of upgraded parts that are wear critical
L_2/L_1 = Relative wear ratio according to equation 4.10 for actual part

The environmental value $M_{steel,y}$ and $M_{steel,z}$ is found in figure 4.1.1-4.1.4. Please also note the text on caution when using cradle to gate data in chapter 4.1, especially for stainless steel.

Let us look at a simple example on a gutter which is worn by medium hard rock. It is upgraded from steel Weldox 355 to Hardox 400. The thickness is 10 mm and is not changed at the upgrading. The question is: what environmental savings could be achieved due to higher wear resistance and longer service life? The results from the wear module used in EcoSteel is shown in Figure 4.3.6.



INPUT DATA	Before (1)	After (2)
Worn Grade[1]	WX	HX
Yield Strength (MPa) (1)	355	🟥
Hardness (HB) (2)	🟥	500
Thickness [mm]	10	10
Weight of abrasive parts [kg]	2000	2000
Abrasive material[2]	MR	
OUTPUT DATA	**Before (1)**	**After (2)**
Hadrness [HB] Given or calculated from yield strength	151	500
Relative wear	2,81	0,90
Thickn ratio t_2/t_1	1	
Life ratio L_2/L_1	3,12	
GWP kg CO_{2eq}/kg Steel	2,18	2,31
Total GWP kg CO_{2eq}	13516	4620
Savings ΔGWP kg CO_{2eq}	8896	
1) Weldox=WX, Hardox= HX, Domex=DX, Domex Wear=DXW, Domex Weathering= DXWE		
2) Soft Rock=SR, Medium Rock=MR, Hard Rock=HR, Steel Scrap= SCR		

Figure 4.3.6. Upgrading of a gutter. Results from the wear module used in the EcoSteel software

4.3.6 Recycling (M5)

This module deals with the differences in dismantling and recycling of structures made of advanced high strength steel compared to conventional steel. There could be less credit in environmental impact for the upgraded structure because the weight is lower and less steel will be recycled. Estimating the environmental value of scrap to be credited in the recycling phase is performed by a method published by worldsteel [4:14]. In the software EcoSteel, described in section 4.3.7 this has been included in the calculation.

Equation 4:12 can be used to get brief estimates of the environmental value of *recycled steel scrap*:

$$M_{scrap} = \Sigma(0.75 * M_{steel,x} * W_{steel,x} * RR)_n \tag{4.12}$$

where

M_{scrap} = Total environmental value of scap
$M_{steel,x}$ = Environmental value (cradle to gate) for grade x [per kg steel]
$W_{steel,x}$ = Weight of steel x [kg]
RR = Recycling rate
n = Number of steel grades

The environmental value $M_{steel,x}$ could be found in figure 4.1.1- 4.1.4. The difference in environmental value for the scrap credit due to the upgrading is calculated by applying equation 4:12 before and after upgrading and calculate the difference (ΔM_{scrap}). In a full cradle-to-grave assessment a burden need to be given for input of scrap, which has being regarded as free of environmental burden in the cradle to gate analysis. The most important factor in this phase is probably the differences before and after upgrading in scrap input at the steel production and scrap recycled at end of life. Examples of this are shown in chapter 4.2 and in some of the case studies in chapter 4.7.

4.3.7 Software tool, Eco Steel

In order to facilitate a full calculation including recycling based on the models above, an engineering tool (EcoSteel) has been developed. Based on steel grades used before and after upgrading, weight and achieved weight reduction, type of structure, energy consumption and type of transport it is possible to calculate the environmental savings and savings in costs. There are also a number of default cases for different vehicles included. Figure 4.3.7 shows the different calculation modules for active and passive applications and figure 4.3.8 the input interface to the software. Figure 4.3.9 finally shows an example of output results for a passive structure.

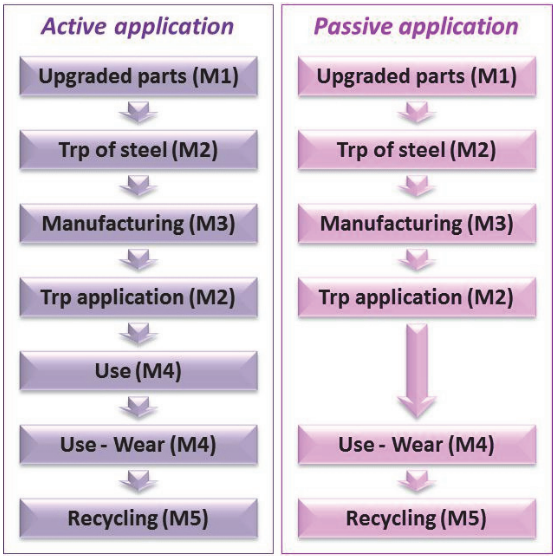
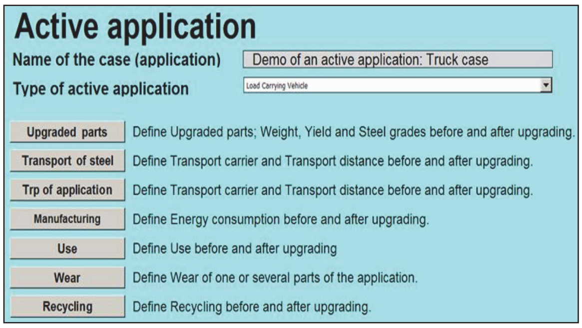


Figure 4.3.7: The modules for active and passive applications.


Active application
Name of the case (application): Demo of an active application: Truck case
Type of active application: Load Carrying Vehicle

Upgraded parts: Define Upgraded parts; Weight, Yield and Steel grades before and after upgrading.
Transport of steel: Define Transport carrier and Transport distance before and after upgrading.
Trp of application: Define Transport carrier and Transport distance before and after upgrading.
Manufacturing: Define Energy consumption before and after upgrading.
Use: Define Use before and after upgrading
Wear: Define Wear of one or several parts of the application.
Recycling: Define Recycling before and after upgrading.

Figure 4.3.8. Input interface to software for calculating the environmental savings with high strength steel, example

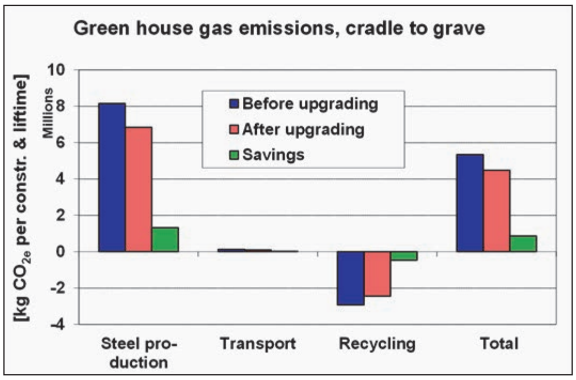


Figure 4.3.9. Total results from EcoSteel example passive structure, example

5. POTENTIAL WEIGHT REDUCTIONS, RELATED TO DESIGN AND STEEL STRENGTH

5.1 Real life upgrading cases

In order to obtain a background for further analysis of the influence of increased steel strength on possible weight reduction, a number of real life upgrading cases have been collected and analysed.

The relative weight as a function of relative steel strength after upgrading from conventional steel to advanced high strength steel is shown in Figure 5.1.1. This graph shows the relative weights of the parts of the structure that have been upgraded. If these parts consist of different subparts with different values of yield strength, the quoted yield strength is a weighted average for those subparts.

Some cases in figure 5.1.1 contain abrasion resistant steel that has been used partly to increase wear resistance and service life. This could be a reason why these cases do not show figures of weight reduction that correspond to the increase in yield strength. Other circumstances of this nature are also present in other cases and are one reason for a fairly high scatter in the result.

The overall result in figure 5.1.1 supports the use of the root formula as a rule of thumb when estimating the potential for weight reduction when using advanced high strength steel.

The results also show that the project goal of 20 % weight reduction for upgraded parts could be achieved.

Passive structures seem to have a higher potential for weight reduction than active structures, which seems reasonable since they normally do not need to be designed for fatigue loading.

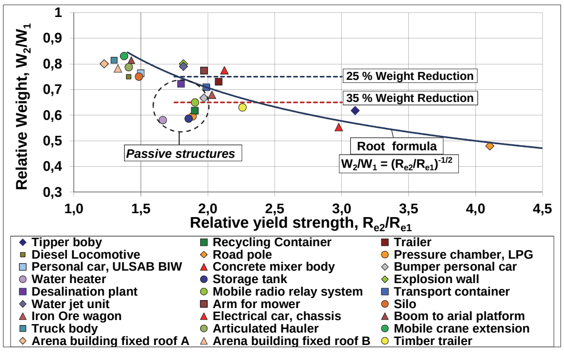


Figure 5.1.1 Summary of weight reduction for upgrading cases

5.2 Design in advanced high strength steel

In principle, there is nothing new or remarkable about using advanced high strength steels in design work. However, buckling, deformations, points of load application and fatigue of welded joints are areas that require a little extra attention.

The design of structures of high strength steel is usually carried out in accordance with two main principles:

-*Relative design*, which is based on an existing structure, material thicknesses being reduced or applied load being increased in some relation to the increase in yield strength.

-*Design from basic principles*, in which a new design is produced for the whole structure on the basis of the loading conditions that apply.

The advantage of *relative design* is that it is relatively simple. The designer can use the known behaviour of the existing structure and the knowledge of how various properties change when the thickness and yield strength are altered. The drawback is that the designer runs the risk of being bogged down in a design approach that has been characterized by the properties of milder steel. Furthermore, he or she is unable to put to use the margins available because of previous over sizing.

Design from basic principles enables the designer to carry out overall optimization of the structure made of the high strength material and thereby achieve the greatest gains. The difficulty is that data relating to the real loads on the structure are often unreliable.

In practice, a relative design is often carried out and a check, and if necessary a partial redesign, is made for buckling, deformation, points of load application and fatigue.

When employing the relative design approach above, it is convenient to use approximate relationships between different design and manufacturing properties, strength of the steel and sheet thickness, Equation 5:1.

$$P = A{*}R^m{*}t^n \qquad (5:1)$$

where

P = Property concerned
R = Yield or Tensile strength, R_e or R_m
A = Constant
t = Sheet thickness
m, n = Constants in accordance with Table 4.4.1

The possible improvement in properties for the *same sheet or plate thickness* is then given by Equation 5:2.

$$P_2/P_1 = (R_2/R_1)^{m} \qquad (5:2)$$

The possible reduction in thickness and weight for *the same design capacity* is given by Equation 5:3.

$$t_2/t_1 = (R_1/R_2)^{m/n} \qquad (5:3)$$

Subscript 1 indicates the reference structure of mild steel
Subscript 2 indicates the structure of high strength steel

Practical experience has shown that an initial assumption that the ratio of thickness or weight between a structure of high strength steel and one of mild steel is inversely proportional to the square root of the ratio of the yield strengths, i.e. to use the so called *root formula* gives a good estimate, Equation 5:4.

$$t_2/t_1 = (R_{e1}/R_{e2})^{0.5} \qquad (5:4)$$

A check is then made to determine whether the resulting deformation is permissible and whether the fatigue strength is adequate. If these requirements are not satisfied, stiffness can be raised by changes in section and the fatigue strength by a choice of welded joints with a lower stress concentration effect. Alternatively, TIG dressing or grinding can be specified. Some of these factors are dealt with in more detail in chapter 5.3.

5.3 Critical design issues to be considered when using advanced high strength steel in structures

The characteristics of modern advanced high strength steel products are the combination of high tensile strength together with good forming and welding properties.

Dual Phase carbon steels and stainless steels in particular have low yield strength in relation to the tensile strength, and excellent stretch-forming properties. When the steel is deformed in a cold-forming process, it is hardened by *work hardening*. This means that processing can be started with a "soft" material and can end up with a strong structural part. It is important to note the significant difference between a DP steel and conventional HSLA steel in this respect, Figure 5.2.1. The figure also demonstrates why the tensile strength rather than yield strength is a measure of the potential of a DP steel to carry load and absorb energy.

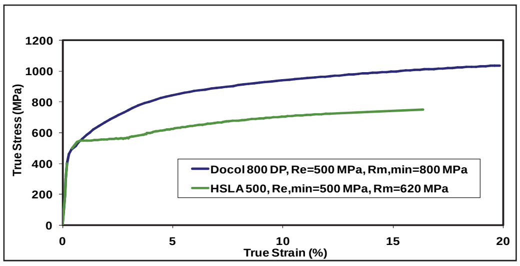


Figure 5.2.1. Comparison of stress-strain curves for a Dual Phase steel and a conventional HSLA steel

Bake hardening during the baking of the paint causes the steel to harden further and become even stronger.

High strength steels offer great potential for weight reduction and cost effective designs. In order to benefit fully from them, structural design and production processes should be adjusted to the properties of the steel. The use of high strength steel for weight reduction is often associated with a reduction in thickness. This means that some specific design issues have to be addressed for successful application of these steel grades. These are stiffness, introduction of loads, buckling, fatigue, crash resistance and toughness for thicker steel plates. When using these steels in production of structural parts, questions of particular concern are mainly related to forming, welding and production economy.

A decrease in thickness will reduce the *stiffness* if no changes are made to the overall geometry of the structure. However, a small material addition for a somewhat higher beam cross-section can give unchanged stiffness as well as reduced weight and cost.

A fundamental principle in design is to transmit loads in the structure by tension rather than by bending. This means that making use of "skin effect" and to avoid "plate effect" leads to lower stresses and deformations. This is particularly important in areas of *load introduction* where the decreased thickness associated with the use of high strength steel can otherwise lead to high stresses and deformations.

Buckling can sometimes limit the load-bearing capacity of high strength steel structures. The critical parameter for buckling is the width to thickness ratio w/t, which decreases with increasing yield strength of the steel. Buckling could be met by design changes that decrease the width of flanges and plate panels loaded in compression, e.g. by introducing folds.

Certain load bearing-parts of a structure may be subject to *fatigue loading*. The fatigue strength of the parent material increases with increasing yield strength and the fatigue strength is highly dependent on the roughness of steel surfaces and edges [5:2]. Welded joints normally contain inherent geometrical defects that make the fatigue strength of welded joints independent of the yield strength [5:3]. When using high strength steel, the design must therefore be improved in order to match higher working stresses and/or the fatigue strength to be increased by post weld treatment such as grinding, peening or TIG dressing, Figure 5.5.2.

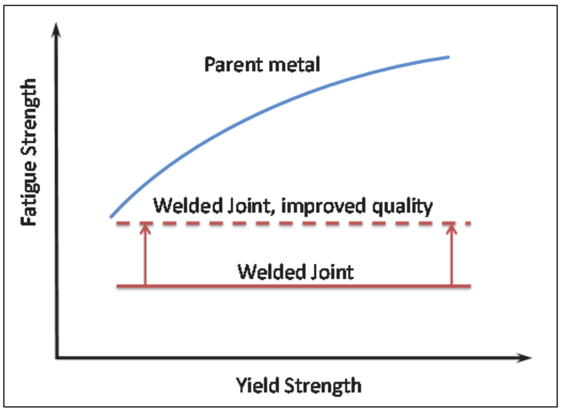


Figure 5.2.2. Schematic of fatigue strength of parent material and welded joints

6. CASE STUDIES

In order to exemplify a full life cycle assessment of the environmental impact when using advanced high strength steel instead of conventional steel, ten case studies have been performed:

1. Semitrailer tipper for scrap transport
2. Storage tank for marble slurry
3. Spiral dewaterer for mines
4. Articulated hauler
5. Loader crane
6. Arena building, Friends Arena
7. Trailer for timber transport
8. Chair frame
9. Bumper to car
10. Tube system for Urea production

The life cycle assessment is based on emission data for different steels assessed in this project [3:1], which is summarized in chapter 4.1. For structures, it is important to assess the environmental performance during the whole life cycle and the assessments in the case studies follow the modular system with modules M1 to M5 described in chapter 4.3. In some cases the software tool EcoSteel is used for the analysis. For purpose of showing the applicability of the models developed, some of the cases are presented in more details than others.

6.1 Semitrailer tipper

6.1.1 Description of the case

The semitrailer tipper is mainly used for transporting steel scrap to steel mills. This vehicle is manufactured by Alkom in Verona, Italy, who also supplied the data needed for the analysis.

The tipper is an active structure, where the main part of the environmental impact is related to the use of the vehicle.

The study is based on the reference unit of one vehicle during a life time of 6 years.

The steels used for the chassis and tipper body were upgraded to higher strength. The upgraded structures are shown in Figures 6.1.1 and 6.1.2.

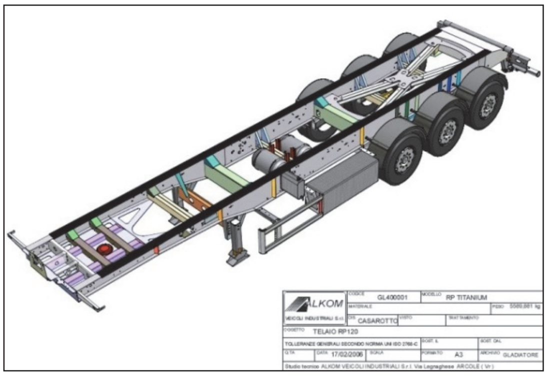


Figure 6.1.1. Chassis of tipper

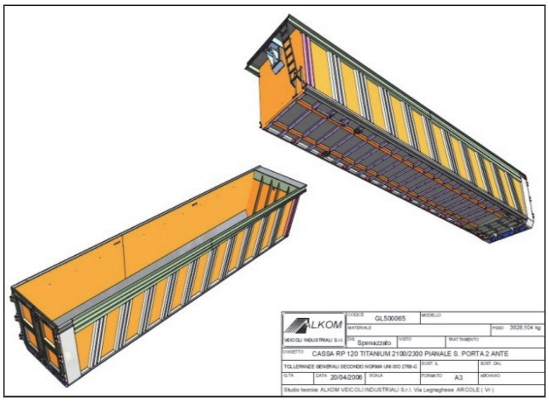


Figure 6.1.2. Tipper body

The steel grades, their yield strength, thicknesses and weights before and after upgrading are shown in Tables 6.1.1 and 6.1.2 for the different structural parts.

The weight reduction of upgraded parts was 1.3 tonne, which on average correspond to a weight reduction of 30 % on these parts. The weight reduction is 25 % if only parts that are mainly designed to carry load are considered, i.e. the floor and sides of the tipper body are excluded.

Table 6.1.1. Upgraded parts on the chassis

CHASSIS	Before upgrading				After upgrading			
Chassis parts	Steel grade	Yield strength [MPa]	Thick-ness [mm]	Weight of part [kg]	Steel grade	Yield strength [MPa]	Thick-ness [mm]	Weight of part [kg]
Longitudinal beams,	S700	700	12	470	Domex 700	700	12	470
Longitudinal beams, web	FE510	355	5	150	Domex 700	700	4	115
Stabilizing profiles	FE510	355	4	200	Docol 1200	950	1,8	85
Cross beams	FE510	355	4	25	Domex 700	700	3	18
Total				845				688

Table 6.1.2. Upgraded parts on the tipper body

TIPPER BODY	Before upgrading				After upgrading			
Tipper body parts	Steel grade	Yield strength [MPa]	Thick-ness [mm]	Weight of part [kg]	Steel grade	Yield strength [MPa]	Thick-ness [mm]	Weight of part [kg]
Floor	HB400	1000	5	1060	Hardox 450	1200	4	680
Sides	HB400	1000	4	2150	Hardox 450	1200	3,2	1520
Floor, cross members	FE510 /S700	355	3	21	Docol 1200	950	1,5	7,9
Floor, longitudinal members	FE510 /S700	355	3	15	Docol 1200	950	1,5	6,3
Ribs	HB400	1000	3	22	Hardox 450	1200	1,5	11
Upper support	FE510 /S700	355	3	90	Docol 1200	950	1,5	45
Lower support	FE510 /S700	355	3	120	Docol 1200	950	1,8	72
Total				3478				2342

For these parts, a possible weight reduction is also related to the increased wear resistance. The rule of thumb described by equation 5:4 indicates a weight reduction of 21 % for an average increase in yield strength of 1.5 times, which is in place in this case for the load carrying parts.

The total weight reduction of 1.3 tonnes means that the curb weight was reduced from 17 tonnes to 15.7 tonnes or by 7.6 %. This also means that the payload capacity was increased by 1.3 tonnes (4.8%) from 27 to 28.3 tonnes at a maximum gross weight of 44 tonnes. The case is described in more detail in the case sub report [6:1].

6.1.2 Life cycle assessment

Steel production (M1)

This module includes the production of steel used for manufacturing of the upgraded parts of the vehicle. According to the manufacturer, the weights of the steel produced are about 10 % higher than the gross weights of the final parts due to yield during manufacturing.

Transport of steel (M2)

There were a number of European suppliers of the steel grades that were used before upgrading. For the transport of these steel grades from the producer to Alkom in Verona, a transport distance of 1000 km by electric train has been assumed. For the generation of electricity, data according to European average generation has been applied.

All steels used after upgrading were purchased from SSAB EMEA in Sweden. The steels were transported by rail and sea, and the total distance was about 2000 km.

Manufacturing (M3)

The vehicle manufacture consists of the following process steps: 1-Preparation, 2-Assembly, 3-Welding, 4-Connection, 5-Sand-blasting and Painting, 6-Pneumatic and electric system installations, 7-Final connection, 8-Finishing.

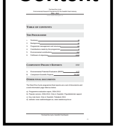
No data (energy consumption, etc.) was provided concerning the manufacture of the vehicle. The upgraded vehicle requires one process step less than before and the amount of welding is also less (about 30 %). However, no quantitative absolute data on the environmental consequences of this have been provided.

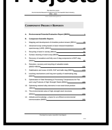
The Manufacturing phase (M3) has therefore been excluded from the environmental analysis. However, this is not a severe data gap since this part is of minor importance for active structures, where the use phase is the dominant part of the lifecycle.

Use phase (M4)

The entire weight reduction of 1.3 tonne can be used to increase the payload, since the transport of steel is weight critical.

The tipper is mainly used for transporting steel scrap to the steel mills. On the return trip, steel products such as coils are transported. According to Alkom an average load factor of about 85 % is representative for the whole transport of scrap and steel.





Before upgrading the vehicle, a typical number of trips per year were 400 (an average distance of 250 km/trip, including the return). This means that 9180 tonne of cargo were transported each year. To transport the same load after upgrading, only 382 trips were needed.

The figures for fuel consumption provided by Alkom are presented in Table 6.1.3.

Table 6.1.3. Fuel consumption for the Alkom tipper

Diesel fuel consumption	Empty [litre/km]	Fully loaded [litre/km]
Before upgrading	0,33	0,4
After upgrading	0,32	0,4

To calculate the environmental load per year, transport data from the Gabi database [3:2] was used. The production of diesel fuel has been included in the analysis. The total environmental impact during the life cycle is obtained by multiplying by the life time, which is estimated by Alkom to be six years.

Upgrading the floor to the harder Hardox 450 abrasion-resistant steel increased the life of the floor about 40 %. If this is included in the life cycle, the decrease in environmental impact in the steel production phase would increase from 30 to 35 %. The corresponding figures for the steel cost reduction are 2 % to 9 %. The increased life of the floor has little effect on the total results and has therefore not been included in the final assessment results.

Recycling (M5)

As mentioned earlier in the report, scrap added in the steel production process is regarded free of environmental burden. When a full life cycle assessment of a structure is performed, it is possible to take into account both the environmental burden of the input scrap and the credit for the recycled scrap.

The analysis shows that the input and output of scrap during the life cycle have little influence on the total result, since the tipper is an active structure. However, the environmental impact in the "steel material eco cycle" (M1+M5) is reduced by almost 50 % if the input and output of scrap are considered.

Impact assessment results

Five different impact categories are used, i.e. global warming, acidification, eutrophication, ozone creation, and abiotic depletion. In this report, only global warming have been chosen to illustrate the results, Figures 6.1.3. However, the total impact assessment results for all impact categories are presented in [3.1]. To see the environmental savings more clearly those are shown in Figure 6.1.4.

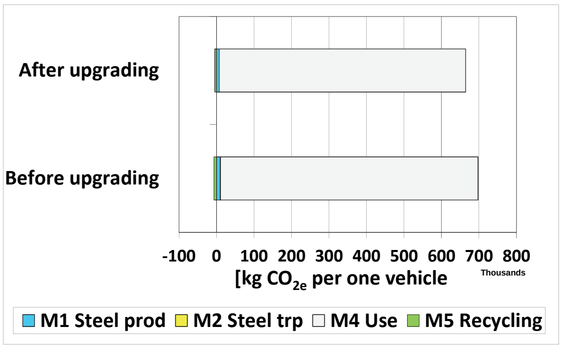


Figure 6.1.3. Total results for the Alkom tipper, Global warming, 6 years life time

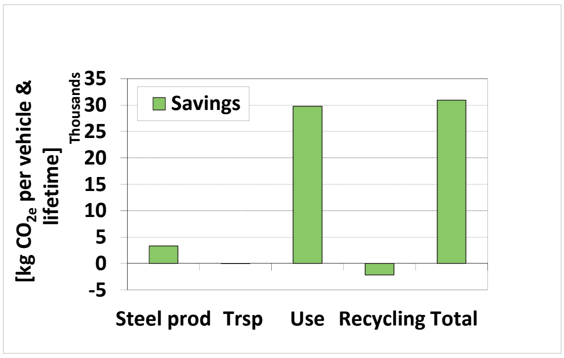


Figure 6.1.4. Total results for the Alkom tipper, Global warming, savings, output from EcoSteel

The vehicle has a 5-6 % lower environmental impact after upgrading for all categories studied. This upgrading was a second step and considerable improvements had already been achieved in a first step

Contributions within the life cycle chain

Assuming a life of 6 years, the use of the vehicle (M4) corresponds to as much as 99 % of the impact. Steel production (M1) corresponds to roughly 1 % and steel transport (M2) to 0.01 %. Considering the *savings* in environmental impact by using advanced high strength steels, figure 6.1.4, about 10 % of the benefit comes from reduced steel production and 90 % from lower fuel consumption. If recycling is considered only about 2 % of the savings come from steel production.

6.1.3 Life cycle cost

Although environmental care is beginning to have a greater influence on decisions on the choice of material, cost is still the main issue. However, in the decision process, the price of the material per unit of weight is often taken into account rather than the life cycle cost (LCC), which is often a more relevant figure to look at.

An analysis of the life cycle cost in the case studies in this project shows this very clearly. Although the steel price per unit of weight is somewhat higher for advanced high strength steel than for conventional steel, both the cost of the manufacture and the cost during use will be reduced, Table 6.1.4.

Table 6.1.4. Life cycle cost of the Alkom Tipper

Total cost	Before upgrading		After upgrading	
	Cost [Euro]	% of tot	Cost [Euro]	% of tot
M1: Steel material costs	7600	2	7473	2
M2: Transport costs, steel$^{(1)}$	---	---	---	---
M3: Manufacturing costs$^{(2)}$	37000	9	37000	10
M4: Use costs$^{(3)}$	355870	89	318838	88
Total	400 470	100	363 311	100

(1) Included in the steel material cost.
(2) The cost after upgrading was not provided and the same cost as before upgrading was assumed.
(3) Includes fuel cost (about 75 %) and maintenance (about 25).

There is a reduction of 10 % in life cycle cost after upgrading. The reduction is mainly associated with lower fuel consumption. It is also interesting to note that only 2 % of the total cost is related to the cost of the steel material.

6.2 Storage tank

6.2.1 Description of the case

A storage tank has been upgraded by replacing conventional stainless steel with a high strength duplex stainless steel, Figure 6.2.1.

The tank is mainly used for storing marble slurry and similar liquids. It is designed for liquid with a density of 1.3 kg/dm^3. Data for the tank before and after upgrading is shown in Table 6.2.1.

The tank wall segments are manufactured in a workshop and are erected on the site where the tank will be in operation.

Figure 6.2.1. A stainless steel storage tank

Table 6.2.1. Data for the storage tank

Data for storage tank in stainless steel	Steel grade	$R_{p0,2}$ min [MPa]	Total weight [ton]	H [m]	D [m]	Vol [m3]	Plate width [m]	Design stress [MPa]
Before upgrading$^{(1)}$	EN 1.4301	210	57,4	14	17	3178	2	140
After upgrading$^{(2)}$	EN 1.4162	480	38,3	14	17	3178	2	260

(1) Conventional stainless steel (EH 1.4301; 18.1 % Cr & 8.3 % Ni) - ref case
(2) Duplex high strentgh stainless steel (EN 1.4162; 21.5 % Cr & 1.5 % Ni)

Thicknesses of the circumferential sheets before and after upgrading are shown in Figure 6.2.2.

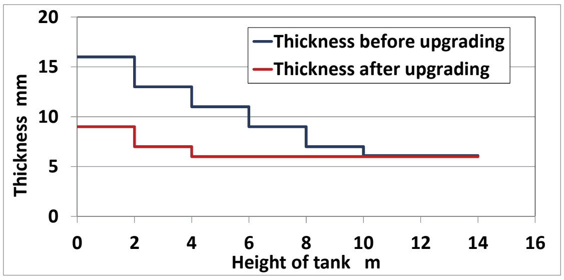


Figure 6.2.2. Thicknesses of the circumferential sheets for the tank

After upgrading, the thickness reduction stops at 6 mm, which constitutes the minimum thickness according to the standard.

The total weight reduction of the storage tank was 19.1 tonne or 33 %.

The information on the storage tank case was provided by Outokumpu Stainless, Avesta. Information on the costs has been supplied by Stålmonteringar AB (STÅLAB) in Trollhättan, Sweden, a manufacturer of this type of tank.

6.2.2 Life cycle assessment

Steel production (M1)

This module includes the production of the steel used for the storage tank. The steel sheets are delivered to site in the correct sizes, i.e. there are no yield losses on site. The yield losses are small when the steel sheets are cut, and are almost the same before and after upgrading. These losses have therefore not been included in the analysis. The steel consumption is therefore assumed to be equal to the weight of the tanks as shown in Table 6.2.1.

Transport of steel (M2)

Since this case is a more general one and no particular erection site is chosen, the transport distance for steel sheets to the site is assumed to be 1000 km. A truck is chosen as the type of carrier used.

Manufacture of the tank (M3)

As mentioned earlier, the tank is manufactured on site where it will be in operation. It is welded together from 2 m wide steel sheets, and 7 sheets are required for the height of 14 m.

The horizontal weld length is 320 m and the vertical length is 35 m. The consumption of welding wire is 825 kg before and 419 kg after upgrading.

The production of the welding wire has been approximated with the production of the corresponding steel grade. The energy consumption for welding is 8247 kWh before and 4186 kWh after upgrading.

Use of the tank (M4)

The environmental aspects related to the use of the tanks could be differences in maintenance, corrosion resistance and service life. In this case, the life is at least 30 years both before and after upgrading.

However, there is a difference in pitting corrosion resistance of the steels used before and after upgrading. This difference would not normally show up within a 30 year life time, but could lead to pitting corrosion earlier if, for example, cleaning of the tank is not performed properly. The resistance to pitting corrosion is often expressed with a Pitting Resistance Equivalent (PRE), which is related to the chemical composition, Equation 6:1.

$$PRE = Cr\,(\%) + 3.3\,Mo\,(\%) + 16\,N\,(\%) \qquad (6{:}1)$$

For the steels used here, PRE=18 for the reference tank and PRE=26 for the upgraded version, which indicates better pitting corrosion resistance of the latter. In this analysis, any changes in maintenance or service life associated which the difference in pitting corrosion resistance have been disregarded. However, in the general case, differences in PRE could have an influence on service life and thereby on the environmental impact during the life cycle.

Recycling (M5)

Since the scrap input is modelled without environmental burden in the cradle-to-gate analysis, which is recommended by Eurofer [6:2]. A stainless steel grade using a large share of scrap then comes out better than a stainless steel grade with a large share of virgin raw materials, even though the latter has a higher content of alloys then the former. See also section 4.1 and 4.2.

Comparable results for a structure are therefore only obtained when the burden for inputs of scrap as well as the credit for scrap generated when a steel product is recycled is considered. This is shown in Figure 6.2.2, in which also the benefit from the lower weight achieved with the use of high strength steel is considered. In this case study, a recycling rate of 90 % has been assumed.

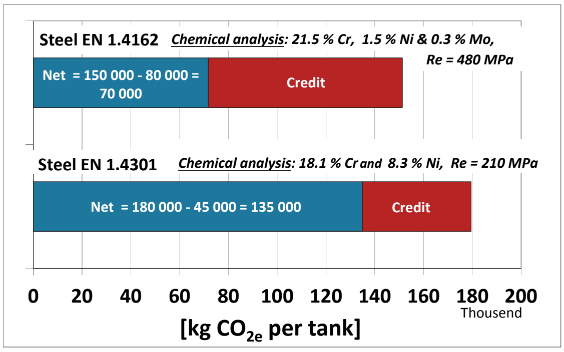


Figure 6.2.2. Total results for the storage tank, Global warming (Net credit = Input burden - Recycling credit)

Impact assessment results

The total impact assessment results for the storage tank are presented in the charts in Figure 6.2.3. Global warming has been chosen to illustrate the results, since the other impact categories show the same pattern as Global warming.

For Global warming, the tank with high strength steel EN 1.4162 have 47 % lower environmental impact than the reference case with conventional stainless steel, EN 1.4301.

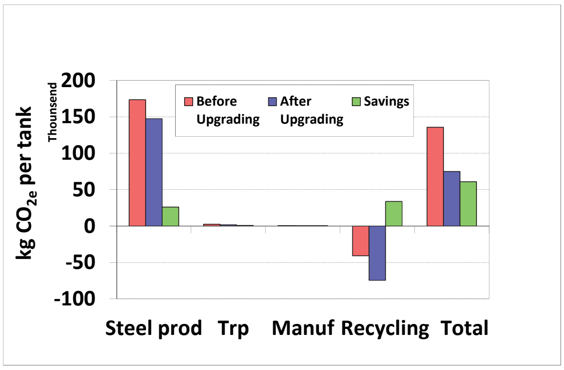


Figure 6.2.3. Total results for the storage tank, Global warming, output from EcoSteel

Contributions within the life cycle chain

Since the storage tank is a passive structure, there is normally little impact on the environment during the use phase (M4). That is why the main impact in this case is related to steel production, which contributes 99 %. The impact from the transport of the steel and the manufacture of the structure is therefore only to about 1 %.

6.2.3 Life cycle cost

Figure 6.2.4 shows a summary of the life cycle cost of the storage tank. The steel prices, including alloy surcharge, have been assumed to be 3450 € and 2600 € for steel EN 1.4301 and EN 1.4162 respectively. The scrap price is set to 1600 € for booth steels. Less welding was needed for the thinner tank after upgrading. This together with other cost reductions resulted in decreased production cost from 132200 € to 86200 €.

By upgrading the material in the tank to a duplex advanced high strength stainless steel with a strength which is twice that of conventional steel, the life cycle cost was be reduced by 45 %. About half of that reduction is due to the fact that less steel is used.

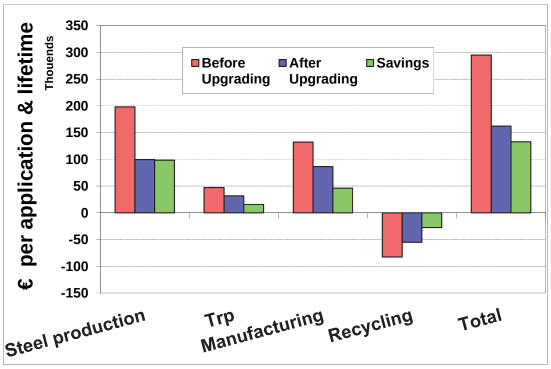


Figure 6.2.4. Cost savings with high strength steel in the storage tank

6.3 Spiral dewaterer

6.3.1 Description of the case

A spiral dewaterer is used to collect dressed ore from slurry in mines. This is a passive structure where conventional mild steel has been replaced by Domex 650 MC steel resulting in many advantages. Data for this study has been supplied by Metso minerals in Sala, Sweden [6:3].

A spiral dewaterer for mine processing has been redesigned and upgraded from mild steel with R_e=220 MPa to high strength steel Domex 650 MC with R_e= 650 MPa**.**

The operating principle for the spiral dewaterer is shown in Figure 6.3.1**.**

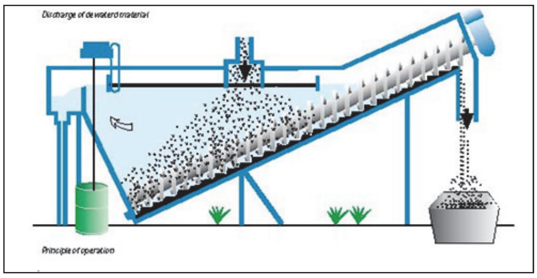


Figure 6.3.1. Spiral dewaterer for mining, operation principle

The old design in mild steel had a lot of external stiffeners in order to withstand the hydrostatic pressure from the water and had a rather flat design of the tank, Figure 6.3.2.

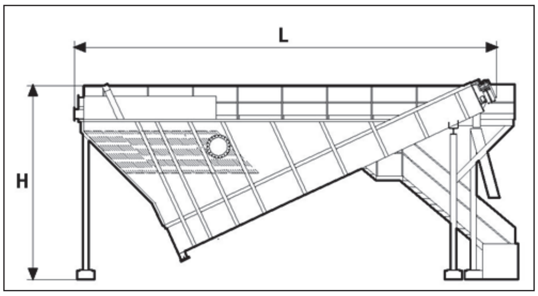


Figure 6.3.2. Old design of spiral dewaterer, total weight 23 tonnes of which the tank weighs 9.7 tonnes

Upgrading from mild steel to high strength steel Domex 650 MC and curving the side plates made it possible to withstand the water pressure without external stiffeners. This resulted in fewer parts (80 instead of 230) and decreased the weight considerably, Table 6.3.1.

Table 6.3.1. Data for Spiral dewaterer

Data for dewaterer	Steel grade	Number of parts	$R_{p0,2}$ min [MPa]	Total weight [ton]	L [m]	H [m]	Weight of tank [ton]	Total weight reduction %	Weight reduction of tank %
Before upgrading(1)	Mild steel	230	210	23	14	6,4	9.7	-	-
After upgrading(2)	AHSS	80	650	17	14	6,4	6.7	26	31

(1) Conventional milds steel, ref case

(2) Advanced high strength steel, with 650 MPa yield strength

The new design of the dewaterer is shown in Figure 6.3.3.

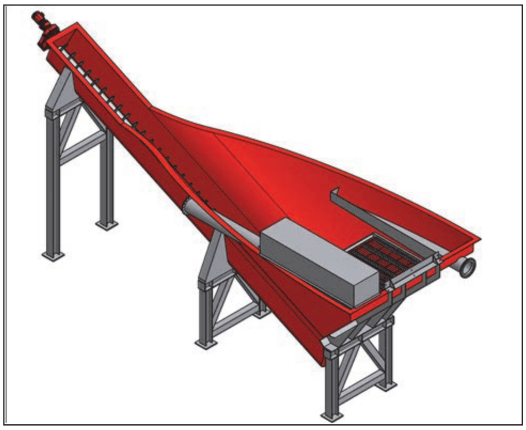


Figure 6.3.3. New design of spiral dewaterer, total weight 17 tonnes of which the tank weighs 6.7 tonnes

The total weight reduction for the spiral dewaterer was 26 % and for the tank alone 31%.

6.3.2 Life cycle assessment

The environmental savings have been evaluated with the earlier mentioned software, EcoSteel and the results are shown as output from that in Figure 6.3.4.

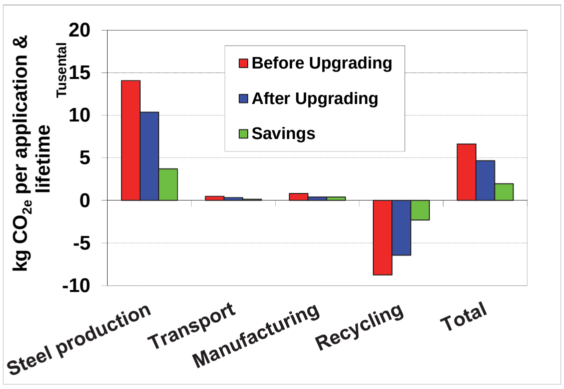


Figure 6.3.4. Environmental savings for one spiral dewaterer made of high strength steel instead of mild steel

The saving in CO_{2e} is totally 1970 kg per unit after recycling.

6.3.3 Life cycle cost

The introduction of longitudinal bolted flange joints instead of welding reduced the manufacturing time from 880 to 570 hours corresponding to a cost saving of 18600 €. The time for assembly on site was also reduced from 240 to 48 hours corresponding to a cost saving of 11520 €. All together this lead to a total cost reduction of 40%.

6.4 Articulated Hauler

6.4.1 Description of the case

Articulated haulers are often used for earth moving and transport of crushed rock at road constructions, Figure 6.4.1. One design issue of major importance when high strength steel is used for light weighting in such an application is fatigue of welded components. A demonstrator from a project dealing with this issue [6:4] is used for assessing the environmental value of high strength in such an application. The bogie beam of the rear frame was analyzed in this case study. Booth the environmental life cycle savings as well as changes in life cycle cost is analyzed.

Figure 6.4.1. Investigated articulated hauler

Structural details

Where the bogie beam is located is shown in Figure 6.4.2. The beam carries the load of an articulated hauler from the rear axles into the frame.

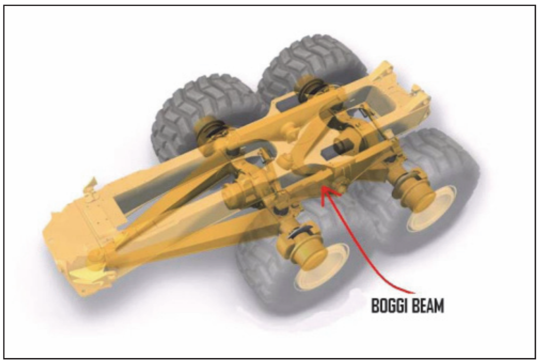


Figure 6.4.2. Position of the bogie beam in the hauler rear frame

Before upgrading this beam is welded from plates in steel with 350 MPa yield strength and formed to a rectangular section.

The design of the bogie beam before and after upgrading is shown in Figure 6.4.3 and Figure 6.4.4.

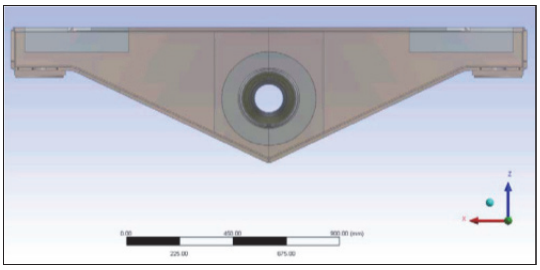


Figure 6.4.3. Design of the bogie beam before upgrading

Since there were some fatigue critical areas in the current design, a redesign was needed. One important change was that the bottom weld was removed and the corner was rounded in such a way that the bottom flange could be continuous.

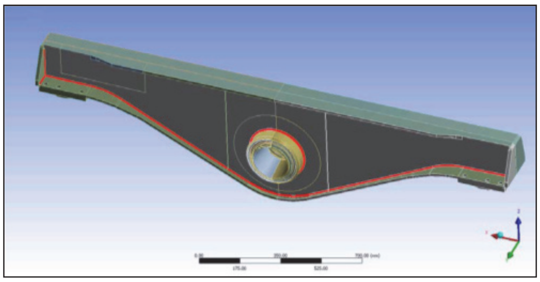


Figure 6.4.4. Design of the bogie beam after upgrading

The weight of the beam before upgrading was 183 kg. The goal with the upgrading was to decrease this weight with at least 20% through thinner plates without altering the overall dimensions. Web and flange thicknesses, weights and grades before and after upgrading are shown in Table 6.4.1.

Table 6.4.1. Structural parts before and after upgrading

Bogie beam	Before upgrading				After upgrading			
Detail	Steel grade	Yield strengt min MPa	Thick-ness [mm]	Weight of part [kg]	Steel grade	Yield strength min MPa	Thick-ness [mm]	Weight of part [kg]
Web plates	HS350	350	8	77	AHSS 600	600	6	58
Upper flange	HS350	350	15	42	AHSS 460	460	12	33
Lower flange	HS350	350	15	28	AHSS 460	460	12	23
Others incl. welds	HS350	350		36	HS 350	350		30
Total				183				144

Totally the weight reduction is 39 kg or 21.3 % and the increase in yield strength on average 41 %. This is somewhat higher than given by the rule of thumb which indicates a weight reduction of 16 %. The net tare weight of the hauler is 31 tonne and the maximum loading capacity 37 tonne. Together this adds up to a gross weight of 69 tonne.

6.4.2 Life cycle assessment

The weight reduction, 39 kg in this case, is of cause very small compared to the total weight of the vehicle but the effort this time was focused on the bogie beam. The case should therefore be seen as an example of what could be achieved and the relative results could be applied to judge the potential if several parts of the structure are upgraded.

Steel production (M1)

This module includes the production of steel used for manufacturing of the upgraded parts of the bogie. According to practice, the weights of the steel produced are at least 10 % higher than the gross weights of the final parts due to yield losses during manufacturing. This is taken into account when the environmental savings from steel production is calculated.

The environmental data used for the steels, were based on figures on SSAB steels derived from this project, since no other such detailed data was published elsewhere.

Transport of steel (M2)

It is assumed that the upgraded steel grades were purchased from SSAB in Sweden. The steel was assumed to be transported 700 km by truck.

There could have been a number of European suppliers of the steel grades that were used before upgrading. For purpose of simplicity the same transport data was used for transports before and after upgrading, this part of the environmental impact being marginal.

Manufacture of the vehicle (M3)

The vehicle manufacture consists of a lot of process steps. However, only a few influence the cost of manufacturing: 1-Cutting of steel sheet and plate, 2-Improvement of fixtures, 3-Weld preparation, 4-Welding of additional weld and 5-TIG dressing. The difference in energy consumption in the production of structures before and after upgrading is small and this was not included in the environmental analysis.

Use of the vehicle (M4)

Articulated haulers are mainly used for transporting heavy gods and when doing so they are regarded to have weight critical transports. If the transport is weight critical, a weight reduction can be directly converted into an increased payload, with corresponding increases in environmental savings and a lower cost for a certain amount of gods transported. However, on the unloaded return trips, which in this case is assumed to be as high as 50 % of the driving distance, it is not possible to convert all weight reduction into reduction in energy used. Some of the energy supplied is then utilized to overcome air resistance and different internal losses. When calculating environmental savings, data on the efficiency of a certain weight reduction are needed. This can for example be evaluated from the fuel consumption of the empty and fully loaded vehicle. Contact with manufacturer Volvo VCE and others [6.5, 6.6 and 6.7] have provided different data shown in Table 6.4.2. The η-value give the relative saving in fuel consumption (FC) expressed in (% of actual FC) for a given weight reduction (% of actual gross weight). SFC gives the absolute savings in litre/h for 100 kg weight reduction.
The data chosen for this case study is shown in the last line in Table 6.4.2.

Table 6.4.2. Data for calculation of fuel savings

Type of Vehicle	Empty loaded			Fully loaded			SFC liter/(h *100 kg WR)	Ref
	Weight tonne	FC litre/h	η %/%	Weight tonne	FC litre/h	η %/%		
AH	31	35	0,24	68	45	0,41	0,027	6.5
AH	31	18	0,65	68	32	0,80	0,038	6.6, 6.7
Truck Town	13	16	0,39	40	29	0,66	0,047	3.2
Truck Regional	13	10	0,39	40	17	0,67	0,029	3.2
Used in this Study	31	20	0,4	68	40	0,6	0,035	

Typically an articulated hauler is driven 2000 hours/year. The economic life time is 5-10 years and then at least 5 more years on a second hand market. A total life time performance of 20000 hours is therefore conservatively assumed. The number of fully loaded trips to transport a certain amount of goods could be increased by 0.039/37*100 = 0.11 % due to the weight reduction of 39 kg. This corresponds to a life time saving of 0.0011*20000*0.5*40= 440 litres of fuel. For the empty trips the fuel saving is 39/100*0.035 *20000*0.5=137 litres, which adds up to a total saving of 580 litres. The use phase then contributes to a life time saving of 1740 kg CO_{2e} (3.0 kg CO_{2e}/litre diesel fuel including production of the fuel [4:12]).

Recycling (M5)

As mentioned, scrap added in the steel production process is regarded as free of environmental burden. When a full life cycle assessment of a structure is performed, it is possible to take into account both the environmental burden of the input scrap and the credit for the recycled scrap. This procedure is shown in [3.1]. In this case study such an analysis is not performed, the environmental impact having marginal influence on the total result for active structures.

Impact assessment results

Five different impact categories are used to describe the environmental impact, i.e. global warming, acidification, eutrophication, ozone creation, and abiotic depletion. In this report, only global warming have been chosen to illustrate the results, Figure 6.4.5.

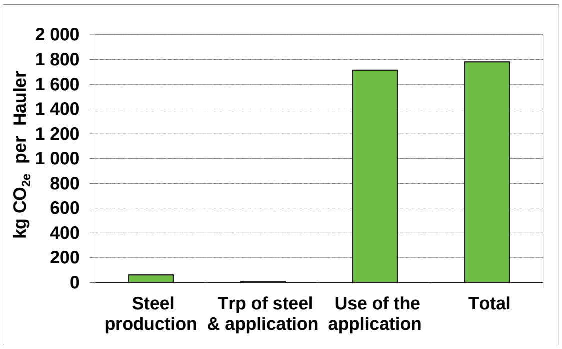


Figure 6.4.5. Total life time CO_{2e}-savings for the Volvo VCE Articulated Hauler

The results shown in figure 6.4.5 is an output from the software tool, EcoSteel, developed in this project.

Contributions within the life cycle chain

As much as 96 % of the environmental saving is derived from less fuel consumption during the vehicle use (M4). The environmental savings due to less steel production (M1) corresponds to roughly 4 % and savings at steel transports (M2) is negligible for active structures.

6.4.3 Life cycle cost

Although environmental care is beginning to have a greater influence on decisions on the choice of material, cost is still the main issue. However, in the decision process, the price of the material per unit of weight is often taken into account rather than the life cycle cost (LCC), which is a more relevant figure to consider.

An analysis of the changes in production cost for different changes related to the use of high strength steel has been performed by Volvo VCE Haulers & Loaders [6.4 and 6.6]. The result of that analysis is shown in Figure 6.4.6.

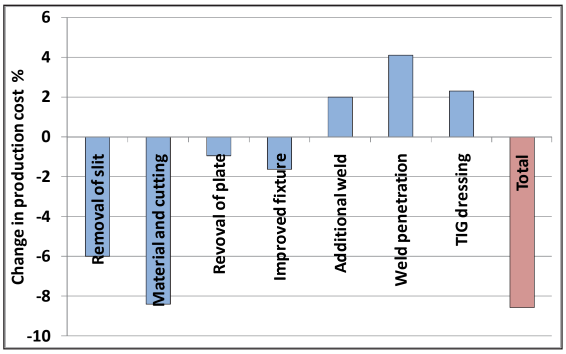


Figure 6.4.6. Change in production cost

The total production cost was reduced by 8.6 % of the total cost for the bogie beam, which is about the same as the reduction in material and cutting. The other changes balance out each other. In addition to the above cost saving the reduced life time fuel consumption gives a cost saving of 900 €, despite the marginal weight reduction of 39 kg corresponding to 0.125 % of the empty tare weight.

6.4.4 Potential for future environmental savings

To reduce weight is an on-going task for many vehicle designers and those who deal with articulated haulers are no exception. The delaying factor for a quick fix in this case is the challenges to reach sufficient weld quality in serial production. This is crucial to meet demands on improved fatigue resistance in welded structures in order to balance out the higher working stresses due to the higher strength of the steel. Measures are under way and improvement in quality level is coming.

A more general analysis of the potential for future environmental savings is performed and based on the overall result from the case study described above. Table 6.4.3 shows that for every ten thousand tonne of advanced high strength steel that replaces conventional high strength steel, there is a potential for saving of 120 ktonne of CO_{2e} and 480 GWh of non-renewable energy resourses.

Table 6.4.3. Environmental savings when ten kton AHSS replaces Conventional HSS

Steel product in Vehicle Body	Total amount of steel regarded ktonne		Weight reduction ktonne	Specific CO_2 emissions steel production		Life time CO_2 savings ktonne		
	AHSS[1]	Conv HSS[2]		AHSS	Conv HSS	M1 Steel	M4 Use phase	Total M1+M4
Strip steel SSAB	3,0	3,8	0,8	1,53	1,46	1,0	35	36
Plate steel SSAB	7,0	8,9	1,9	2,23	2,19	3,9	82	86
Total	10,0	12,7	2,7	2,02	1,97	4,9	117	122
	Total life time CO_2 saving, ktonne, (M1+M4)							122
	Total life time saving in energy resouses, GWh							479
1) AHSS = Advanced High Strength Steel R_e =460-700 MPa								
2) Conv HSS = Conventional High Strength Steel R_e =350 MPa								

6.5 Loader Crane

6.5.1 Description of the case

Advanced High Strength Steel is very effective to use for weight reduction in the extensions of the boom of mobile cranes, Figure 6.5.1. Weight is a critical issue in loader crane designs. The main reasons are that low dead weight of the arm system gives higher payload and low dead weight of the whole vehicle gives higher transport capacity when the crane is mounted an a truck.

If the design can be improved and stress raisers be avoided in highly stressed regions, a static design criterion can be applied and the high strength of the steel be fully utilized. A demonstrator from a project dealing with this issue [6:8] is used for assessing the environmental value of high strength in such an application.

Figure 6.5.1. Investigated Mobile Crane

Structural details

Hexagonal extension

The loader crane extension system consists, in this case, of up to ten telescoping extensions with hexagonal cross-section.

The extensions are today manufactured by bending steel plates in five bends and welding with one longitudinal weld at the lower corner of the extension, Figure 6.5.2. This manufacturing technique is chosen mainly for productivity reasons since the extensions could be manufactured from one single plate and with only one longitudinal weld.
However, from a structural strength point of view, the position of the weld is not good since the weld is situated in a highly stressed region.

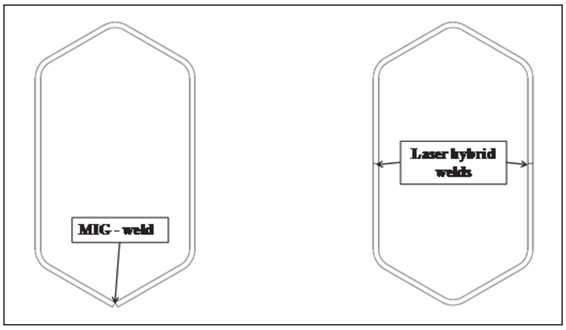


Figure 6.5.2. Cross section of crane boom extension before and after redesign

After redesign, the hexagonal cross-section has been divided into two halves to make it possible to position the weld in the neutral layer of the cross-section, where stresses from both global beam bending and the local bending from slide pads are close to zero. By doing so, the weld will not be exposed to fatigue, and it will be more advantageous to use high end high strength steel with high resistance to static stresses.

Before redesign 6 mm strip steel were used. If the weld is moved to the neutral layer the steel yield strength can be increased from 800 MPa to 1100 MPa and the thickness be reduced to 5 mm. The weight of the hexagonal profiles is then reduced by 17%.

Stabilizer extension

Stabilizers are needed to avoid tipping of the vehicle when the loader crane mounted on the vehicle is working. Stabilizer legs that are forced towards the ground are mounted in stabilizer extensions which can be retracted into a stabilizer beam, Figure 6.5.3.

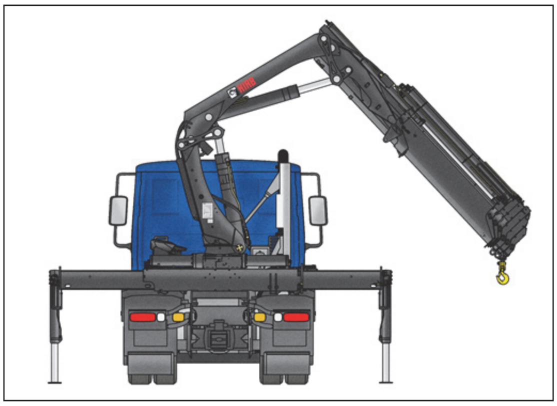


Figure 6.5.3. Mobile crane with stabilizer mounted on a truck

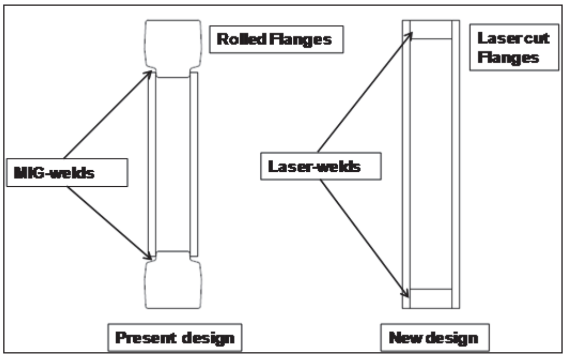


Figure 6.5.4. Cross-sections of stabilizer extensions

The present standard design of the stabilizer extensions is a MIG-welded beam with web plates and rolled flanges, see left side of Figure 6.5.4. In the new design the web plates have the same height as the complete cross-section and the flanges are laser cut plates laser welded to the web plates, see right side of Figure 6.5.4.

The advantages with the new design compared to the old one are that the new flanges can be cut from a plate with higher yield strength (R_e = 800-960 MPa) than the old rolled flanges (R_e = 570 MPa). The extensions can also be made straighter, since laser cut plates are straighter due to less heat input.

The cross-sectional area of the stabilizer extension was reduced by 31 % which will give a weight reduction of 50 kg for a crane in the 15 ton-meter class. However, due to the fact that some modifications to the existing stabilizer extension has already been made a somewhat more conservative approach on the remaining weight reduction potential is taken and it is assumed to be 20 % instead of 31 %.

The above results on possible weight reductions have been applied to the three capacity classes Light, Medium and High and the results are shown in Table 6.2.1.

Table 6.2.1. Weight reduction potential on some parts of Hiab Mobile Loader Cranes

Loader cranes [funtionsal unit: one crane]

Capacity		Examplification (HIAB type)	Lifting capacity	Weight of crane	Weight of stabilizer average	Weight of hexgonal part of boom	Weight reduction of hexgonal part of boom	Weight of upgraded part of stabilazer	Weight reduction of stabilizer	Total weight reduction of boom and stabilazer
	[tm]		[kNm]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]	[kg]
Light	> 10	XS 066 D-3 HiDuo	60	895	122	190	32	68	12	44
Mid	10 - 23	XS 166 E-5 HiDuo	151	2260	325	479	81	180	33	114
High	> 23	XS 600 E-7 HiPro	511	6100	1183	1293	220	655	118	338

The total weight reduction of the upgraded parts of the crane exemplified with the mid class is 114 kg or 17.2 %. The yield strength is on average increased by 41 % (737 to 1040 MPa) on those parts. The net tare weight of the crane including stabilizer is 2585 kg. The weight reduction of 114 kg then corresponds to 4.4 % of the total weight.

6.5.2 Life cycle assessment

The environmental savings of the weight reduction could be exemplified by the case when the crane is in service on a truck. The use phase of the life cycle assessment will as is normal for active structures like vehicles be of most importance. However, all the life cycles will be commented on to show the methodology, which is explained in more detail in [3:1].

Steel production (M1)

This module includes the production of steel used for manufacturing of the upgraded parts of the crane and stabilizer. According to practice, the weights of the steel produced are at least 10 % higher than the gross weights of the final parts due to yield during manufacturing. This is taken into account when the environmental savings from steel production is calculated.

The environmental data used for the steels, are based on results for hot rolled steels derived from this project. The environmental savings are expressed as GWP (Global Warming Potential) in CO_{2e}. The environmental saving were calculated as the difference between the weights times GWP for the actual steels before and after upgrading.

Transport of steel (M2)

It is assumed that the upgraded steel grades were purchased from SSAB in Sweden. The steels are assumed to be transported by truck, and the total distance to be 240 km. For purpose of simplicity the same transport data is used for transports before and after upgrading.

Manufacture of crane (M3)

The mobile crane manufacturing consists of a lot of process steps. However, very few of them will be influenced from the environmental point of view in this case. The main differences in manufacturing are associated with bending of hexagonal boom and welding operations for both parts. The difference in energy consumption in the production of structures before and after upgrading is small and this is therefore not included in the environmental analysis here.

Use of the vehicle with crane (M4)

As mentioned the case with the crane mounted on a truck is analyzed here. For purpose of simplicity 50 % of the life time truck distance is assumed to be empty trips or trips that do not have weight critical transports i.e. 50 % of the transport distance is assumed to be weight critical. The specific reduction in fuel consumption is investigated in detail in this project and is shown for trucks in figure 4.3.4 and table 4.3.1 in section 4.3.4.

A truck has an average life time driving distance of 1200000 km when 5 years on a second hand market is included. The number of fully loaded trips (50 %) to transport a certain amount of goods could in this case be increased by 0.44 % due to the weight reduction of 114 kg. This corresponds to a life time saving of 1037 litres of fuel. For the empty and volume critical transports the fuel saving is 479 litres if a value of 0.07 litres/(100 km and 100 kg WR) is picked from figure 4.3.4. This adds up to a total life time saving of 1516 litres of fuel. The use phase then contributes to a life time saving of 4548 kg CO_{2e} (3.0 kg CO_{2e}/litre diesel fuel including production of the fuel [4:12]).

Recycling (M5)

Scrap added in the steel production process is regarded free of environmental burden in a cradle to gate study. When a full life cycle assessment of a structure (cradle to grave) is performed, it is possible to take into account both the environmental burden of the input scrap and the credit for the recycled scrap.

In doing so the added scrap at steel production must be loaded with an environmental burden. Estimating the environmental value of recycled scrap is rather complicated and software developed in this project for the full “cradle to grave lifecycle” is used to demonstrate this effect. This is included in the graph on the total results described in next paragraph. The recovery rate has been assumed to be 90 %.

Impact assessment results

As mentioned, only global warming (GWP) has been chosen to illustrate the results in this report. Figure 6.5.5 shows the total results for all parts of the life cycle considered.

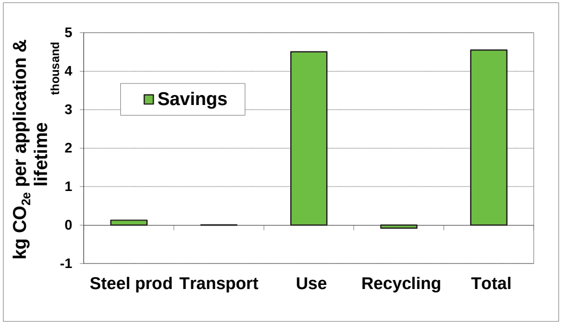


Figure 6.5.5. Total CO_2 savings for the case study, HIAB Loader Crane

In addition to savings in carbon dioxide the upgrading gives a saving of 70000 MJ of non-renewable energy resources.

Contributions within the life cycle chain

As much as 99 % of the environmental saving is derived from less fuel consumption during the vehicle use (M4). The environmental savings due to less steel production (M1) corresponds to 2.8 % and savings at steel transports (M2) corresponds to 0.04 %. The recycling burden and credit affects the result by -1.8 % only since this is an active structure.

Life cycle cost

In addition to the environmental saving reduced fuel consumption gives a life time cost saving of 2273 €/vehicle (1.5 €/litre) despite the small total weight reduction in this case. The weight reduction of 114 kg only corresponds to 0.5 % of the empty tare weight of the truck including the loader crane.

6.5.3 Potential for future environmental savings

A more general analysis of the potential for future environmental savings in cranes is performed and based on the overall result from the case study described above. For every 6.5 thousand ton of advanced high strength steel that replaces conventional high strength steel in mobile cranes (4000 cranes), there is a potential for life time savings of 68 ktonne of CO_{2e}, 268 GWh of non-renewable energy recourses and 33 million € in fuel cost, Table 6.5.2.

Table 6.5.2. Environmental savings when 10 ktonne Advanced High Strength Steel replaces 12.5 ktonne conventional HSS in Loader cranes

Steel product in Loader Crane	Total amount of steel regarded ktonne		Weight reduction ktonne	Specific CO_2 emissions steel production kg CO_{2e}/kg steel		Life time CO_{2e} savings ktonne		
	AHSS[1]	Conv HSS[2]		AHSS	Conv HSS	M1 Steel	M4 Use phase	Total M1+M4
Strip steel	4,55	5,69	1,14	1,74	1,55	1,0	45	46
Plate steel	2,05	2,56	0,51	2,40	2,32	1,1	20	22
Total	**6,60**	**8,25**	**1,65**	**1,95**	**1,79**	**2,1**	**66**	**68**
	Total life time CO_2 saving, ktonne, (M1+M4)							**68**
	Total life time saving in energy resosues, GWh							**268**
	Total life time saving in fuel cost, million €							**33**
1) AHSS = Advanced High Strength Steel R_e=800 - 1100 MPa								
2) Conv HSS = Conventional High Strength Steel R_e=570 - 800 MPa								

The detailed results from this case study are found in [6:10].

6.6 Friends Arena

6.6.1 Description of the case

The Friends Arena, Figure 6.6.1 and 6.6.2, has been built with 32 % steel in higher strengths than the conventional S355 steel with 355 MPa yield strength. In order to calculate the environmental savings of using high strength steel the actual arena has been recalculated by Sweco to a hypothetical reference arena in steel grade S355 only [6:11]. To evaluate what further potential there would be for weight savings by using more high strength steel another calculation has been performed which resulted in a high strength steel usage of 54 %. This case is designated alternative B while the actual arena is designated alternative A. The weight savings and environmental savings with the upgraded roof was evaluated as the difference in weight and environmental value of the actual construction (alternative A), the one with 54 % high strength steel (alternative B) and the reference structure entirely manufactured of conventional steel S355.

Weights of the final elements in the fixed roof which was *modified* when upgrading as well as the environmental values of the steels are shown in Table 6.6.1. The production yield losses were estimated to 5 % when producing the final elements.

Figure 6.6.1. Friends Arena, overview

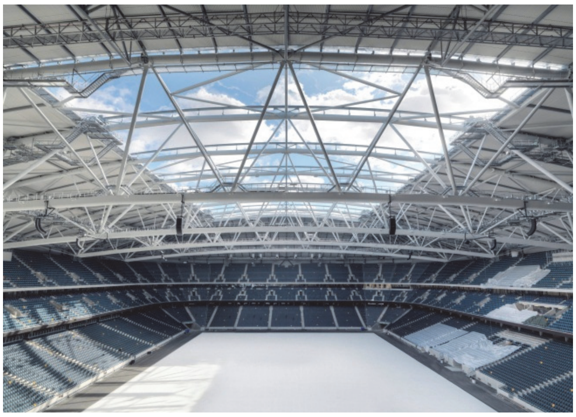


Figure 6.6.2. Friends Arena, roof framework

Table 6.6.1. Grades and steel weights before and after upgrading and the environmental value for steel tubes, frames and plates

Before upgrading				After upgrading						Environmental value GWP, tubes and frames [kg CO_2/kg steel]	Environmental value GWP, plates [kg CO_2/kg steel]
Reference						Alternative A		Alternative B			
Grade	Yield strength [MPa]	Weight alt. A [tonne]	Weight alt. B [tonne]	Grade	Yield strength [MPa]	Weight [tonne]	Weight reduction [tonne]	Weight [tonne]	Weight reduction [tonne]		
S355	355	1 506	564	S355	355	1 508	-2	561	4	2,340	2,044
S355	355	1 149	2 091	S460	460	920	230	1 719	372	2,385	2,089
S355	355	600	600	S690	690	307	293	307	293	2,489	2,188
S355	355	107	107	S900	900	43	64	43	64	2,581	2,278
Total		3 362	3 362	Total		2 778	584	2 630	732		

Some parts remaining in steel S355 after upgrading have also been modified. This means that although the total mass of these parts is unchanged, the mass have been redistributed between elements which resulted in an optimized upgraded design.

The total weight of the fixed roof was calculated to 4584 tonne before and 4000 tonne after upgrading, that is. the actual arena. This corresponds to a total weight reduction of 13 % and of 21 % on the elements involved in the upgrading only. For the roof where more than half of the steel had higher strength than 355 MPa the weight of the roof was 3852 tonne which gives a total weight reduction of 16 % and 28 % on the elements involved in the upgrading.

6.6.2 Life cycle assessment

Calculation of environmental savings in steel production (M1)

Environmental data chosen for the cradle to gate analysis is shown in figure 6.6.3 [6:12 and 6:13].

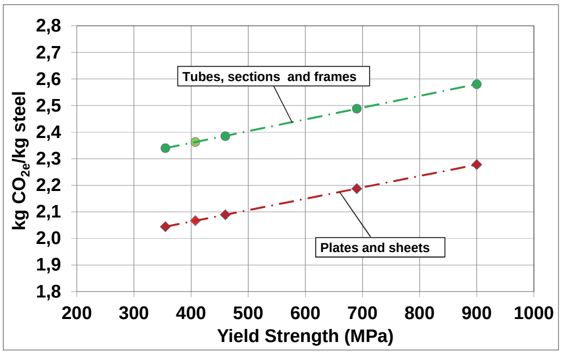


Figure 6.6.3. GWP [kg CO_{2e}/kg steel] as a function of yield strength for steels from Ruukki adjusted for the influence of yield strength with data from SSAB EMEA

The data is adjusted for different steel strengths based on data from SSAB EMEA Oxelösund and recalculated in accordance with the procedure described in the worldsteel methodology report [4:14]. The bottom chord of the trusses and the diagonals that connect to the end supports was manufactured of plates and the environmental value for plates was therefore chosen for grade S690 and grade S900. For the reference structure in grade S355 a weighted average environmental value of 2.303 was used.

The total environmental value was calculated by equation 4:2 originally shown in section 4.3.1

$$M_{steel} = \Sigma(M_{steel,x} * W_{steel,x})_n$$

where

M_{steel} = Environmental value (cradle to gate) of all upgraded parts of the structure
$M_{steel,x}$ = Environmental value (cradle to gate) for grade x [per kg steel]
$W_{steel,x}$ = Weight of steel x [kg]
n = Number of grades

The environmental value $M_{steel,x}$ is found in table 6.6.1. The total environmental *saving* was calculated by applying equation 4:2 before and after upgrading and calculate the difference (Δ). By doing so the saving during steel production including upstream impact expressed as GWP is: $\Delta M_{steel,alt.A}$ = 1316 tonne and $\Delta M_{steel,alt.B}$ = 1643 tonne of CO_{2e}.

Calculation of environmental benefits during transports (M2)

Profiles, tubes and rods to the roof construction were manufactured at the factory near the port 85 km from the steel mill. These transports were performed by trucks.

After production of profiles and tubes the finished structural elements were transported by boat 275 km and then another 616 km by truck.

The total environmental value of the transports was calculated with equation 4:3.

$$M_{trsp} = \Sigma(M_{trsp,y} * W_{steel,y} * TD_y)$$

where

M_{trsp} = Total environmental value for transport of upgraded parts of the structure

$M_{trsp,y}$ = Environmental value (cradle to gate) for y-type of transport vehicle [per tonnekm]

$W_{steel,y}$ = Total amount of steel transported with y-type of transport vehicle [tonne]

TD_y = Transport distance with carrier y [km]

n = Number of types of carriers

The environmental value $M_{trsp,y}$ was found in figure 4.2.1, where the figures 0.043 and 0.012 kg CO_{2e}/tonnekm was evaluated for the actual truck and ship respectively.

According to equation 4:3 the total environmental *savings* during transport is Δ M_{trsp} = 21 tonne of CO_{2e} for alternative A and 26 tonne CO_{2e} for alternative B.

The overall environmental benefits because less steel need to be manufactured and transported is for alterative A: 1337 tonne of CO_{2e} and for alternative B: 1668 tonne of CO_{2e}.

Calculation of environmental benefits in manufacture of the construction (M3)

Although there should be a number of environmentally positive factors in the manufacture and installation of the upgraded design, the manufacturer had difficulties to quantify those. Positive factors include the handling of lighter parts, less welding because of thinner steel thicknesses etc. This analysis does not take these differences into account because they are considered to be relatively small compared to the total environmental savings.

Calculation of environmental load and credit of scrap added and recycled (M5)

In order to determine the total environmental impact over the whole life cycle (cradle-to-grave) one should also make credit for the recycled scrap. In doing so the added scrap at steel production must be loaded with an environmental burden since in a cradle-to-gate analysis the added scrap is considered free of environmental burden. Estimating the environmental value of recycled scrap is rather complicated and software developed in the Steel Eco-Cycle research program for the full “cradle-to-grave” lifecycle was used to demonstrate this effect. This is included in the graphs showing the total results below. To make the results more general a recycling rate of 60 % has been assumed, a value commonly used for building constructions.

Total environmental result of upgrading the Friends Arena (M1-M5)

The overall results calculated by the software tool EcoSteel expressed as Global Warming Potential (GWP) is shown in Figure 6.6.4. The total savings decrease when the recycled scrap is taking into account. This is because a larger amount of conventional steel will be recycled, the construction being heavier before upgrading. However, the total environmental impact decreases when the effect of recycling is included.

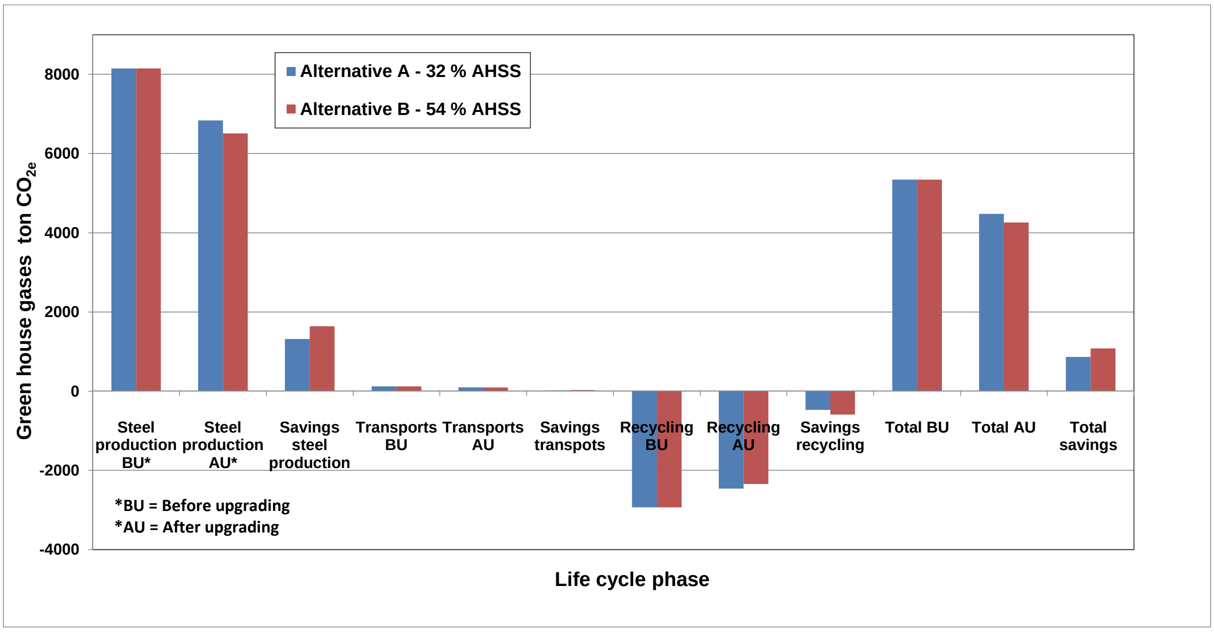


Figure 6.6.4. Total environmental results for Friends Arena, cradle to grave

Increasing the amount of AHSS from 32 to 54 % might seams to result in a fairly low additional benefit but the increase in yield strength expressed in terms of weighted average is only about 80 MPa and the weight reduction associated with such an increase in yield strength according to the root formula, represented by the blue dotted line, is lower than the actual weight reduction of upgraded parts in this case. The final result here seems to be more a 1:1 relationship between yield strength and weight reduction, the red line in Figure 6.6.5.

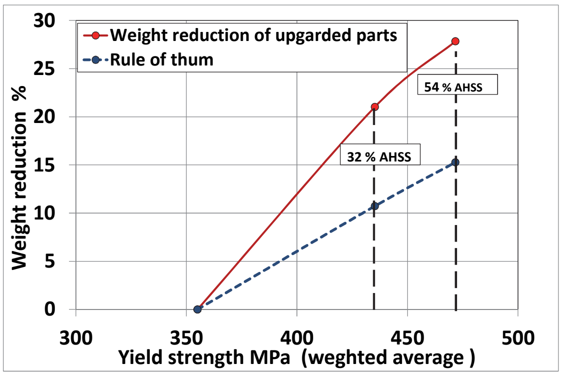


Figure 6.6.5 Weight reduction and environmental savings vs. weighted values of yield strength

Cost savings

The total cost savings for the actual fixed roof structure with 32 % high strength steel compared to a roof in steel S355 only is calculated by the manufacturer to 2.2 million €. This cost saving is mainly related to the manufacturing of the structural elements to the roof.

6.7 Trailer for Timber Transport, MST

Logistics is a key element in forestry for saw logs, pulpwood or biofuels. It is in all cases about managing large and complex commodity flows in an efficient manner. A large proportion of timber transport is performed by truck in Sweden. It is therefore an important part of logistics development to produce more efficient vehicles, so that transport costs and carbon dioxide emissions can be reduced.

6.7.1 Description of the case

A case study has been performed on a type of trailer which is a part of the timber transport vehicle shown in Figure 6.7.1. This trailer is manufactured by Mjölby Släp & Trailer AB, MST in Sweden, who also supplied the data needed for the analysis. More details regarding this case is found in the case project report [6:14].

Figure 6.7.1. Timber transport vehicle

The environmental advantages of upgrading the steel strength in the chassis structure are analyzed. By choosing new design solutions the curb weight for the entire package, including truck, crane and trailer, there is a goal to reduce the curb weight from 21 tonne to 19 tonne.

Structural details

In this case study a first step is reported in which the weight of the trailer is reduced by 500 kg.

The longitudinal beams of the trailer have been upgraded from conventional rolled IPE profiles in S310 steel to welded beams in steel Domex 700. The grade of the cross members were unchanged. The trailer frame arrangement after upgrading is shown in figure 6.7.2.

Figure 6.7.2. The analysed trailer after upgrading

Data on strengths and weights before and after upgrading is shown in Table 6.7.1.

Table 6.7.1. Main parts of the upgraded trailer chassis

Trailer chassies	Before upgrading				After upgrading			
	Steel grade	Yield strength min MPa	Thick-ness [mm]	Weight of part [kg]	Steel grade	Yield strength min MPa	Thick-ness [mm]	Weight of part [kg]
Flanges	HS310	310	12.7	943	Domex 700	700	8	593
Web plates	HS310	310	8		Domex 700	700	4	
Cross members	HS350	350		257	HS350	350		257
Total main steel parts, chassis				1200				850
Total tare weight of traler				6330				5270

The weight reduction of upgraded parts was 350 kg, which correspond to a weight reduction of 37 % on these parts.

This is in good agreement with the rule of thumb which indicates a weight reduction of 33 % for an average increase in yield strength of 2.3 times, which is in place in this case for the upgraded parts.

The total weight reduction due to the steel upgrading only (350 kg) means that the curb weight of the trailer was reduced from 5770 kg to 5420 kg or by 6,1 %. In addition to this the weight was further reduced by 150 kg due to changes in design and weight savings in other parts of the chassis. This meant that the total payload capacity of the trailer was increased by 500 kg from 30230 kg to 30730 kg at a maximum gross weight of the trailer of 36 tonnes.

6.7.2 Life cycle assessment

The life cycle assessment of the trailer is based on the reference unit of one vehicle during a life time of 7 years with an average mileage of 175 000 km/year. In average it is assumed that 50 % of the distance is driven with empty trailer. The environmental assessment below follows the system with different life cycle modules described in [3:1] and chapter 4.

Steel production and transports (M1 and M2)

This module includes the production of the steel used for manufacturing of the upgraded parts before and after upgrading. The steel consumption is assumed to be 10 % higher than the weights of the final parts due to yield losses during manufacturing.

The environmental impact data for rolled IPE-beam grades used before upgrading was not analysed in this project, but similar data for strips from this project was chosen for the inventory analysis. The environmental saving (CO_{2e}) due to the fact that less amount of steel needs to be produced after upgrading is 550 kg CO_{2e} for each trailer. About 10 % of that is savings during transports.

Manufacture of the vehicle (M3)

There is no information on differences in energy consumption when manufacturing before and after upgrading. If there are some they need to be very small.

The manufacturing phase (M3) has therefore been excluded from this analysis. However, this is not a severe data gap, since the manufacture as such would be of minor importance compared to steel production and particularly compared to the use phase.

Use of vehicle (M4)

For the share of the transports which are weight critical transports, the entire weight reduction can be used to increase the payload. The increased payload means fewer trips to transport a certain amount of goods and corresponding savings in environmental impact.

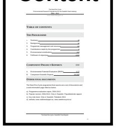
In order to analyse the fuel savings resulting from a weight reduction for the volume critical and empty loaded parts of the transports, the specific fuel saving for a certain weight reduction (litres/km and kg weight reduction) could be evaluated. Data on fuel consumption of the entire vehicle, empty and fully loaded, needed for the calculation, is given by MST to 0.35 litres/km and 0.71 litres/km respectively. The maximum pay load is 40000 kg for the entire vehicle.

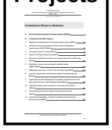
For the type of vehicle analyzed here the specific fuel saving could be calculated by {SFC = (0.71-0.35) (FC full-empty loaded, litre/ km)/40000 (Maximum pay load) = $9*10^{-6}$ litre/ km and kg weight reduction}.

For the empty loaded and volume critical parts of the transports the life time fuel saving is {$9*10^{-6}$*500 (weight reduction kg)*175000 (km/y) *7 (years)*0.5 (share of life time transport distance for empty and volume critical transports, km)} = 2756 litres of diesel fuel/vehicle.

For the weight critical transports, the following life time saving in fuel consumption is obtained: {175000 (km/y)*7 (years)*0.5 (fully loaded trips)* 500 (weight reduction)/40000 (maximum payload of the entire vehicle, kg))]*0.71 (litre/km)} = 5436 litres of diesel fuel/vehicle.

This adds up to a total life time saving of 2756+5436 = 8192 litre of diesel fuel/vehicle. The use phase then contributes with a life time saving of 24.6 tonne CO_{2e} (3.0 kg CO_{2e}/litre diesel fuel





including production of the fuel [3:2 and 4:12]) for each trailer.

Recycling (M5)

Scrap added in the steel production process is regarded free of environmental burden in a cradle to gate analysis. When a full life cycle assessment of a structure (cradle to grave) is performed, it is possible to take into account both the environmental burden of the input scrap and the credit for the recycled scrap. The recycling rate for the trailer has been assumed to be 90 %.

Impact assessment results

The results on global warming is illustrated Figure 6.7.3.

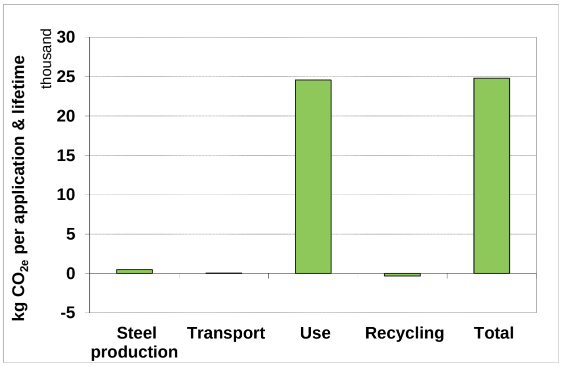


Figure 6.7.3. Summary of savings in carbon dioxide emissions due to upgrading, per trailer, output from EcoSteel software

In addition to savings in carbon dioxide the upgrading gives a saving of 100 MWh of non-renewable energy resources.

Contributions within the life cycle chain

As much as 99 % of the environmental saving is derived from less fuel consumption during the vehicle use (M4). The environmental savings due to less steel production (M1) corresponds to 2 % and savings at steel transports (M2) corresponds to 0.2 %. The recycling burden and credit affects the result by -1 % only since this is an active structure.

6.7.3 *Life cycle cost*

In this case the cost for manufacturing increased due to the introduction of laser cutting and welding but was reduced due to more rational production and less material to bye and handle. Altogether various cost items for material, manufacturing and transports evened out each other.

However, cost savings due to reduced fuel consumption give a life time cost saving of 12300 €/vehicle (1.5 €/litre).

6.7.4 *Potential for future environmental savings*

The timber vehicle fleet in Sweden is about 2000 vehicles. A calculation is performed of what potential there is for environmental savings if conventional steel is replaced by advanced high strength steel in these vehicles. Estimates by MST indicate another reduction of 2000 kg could be expected for each complete vehicle and let us assume that half of that reduction is related to the upgraded steel.

The analysis shows life time savings of about 50 ktonne of CO_{2e}, 200 GWh of non-renewable energy recourses and 25 million € in fuel cost, Table 6.7.2.

Table 6.7.2. Potential savings if advanced high strength steel replaces conventional steel in 1000 Timber trucks

Steel product in trailes chassies	Total amount of steel regarded ton		Weight reduction ton	Specific CO_2 emissions steel production kg CO_2/kg steel		Life time CO_2 savings ton		
	AHSS[1]	Conv[2]		AHSS[1]	Conv[2]	M1 Steel	M4 Use phase	Total M1+M4
Hot rolled strip or beam	1858	2858	1000	1,56	1,45	1246	48359	49605
	Total life time CO_2 saving, tons, (M1+M4)							49605
	Total life time saving in energy resources, MWh							199849
	Total life time saving in fuel cost, million €							24

1) AHSS = Advanced High Strength Steel R_e=700 MPa

2) Conv = Conventional Steel R_e=310 MPa

6.8 *Chair frame, IKEA*

The knowledge of environmental impact from material production and transports are of vital importance for IKEA in order to keep those figures low. The purchase of material and components as well as selling products in extremely large numbers globally adds up to an enormous environmental saving potential.

6.8.1 *Description of the case*

In order to figure out the size of that saving for one specific product a case study has been performed on a frame to a chair, Figure 6.8.1. Data have been supplied by IKEA of Sweden [6:15].

The steel in the frame was upgraded from conventional cold reduced DC 01 with yield strength of 200 MPa to high strength steel with 400 MPa yield strength. This resulted in a weight reduction from 1.648 kg to 1.468 kg i.e. with 0.18 kg/frame.

The assessment is made for a yearly number of 1.2 million frames and covers cradle to gate analysis of steel, transports including the changes in packaging before and after upgrading and recycling.

Figure 6.8.1. Analysed chair, IKEA

6.8.2 Life cycle assessment

Steel production (M1)

With an assumed production yield of 80 % when manufacturing the frames the total environmental saving for steel production is:

1200000*(1.648*1.44-1.468*1.47)/0.8 = 325 tonne CO_{2e} per year.

Packaging and Transport (M2)

Container transports with ship are normally used in this case and all specific environmental impacts are referred to one container since the transports normally are volume critical.

The weight reduction, which was achieved due to the upgrading, allowed the design of the frame to be altered in such a way that more pieces could be packed on a pallet. This resulted in a much better utilisation of the container in which the frames were transported.

Packing before upgrading: 40 pieces/pallet * 60 pallet/container = 2400 pieces * 1648 g = 3955 kg

Packing after upgrading: 100 pieces /pallet * 60 pallet/container = 6000 pieces * 1468g = 8808 kg

Transport before upgrading:
1200000 pieces /2400 = 500 containers/year * 10000 km (purchase in Kina) * 3 g CO_{2e}/m^3km * 60 m^3 = 900 tonne CO_{2e}.

Transport after upgrading:
1200000 pieces/6000 = 200 containers/year * 10000 km (purchase in Kina)* 3 g CO_{2e}/ m^3km * 60 m^3 = 360 tonne CO_{2e}.

Saving: 540 tonne CO_{2e}/year

Recycling (M5)

A recycling rate of 75 % is assumed.

Total results (M1+M2+M5)

The total result calculated with the software EcoSteel is shown in Figure 6.8.2. The possible difference between manufacturing in mild steel and high strength steel is then not taken into account. The total saving is 865 tonne CO_{2e}, cradle to gate and 720 tonne CO_{2e} per year cradle to grave then including recycling credits.

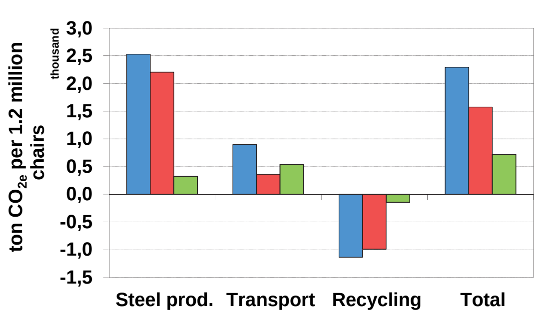


Figure 6.8.2. Summary of savings in carbon dioxide due to upgrading, for 1.2 million chair frames per year

6.9 Bumper, Outokumpu

Tougher and tougher regulations on tale pie emissions for cars means that the automotive industry continuously is looking for new alternative materials and structural solutions which can increase crash performance at lowest possible weight.

6.9.1 Description of the case

This case study describes a project [6:16] where a bumper is upgraded to ultra-high strength carbon steel and stainless steel. Especially the use of stainless steel can make the structure to take large amounts of energy in a crash situation without cracking. This is because the stainless steel has a very large strain hardening range. Also the formability of ultra-high strength stainless steels is high, that makes it possible to fabricate intricate shapes not possible with UHS carbon steels.

The bumper is shown in Figure 6.9.1 and data for steel grades, weights, yield/proof strength and weight reductions are shown in Table 6.9.1 for the different parts of the bumper structure.

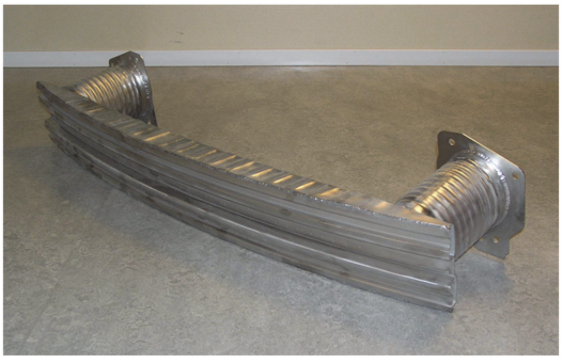


Figure 6.9.1. Bumper in ultra-high strength steel

Table 6.9.1. Structural details for the bumper which are upgraded

Part	Before upgrading			After upgrading			
	Steel grade	Yield strength [MPa]	Weight [kg]	Steel grade	Yield/Proof strength [MPa]	Weight [kg]	Weight reduction [kg]
Front rail	HS 500	500	3,5	Docol 1200	1000	3	0.5
Back rail	HS 500	500	5	HyTens 1200	1000	3	2.0
Crash boxes	HS 500	500	2	HyTens X	900	1	1.0
Total bumper	HS 500	500	10,5	Weighted average	981	7	3.5

Table 6.9.2. Life cycle assessment of the upgraded dumper parts

Upgraded bumper part	Total amount of steel [tonne]		Grade		Weight reduction [tonne]	Specific CO_{2e} emissions, steel production CO_{2e}/tonne steel		Life time CO_{2e} improvement tonne			
	Before	After	Before	After		Before	After	Steel prod	Trsp	Use	Recyc-ling
Front rail	700	600	HS500	Dc1200	100	1,690	1,648	194		810	-121
Back rail	1 000	600	HS500	HyT1200	400	1,690	3,581	-459		3240	721
Crash boxes	400	200	HS500	HyT1200	200	1,690	3,581	-40		1620	242
Fixing plates	200	200	HS500	LDX2101	0	1,690	3,421	-346		0	352
Total	**2 300**	**1 600**			**700**	**1,543**	**2,409**	**-651**	**18**	**5670**	**842**

6.9.2 Life cycle assessment

The assessment is made for a yearly number of 200000 bumpers to personal cars.

The weight reduction for 200000 bumpers is 700 ton. According to table 4.2.1 in chapter 4 the specific saving in fuel consumption (SFC) is on average 0.135 litre/(100 km and 100 kg weight reduction) for cars with non-resized power train, which is used in this case since the total weight reduction is rather small compared to the curb weight. The total life time distance is assumed to be 200000 km also according to table 4.2.1.

The additional total life time saving of CO_{2e} /year, if one litre of fuel give 3 kg of CO_{2e} when consumed, then become:

$\Delta M4 = 200000/100 * 0.135 * 700000/100 * 3 = 5670$ tonne of CO_{2e}. Figure 6.9.2 give more detailed information on the environmental improvements in all phases.

Figure 6.9.2. Summary of savings in carbon dioxide due to upgrading, per 200000 bumpers, EcoSteel software

There is a somewhat unusual result outcome with a negative saving in steel production and a positive saving when recycling although less steel is recycled after upgrading. This is due to upgrading from carbon steel to stainless steel and the fact that the credit for scrap in the recycling face increases with increasing amount of alloys for stainless steel.

6.10 Pipe system for Urea production, Sandvik

6.10.1 The case

This case study is an analysis of a pipe system which is a part of a Urea production plant. An example of a urea plant is shown in Figure 6.10.1. Background data for this case study has been supplied by Sandvik Materials Technology and more details of the case are found in [6:17].

Figure 6.10.1 Example of a urea production plant

Two steel grades, a conventional one, 3R60UG and a specially developed grade, Safurex are compared. The alloy content in the steel grades is shown in Table 6.10.1.

Table 6.10.1 Alloy content of steels

Alloy content [%]	Cr	Ni	Mo	Mn
3R60UG	17.5	14.0	2.6	1.7
Safurex	29.0	7.0	2.3	1.0

Safurex has a duplex austenite-ferrite structure which has several advantages compared to the austenitic steel. Safurex has a yield/proof strength which is 550 MPa compared to 190 MPa for the conventional steel. The higher strength can be used for reducing the thickness of the pipes compared to the conventional steel grade 3R60UG, and this reduces the steel consumption.

The urea pipe systems consist of different dimensions and different amounts of each dimension depending on steel grade used for producing the pipe system, Table 6.10.2.

Table 6.10.2 Definition of the pipe systems concerning dimensions and weight

Pipe dimension	3R60UG [kg/pipe system]	Safurex [kg/pipe system]
0.75 to 4 inch	447	312
6 inch	377	3 098
8 inch	7 461	721
10 inch	1 925	1 073
12 inch	2 666	7 380
14 inch	15 372	1 762
16 inch	4 080	0
Total	**32 328**	**14 346**

6.10.2 LCA for steel grades and pipes

Life cycle assessment (LCA) was performed for the two steel grades and for the relevant pipe dimensions. The exact methodology, the data used etc. is not reported here, but in [3:1].

A "cradle-to-gate" LCA was made based on steel works data provided by Sandvik. The LCA includes the production of raw materials such as alloy materials and other raw material inputs, production of fuels and electricity, transportation of raw materials as well as steel production at the steel works at the Sandvik site.

LCA was also performed for the production of the different pipe dimensions for each steel grade. This includes production of bars and pipes from the bars based on data provided by Sandvik.

6.10.3 LCA for the urea pipe system

The LCA data on the different pipe dimensions and for each steel grade were used to calculate the whole urea pipe system. This LCA covers the whole life cycle which means that it also include the use phase of the urea pipe systems. To calculate the whole "cradle-to-grave" LCA involves many steps and a complicated methodology, which is thoroughly described in [3:1]. In short it means that the full cradle-to-grave analysis is calculated according equation 6:1:

Cradle to grave = Cradle to gate + Burdens for steel scrap inputs + Use - Credit for amount of recycled steel *(6:1)*

where

Cradle-to-gate: the LCA results of the production of tubes to the urea pipe systems

Burdens for steel scrap inputs: amount of each steel scrap grade * the environmental value of scrap for each steel scrap grade

Use: In this study – the impact from the energy use during the life time

Credit for amount of recycled steel: amount of recycled steel the environmental value of scrap for the relevant steel grade

Burdens for the inputs of steel scrap to the steel production are added since the steel scrap is considered as "free" from environmental burden in the "cradle-to-gate". This is certainly in line with the worldsteel methodology who recommends to put zero burdens on scrap when performing a "cradle-to-gate" study and to give the scrap a burden when performing a full "cradle-to-grave" study when the steel is used in a steel application.

Environmental values of scrap required for these calculations, as well as for the calculations of the recycling credit, were compiled in the project based on a methodology developed by worldsteel.

6.10.4 Data for the use phase

Based on information from Sandvik, the following assumptions were made for the use phase of the urea pipe systems, Table 6.10.3.

Table 6.10.3 Definition of the pipe systems concerning dimensions and weights

Type of data assumed	Number	Sort
Urea production per day (according to Sandvik)	3000	tonne
Number of days per year (assumed)	350	days
Urea production per year (calculated)	1050000	tonne
Lifetime of the urea system (according to Sandvik)	20	years
Urea production per lifetime (calculated)	21000000	tonne

According to Mark Brower funder of UreaKnowHow.com, the use of Safurex can decrease the energy consumption in the urea production by 7%. This is due to higher corrosion resistance of the Safurex steel compared to steel 3R60UG, which in turn makes it possible to run the process with lower content of oxygen.

The energy use was assumed to be about 1.7 MJ of steam, which means about 2 MJ fuel/kg urea (efficiency of 85 %). This is based on theoretical and stoichiometric information about urea production made by IVL.

In the calculation of the use phase, 2 MJ fuel/kg urea was used for the 3R60UG-system and a 7 % lower figure was used for the Safurex-system. It was assumed that the energy carrier was oil. In addition to oil, 0.05 MJ of electricity/kg urea was used in the calculations. This was also based on the model of urea production made by IVL.

6.10.5 Cradle-to-gate results for the steel works

The Cradle-to-gate results for the steel works are presented in the Figure 6.10.2. Global warming *kg CO_{2e} per tonne steel slabs out from the continuous casting process* was chosen to illustrate the results.

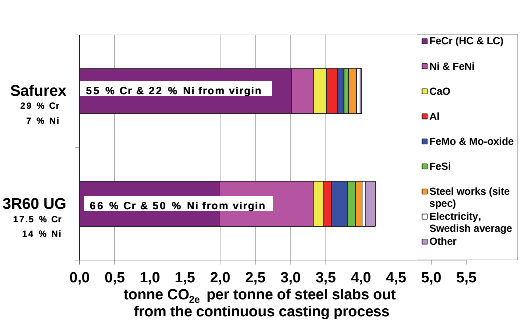


Figure 6.10.2 Global warming kg CO_{2e} per tonne steel slabs out from the continuous casting process

There is no significant difference between the two steel grades. The results are however *not comparable in the first place* since one steel grade require less material to fulfil a *specific function*. The life-span of the steel application might also increase when using a certain steel grade. This means that the same function is not compared if only the “cradle-to-gate” results per tonne of steel are considered.

Another reason for not comparing the “cradle-to-gate” results is that the input of steel scrap has been considered as ”free” of environmental burden. For stainless steel grades, it is furthermore a fact that different steel grades receive different *shares of alloy elements* from steel scrap and from virgin raw materials. Since scrap is considered as free from environmental burden in the “cradle-to-gate” phase, a steel grade with a large share from scrap comes out better.

6.10.6 Cradle-to-grave results for the urea pipe system

Use phase excluded

The cradle-to-grave life cycle results with the use phase excluded are shown in Figure 6.10.3.

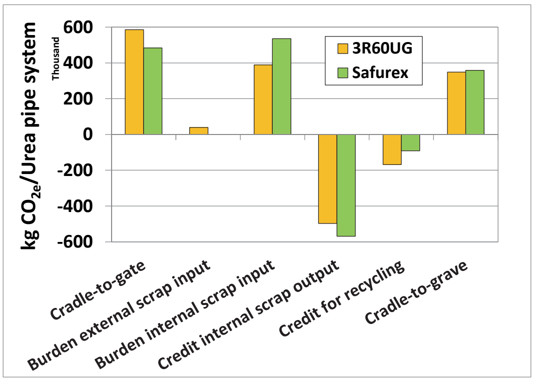


Figure 6.10.3 Life cycle results excluding the use phase

The recycling credit is based on a recycling rate of 90 %.

The difference in cradle to grave result, not considering the use phase, between the cases is small and not significant.

Use phase included

When also include the use phase of the urea pipe systems, another picture appears, Figure 6.10.4.

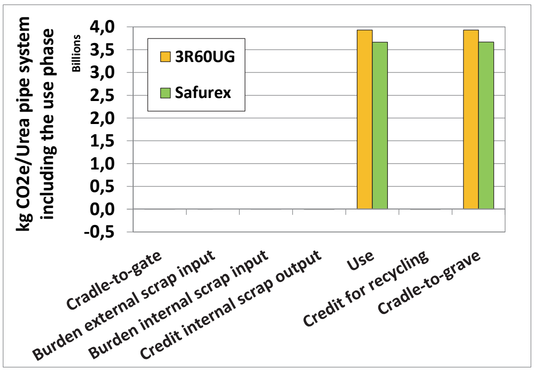


Figure 6.10.4 Life cycle results including the use phase

The use phase dominates which means that the other life cycle phases shown in figure 6.10.2 disappear.

The saving in environmental impact due to the use of the Safurex system is in terms of Global warming is about 265000 tonne of CO_{2e}.

This corresponds to the annual use of 60000 Volvo cars or to drive 30000 loops around the world in a Volvo car.

6.11 Summary of results from case studies

To get an easier access to the primary results of the case studies they are summarised in Table 6.11.1.

Table 6.11.1 Summary of results from case studies

Case study	Weight reduction[1] WR		CO_{2e} saving[2] [kg]	Energy saving[2] [kWh]	Specific CO_{2e} saving [kg/kg WR]	Specific Energy saving [kWh/kg WR]
	[kg]	[%]				
Active structures						
Semitraler tipper	1 136	25	30 000	120 000	26	106
Articulated hauler	39	21	1 600	6 400	41	164
Loader crane	114	17	4 650	18 600	41	163
Trailer	500	37	25 000	100 000	50	200
Bumper to car	3,5	33	29,5	118	8	34
				Average	**33**	**133**
Passive structures						
Storage tank	19 100	33	65 000	227 500	3,4	12
Spiral dewaterer	3 000	31	1 970	7 880	0,7	3
Friends Arena case A, tonne	585	21	900	3 600	1,5	6
Friends Arena case B, tonne	732	28	1 000	4 000	1,4	5
Chair frame 1.2 million, tonne	325	11	719	2876	2,2	9
				Average	**1,8**	**7**
1) Weight reduction of uppgraded parts 2) Including recycling						

Besides weight reduction of upgraded parts, savings in carbon dioxide emissions and energy resources per one structure also the specific values per kg weight reduction is given. This makes it possible to compare different cases in terms of effectiveness of using high strength steel. What is obvious from table 6.11.1 is, not surprisingly, the big difference between active and passive structures. This is related to the fact that active structures have a considerable use phase and will save environmental impact during its whole life time. The difference is in the order of 20 times in advantage for active structures.

A special case is the pipe system for urea production which is a passive structure where a better corrosion resistance of the upgraded steel makes it possible to reduce the energy consumption when the plant is in operation, see section 6.10. This resulted in a kg CO_{2e} to kg weight reduction ratio of 5 500.

A similar case were a special heat resistance steel, Sanicro 25 has been used to increase efficiency in a passive plant for power generation, is worth mentioning although it is a bit outside of the scope for this project, Figure 6.11.1 This steel has 30 % higher creep strength which in turn allow for higher operating temperatures and 40 % higher efficiency in power generation. This finally resulted in a 33 % reduction of carbon dioxide emissions equal to 300 kg CO_{2e}/MWh for a 900 MW power plant.

Figure 6.11.1 Manufacturing of super heater coil in steel Sanicro 25

7. ENVIRONMENTAL IMPROVEMENTS FOR ROAD AND RAIL VEHICLES

The introduction of high strength steel takes a rather long time. The companies and sectors that are in the forefront of development are in the transport and crane segments. The car segment in particular has been under pressure for a long time to reduce greenhouse gases and at the same time meet growing demands from safety standards. During the last decades demands from for example safety standards and comfort have increased. This has led to that car manufacturers in particular have successively increased their share of advanced high strength steel in the car body to meet those demands rather than make large weight reductions. This is of cause an excellent way of using advanced high strength steel for increased material and energy efficiency, but it is not so easy to transform those benefits to pure weight reduction.

Reductions in greenhouse emissions have also been achieved with other means like for example more efficient power trains, decreased drag and alternative fuels.

In the following analysis the potential improvement in environmental and economic impact also include the benefits achieved for other purposes than weight reductions by comparing with a scenario if advanced high strength steel has not been used.

Manufacturers of large trucks and earthmoving machinery have also been using high strength steel for same time, however, they need to take the next step and use more advanced high strength steel. The main obstacles for doing so are associated with low consistency and quality in the production process, especially for welded parts. Mobile crane manufacturers have successively used extra-high strength steel with strength levels of 900-1100 MPa for the outer parts of the crane boom where the load spectrum is less fatigue critical.

In spite of the fact that some companies in some segments already use high strength steel, there is still a very large potential for increased use of these steels, such as for various types of bodywork for trucks, trailers, machinery, railway rolling stock etc. Many SME companies booth as full suppliers or subcontractors are supplying those structures or parts to the market. The increased focus on environmental issues should promote a development towards higher shares of advanced high strength steel.

One should also remember that even if carbon dioxide emissions can be reduced in the future there will still be a need for resource and energy effective transports independent of the type of energy source. This means that mass reductions will be of crucial importance in the future.

The vehicle segment is very important in terms of possible environmental reductions since vehicles are so called active structures which save environmental impact during its whole life when the weight is reduced.

7.1 Road vehicles

A calculation is performed with a scenario that half of the vehicle fleet in Sweden is replaced by lighter vehicles. This could be reached within a time frame of about 6-8 years from introduction if all new registered vehicles are of light weight type. The yearly registration of new cars and trucks [7:1 and 7:2] corresponds to 6 % of the fleet, which should allow for an increase in the size of the fleet as well as for vehicles reaching end of life. The lead time for development could be an additional five years, reference [7.1]. The results of the calculation are shown in Table 7.1.1.

Table 7.1.1. Estimate of improvement potential for reduction of CO_{2e}-emissions and energy recourses from road vehicles, supposing that half of the fleet is replaced by new lighter vehicles

SE and EUR Fleet penetration 50%																		
Type of Vehicle	Registr 2009 Million vehicles/y		Total fleet 2009 Million vehicles		Curb weight	Weight saving[1]	Weight saving of upgraded parts	Fuel saving l/(100 km*100 kg WR)[3]	Life time performance km ref (15,16)		Life time CO_{2e} saving t/100 kg WR Use		Life time CO_{2e} savings on steel ktonne		Life time CO_{2e} savings Use ktonne		Years to penetrate share of fleet[4]	
	SE	EUR	SE	EUR	kg/veh	kg/veh	%		SE	EUR	SE	EUR	SE	EUR	SE	EUR	SE	EUR
Car	0,3050	13,607	4,401	235,5	1100	40	17%	0,30	240000	200000	2,10	1,75	214	8166	1851	82519	7,2	8,7
LCV < 3,5 ton	0,0464	2,104	0,437	31,50	2000	80	20%	0,20	280000	300000	1,67	1,79	39	2354	293	22604	4,7	7,5
MHV >3.5t <16 t	0,0014	0,1550	0,023	2,15	6000	400	20%	0,15	300000	375000	1,35	1,68	11	854	62	7246	8,2	6,9
HT >16 t, VC[2]	0,0049	0,2207	0,044	1,92	14000	900	20%	0,07	750000	1000000	1,57	2,09	41	1752	312	18084	4,5	4,4
HT >16 t, WC[2]	0,0012	0,0736	0,011	0,48	20000	1200	20%	0,12	750000	1000000	2,69	3,59	14	584	179	10333	4,6	3,3
Buses >16 t	0,0160	0,0251	0,014	0,55	11000	800	20%	0,10	850000	800000	2,54	2,39	13	436	142	5253	0,4	10,9
												Total	**332**	**14147**	**2838**	**146039**	**6,2**	**7,7**
									Total life time CO_2 saving, ktonne, (M1+M4)						3170	160186	Weighted average (bold)	
									Life time saving in energy resouses, GWh						12205	619893		

1) Including weight savings of trailers and bodywork
2)VC=Volume critical transport and WC=Weight critical transport which is asumed to be 20 % of all Heavy Trucks
*3) See table 3, Fuel saving 0.12 l/100 km*100 kg WR for HT WC is based on 20% empty trips*
4) If all new registrated vehicles are light weighted and the fleet size is constant

One figure which influences the total result in table 7.1.1 most is the value of SFC (fuel saving, litre/(100 km and 100 kg WR) for cars, which here is assumed to 0.30.

This is a conservative value for cars with resized powertrain, se Figure 4.2.3. It is assumed that the level of resizing of the powertrain is performed in such a way that the performance of the vehicle is unchanged. The assumed weight reduction in Table 7.7.1 includes the increase in weight that would have been needed if conventional steel were used instead of high strength steel to meet increased safety demands (primarily for cars). For trucks, the quoted weight reduction also includes the weight reductions on trailers and other bodywork. The assumed total curb weight reduction varies from 4 % on cars and up to 6 % on trucks and other body work. The assumed weight reduction for upgraded parts of 17 -20 % corresponds to an increase in yield strength of 50 to 100 %. All vehicles are considered to have volume critical transports (vc) except for 20 % of the heavy trucks (construction, heavy haulage, forestry trucks and tanker trucks). Table 7.1.1 shows that use of advanced high strength steel in the Swedish road vehicle fleet can give a life time saving of 3170 ktonne of CO_{2e} and a saving of 12200 GWh of non-renewable energy resources. In a European perspective, these figures would be 50 times higher, and 300 times higher on a global basis [7:2]. The environmental savings shown in table 7.1.1 is sensitive to the total life time performance. In order to get figures on life time performance, data from IFEU [4:3, 4:4], Eurostat [7:4] and Transport Analysis, Sweden [7:5] has been analysed.

Figure 7.1.1 shows yearly driving distances as a function of age for different vehicles in Sweden. Data are from year 2009 and the figure also gives average driving distances per year [7:5].

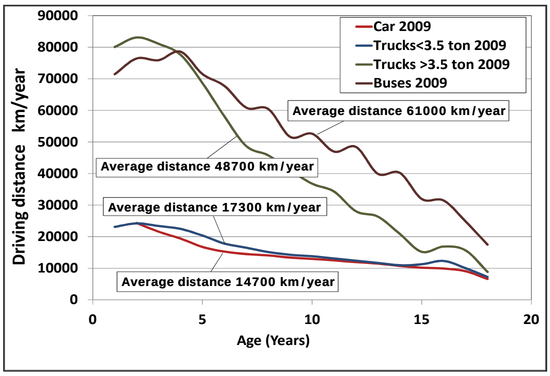


Figure 7.1.1. Yearly driving distances for different vehicles, Sweden 2009 [7.5]

Unfortunately similar figures on driving distances in other countries have not been found.

The total life time performance for Swedish vehicles is found in statistics from Bilsweden [7:6]. Sweden has a fairly old vehicle fleet with an average life time, year 2009, of 16.6 years for all vehicles below 3.5 tonnes total weight. Unfortunately similar figures on the total life time performance for other countries have not been found. In order to estimate the total life time performance for the European vehicle fleet, age distributions between Sweden and Europe have been compared. The comparison of number of vehicles in different age classes, based on figures from Eurostat [7:4], is shown in Figure 7.1.2.

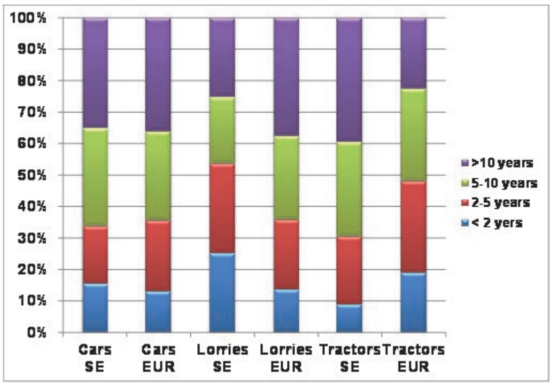
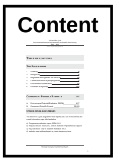


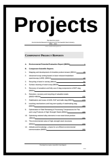
Figure 7.1.2. Age distribution of vehicles, comparison between Sweden and Europe [7:4]

It is surprising that the age distribution for cars do not differ significantly between Sweden and Europe, for Lorries Europe seems to have an older fleet than Sweden and for tractors the opposite. For the analysis shown in table 7.1.1, figures for the total life time performance for Sweden and Europe are from reference [7.5] and, [4:3, 4:4] respectively.

The total amount of high strength sheet steel needed to achieve the weight reduction quoted in table 7.1.1 is about 5 800 ktonne/year at the European level. Predictions made by the steel industry of the additional amount of high strength steel that will be on the market in Europe five years from now is about 10 000 ktonne/year. This means that the assumptions of weight reductions made in Table 7.7.1 seem reasonable, since the automotive and heavy transport segments are by far the largest segments in terms of high strength steel usage.

In order to facilitate the understanding of the environmental value of advanced high strength steel, a general case study has been performed. The scenario was that one million tonne of such steel





replaces 1.3 million tonne of conventional steel in a vehicle fleet of European mix, Table 7.3.1. This corresponds to a weight reduction on upgraded parts of 25 %. This higher figure was chosen since the parts which should be upgraded can be chosen more selectively than was assumed for the analysis shown in table 7.1.1

Table 7.3.1. The environmental value of using one million tonne of advanced high strength steel into a vehicle fleet

Type of Vehicle	Total amount of steel regarded ktonne		Weight reduction ktonne	Specific CO_2 emissions steel production kg CO_2/kg steel		Life time CO_2 savings ktonne	Life time CO_2 savings ktonne	Total life time CO_2 savings ktonne
	AHSS[1]	Conv		AHSS	Conv	M1 Steel	M4 Use phase	M1+M4
Car	561	747	187	2,25	2,13	413	3494	3908
LCV < 3,5 ton	114	152	38	2,19	2,10	82	1057	1139
MHV >3.5t <16 t	30	40	10	2,15	2,05	21	179	200
HT >16 t, VC[2]	216	288	72	2,15	2,05	140	1510	1650
HT >16 t, WC[2]	54	72	18	2,15	2,05	35	755	790
Buses >16 t	26	34	9	2,15	2,05	18	205	222
Total	**1000**	**1334**	**333**	**2,21**	**2,10**	**708**	**7201**	**7909**
1) AHSS = Advanced High Strength Steel	**Total life time CO_2 saving, ktonne, (M1+M4)**							**7909**
	Total life time saving in energy resouses, GWh							**31271**

The analysis shows that if one million tonne of advanced high strength steel replaces 1.3 million tonne of conventional steel in a road vehicle fleet it results in life time savings of 8 million tonne CO_{2e} emissions. Further 31 TWh of non-renewable energy recourses are saved. About 90 % of these savings are related to the use of the vehicles.

7.2 Rail vehicles

The potential for weight savings is great for rail vehicles since this has not been a prioritized area due to the cost of consumed energy is low compared with the total operating cost. Further the life-time of rail vehicles is long compared to other vehicles and a somewhat conservative approach to an aggressive development has been hindered by regulations and standards in this field, especially for cargo trains. However, the environmental aspects have gained ground as well as increased crash resistance for improved safety. This together with the increasing weight due to an increasing number of subsystems and increasing rail wear has increased the interest for weight reduction by using advanced high strength steel.

If the total rail transports during 2010 are considered, the following is stated by Eurostat for EU 25 [7:4]:

- Passenger transport work $420 \cdot 10^9$ passenger-km/year
- Cargo transport work $400 \cdot 10^9$ tonne-km/year

Assuming an average energy consumption of 100 Wh/pass-km and 34 Wh/gross t-km in average for electric and diesel cargo trains [7:7, 7:8] one arrive at a total yearly final energy consumption of 56 TWh. This means a primary energy consumption of 153 TWh if 35 % diesel driven trains is supposed [4:4]. The Cargo Capacity Utilisation (CCU)) for cargo trains is estimated to 50%. A conservative estimate of an average weight reduction of 7 % of the actual gross weight will lead to a potential primary energy saving of 3.5 % with $\eta=0.5$. This means a potential primary energy saving of 5.4 TWh/year or a life-time saving of 162 TWh for an average life-time of 30 years. The corresponding potential for life-time carbon dioxide saving is 45 million tonne. In Sweden where the diesel driven trains amount to 4 % the corresponding potential for the life-time primary energy saving is 2 TWh and the carbon dioxide saving 200 kton. The low figure on CO_{2e} is a result of very low emissions when producing electricity in Sweden.

7.3 Potential life-time improvements for the whole vehicle segment

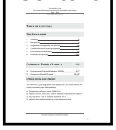
A second way of validating the results shown in table 7.1.1 in chapter 7.1 is to perform a brief calculation based on the yearly carbon dioxide emissions for different vehicle segments. By assuming a percentage of possible weight savings and a fuel saving efficiency η (see section 4.2.4) related to the average driving cycle of the specific vehicle segment, the life time improvement potential in carbon dioxide emissions during the use phase for active structures could be calculated by Equation 7:1. From that result also savings in primary energy resources as well as economical improvements could be estimated.

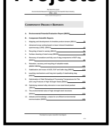
$$\Delta M_{impr} = \Sigma(M_{em,y} * WR_{segm,y}/100 * \eta * LT_y)_n \quad (7{:}1)$$

where

ΔM_{impr} = Total life time improvement of carbon dioxide emissions by upgrading, tonne CO_{2e}
$M_{em,y}$ = Total yearly CO_{2e}-emissions from segment y, tonne
$WR_{segm,y}$ = Average weight reduction in segment y, %
η = Efficiency defined in section 4.2.4
LT_y = Life time considered, years
n = Number of segments

Such an analysis have been performed for road, rail and domestic water transports in Sweden assuming 50% fleet penetration as in table 7.1.1 Input to this calculation is based on data from ACEA [7:1], Eurostat [7:4], Trafikverket [7:9], Anfac [7:10] and IEA [7:11]. The transports included in the analysis





represent together one third or 22 Mton of the greenhouse gases emitted in Sweden.

The assumed weight reduction varies from about 20 % for upgraded parts in active structures and 30 % for upgraded parts in passive structures.

The results for carbon dioxide savings are summarised in Figure 7.3.1.

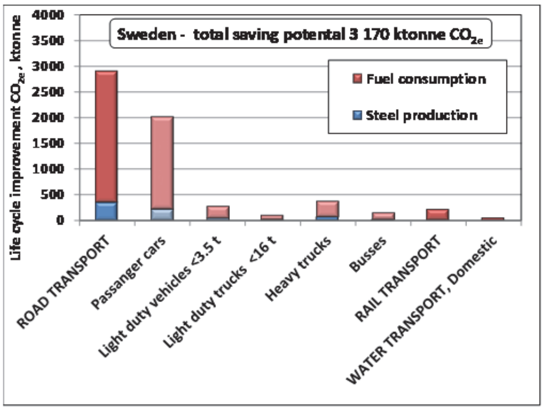


Figure 7.3.1. Life cycle carbon dioxide improvement when high strength steel replaces conventional steel in vehicles, 50 % fleet penetration in Sweden

It is amazing how well the figure of 2 900 ktonne for the road vehicle segment conforms to the figure of 3 170 ktonne shown in table 7.1.1, although the calculations are performed differently and with different data input sources.

The primary energy resources have been calculated by the Swedish Environmental Research Institute (IVL) considering the energy content in respective energy resource consisting of crude oil, natural gas, coal, lignite and uranium. The result is shown is Figure 7.3.2.

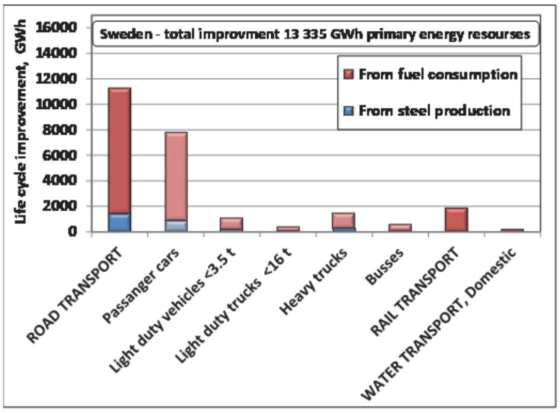


Figure 7.3.2. Life cycle improvement in primary energy resources when high strength steel replaces conventional steel in vehicles, 50 % fleet penetration in Sweden

The economic potential related to the fact that less steel need to be produced and transported after than before an upgrading is, both for active and passive structures, calculated by multiplying the energy saving with the general energy price for Sweden assumed to 0,0561 €/kWh. The economic gains in the use phase have been calculated by multiplying the energy savings with the energy price for respective energy source (0.1823 €/kWh for gasoline, 0.1641 €/kWh for diesel and 0.0561 €/kWh for electricity).

An estimate of the economic potential in the scenario outlined above is shown in figure 7.3.3.

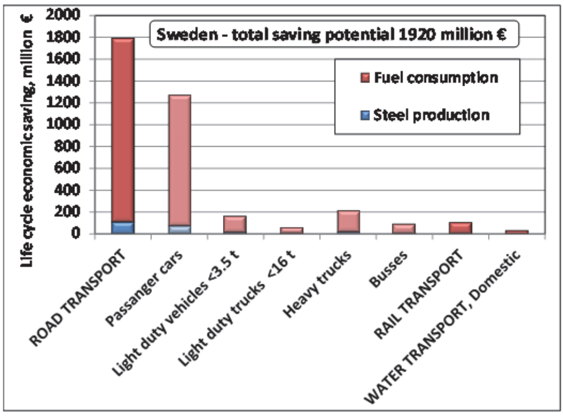


Figure 7.3.3. Life cycle improvement in economy when high strength steel replaces conventional steel in vehicles, 50 % fleet penetration in Sweden

The corresponding figures for Europe would roughly be 50 times higher than those shown in figures 7.3.1 to 7.3.3.

The total results on life time savings are summarised in Table 7.3.1. In this summery also savings in carbon dioxide emissions have been given a credit corresponding to a conservative estimate of the price of carbon dioxide certificates. For the use of vehicles a carbon dioxide tax of 0.291€ (=2.50 SEK)/litre of fuel has been used to calculate the economical improvements related to the carbon dioxide emissions during the use phase.

Table 7.3.1 Summary of life time improvements in the Swedish vehicle fleet

Description	Physical balance		Economy		
	CO_{2e} [ktonne]	Energy [GWh]	CO_{2e} [M€]	Energy [M€]	Total [M€]
Steel production	365	1460	3	82	85
Use of vehicles	2 805	11 875	272*	1 563	1835
Total vehicles	3 170	13 335	275	1 645	1 920

**) This figure refers to Swedish carbon dioxide tax on fuel*

8. CONCLUSIONS

The results of the project can be concluded by the following.

The life cycle assessment of the production (cradle to gate) of the selected carbon steel and stainless steel shows, as expected, a slight increase in environmental impact with increasing steel strength when expressed per unit of steel weight. For carbon steel this increase can be related to the type of steel and the yield strength. For stainless steel, a better correlation is achieved if the environmental load is related to the chemical composition.

Environmental impact related to acidification, eutrophication, ozone creation, abiotic depletion and the non-renewable energy resources are closely related to the CO_{2e}-emissions - a relationship that is almost independent of the type of steel grade produced at a specific production site.

Real life upgrading cases show that it is possible to achieve the project goal of 20 % weight reduction for parts in which conventional steel is replaced by high strength steel. The analysis also indicates that there is an even greater potential, especially for passive structures.

In principle, there is nothing new or remarkable about using advanced high strength steels in design work. However, buckling, deformations, points of load application and fatigue in welded joints are areas that require extra attention.

Developed models for life cycle assessment of high strength steel structures have been validated with ten different case studies. A software tool has been developed. This has met the industrial goal of presenting engineering tools for easy assessment of the environmental savings which can be achieved by using advanced high strength steel.

The energy efficiency, η, that expresses how much of a weight reduction that can be converted into a reduction in fuel or electricity consumption has been evaluated. This facilitates assessment of the environmental impact during the use phase for non-weight critical transports.

Case studies on ten different applications were advanced high strength steel have been used instead of conventional steel have been performed. The CO_{2e}-emissions for active structures could be reduced by 5-20 % and the cost by 10-30 % over a life cycle. The case with a spiral dewaterer in carbon steel, which like the storage tank in stainless steel is a passive structure, show a CO_{2e} reduction of 31 % and a reduced cost of 40 % when conventional steel was replaced by high strength steel.

Calculations show that every million tonne of advanced high strength steel that replaces conventional steel in the road vehicle fleet would result in a saving of 8 million tonne CO_{2e}-emissions and 31 TWh non-renewable energy recourses in a life cycle assessment, including the use phase. Over 90 % of these savings are related to the use of the vehicles.

For trains in Europe there is a potential for a life-time primary energy saving of 162 TWh for an average life-time of 30 years. The European potential for life-time carbon dioxide saving is 45 million tonne, if 35 % diesel driven trains is supposed.

A valuation of the environmental and economic life cycle improvements that would be possible for vehicles in Sweden is 3170 ktonne of CO_{2e}, 13335 GWh of primary energy resources and 1920 M€ in economic savings.

Results from this project have been published and presented in a number of papers and conferences. In addition the project members have been main authors in the handbook "Environmental assessment of steel and steel structures", which is a handbook for engineers, designers, researchers and students. Further software for environmental assessment of steel and steel structures has been developed in the project.

9. FUTURE UTILISATION OF PROJECT RESULTS

The project has delivered booth methods to calculate and concrete results on the environmental and economic advantages of using advanced high strength steel for lowering weight and reducing environmental impact.

This means that industry and society now have booth knowledge the tools to verify and communicate these results.

The tools represented of a numbers of case studies, software for calculation of the environmental and economic benefits and a handbook on assessing the environmental value of using advanced high strength will indeed be a necessary precondition in this process.

Having regard to the great potential for environmental and economic improvements shown in the project, the use of the developed knowledge and tools can lead to a substantial step towards a more sustainable society.

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Cederfeldt L. and Sperle J.O.
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10.3 Project reports

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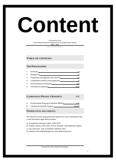

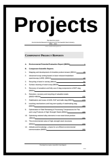

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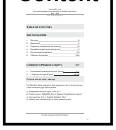

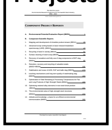

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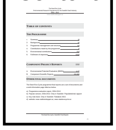

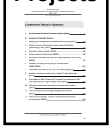

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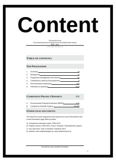
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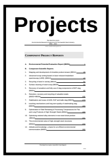
Projects

Attitude and knowledge – a basis for an efficient environmental communication

(88052)

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Abstract

Stakeholder involvement is necessary for an organisation to be able to work efficiently with sustainability issues. ISO 26 000 states that stakeholder involvement must include a dialog between the stakeholders involved and the operation. The first step in this process is to identify which key issues the stakeholders find most important and to find out if there were any differences between the organisation and its stakeholders in their priorities of environmental issues.

Within the two project periods 2004-2007 and 2009-2012, a research project has been carried out in cooperation between the Linnaeus University (former University of Kalmar) and the Swedish steel industry. Environmental evaluation techniques such as conjoint analysis, focus group discussions and Q-methodology were used to evaluate stakeholder preferences for steel trade environmental issues. To the best of our knowledge, such an approach has not been used before to evaluate stakeholder preferences for environmental issues within an industry trade like the steel industry.

Nine studies have been carried out in the framework of project 88052. The studies include: a literature review, method evaluation, evaluation of environmental objectives in stakeholder groups, screening of relevant factors, evaluation of steel environmental characteristics, identification of barriers to the introduction of new materials, impact of knowledge on preferences for environmental issues, impact of training on attitudes toward environmental issues, driving forces for environmental decisions within the steel industry and finally the general publics view on environmental improvements from the steel trade.

It can be concluded that the methods applied in the studies works well. It has been possible to show how different stakeholder groups as well as individuals prioritise environmental objectives and sustainability issues. Successful tests have been made where the results were brought back to the respondents in order to stimulate discussions cross different stakeholder groups. It has also been possible to establish some main driving forces to strategic environmental decisions and finally to compare how the general public and legislators view the environmental issues and the responsibility for minimising environmental impact that derives from the steel industry.

1. INTRODUCTION

Sustainability issues concern the steel industry constantly, both in order to approach a sustainable development but also and as a means of competition. The steel industry in Sweden, has been working with sustainability issues for many years. Gradually several causes of environmental impacts have been minimized by technical improvement and minimized resource consumption.

But there are also sustainability issues which could not easily be solved by technology, since sustainability is linked to human behaviour. Unfortionately, there are often weak links between attitudes and behaviour [1-3]. An attitude is always evaluated by the individual, from a cognitive view (what you think and know), an emotional view (what you feel) and a behavioural view (if you act in order to show if you think the behaviour in focus is good or bad). This means that awareness must increase on the consequences of a specific behaviour in order to inspire people to change behaviour[1, 2]. Knowledge on the connection between attitudes and behaviour is important for managers within as well as outside the industry. Strategies to raise awareness and increase engagement in sustainable development issues are, according to Gardner & Stern [4], basic values, information and education, incentives and community management - meaning dialogue groups and communication.

Traditional stakeholder management provides opportunities to address issues concerning awareness and engagement in sustainability issues. The first task is to identify stakeholders connected to the industry from an environmental perspective. A stakeholder is defined by ISO [5] as "individual or group that has an interest in any decision or activity of an organization". ISO further defines stakeholder engagement as an "activity undertaken to create opportunities for dialogue between an organization and one or more of its stakeholders with the aim of providing an informed basis for the organization's decisions." Stakeholders are thus either affected by the decisions' and activities under taken by the organization or affect the decisions' and activities themselves. Stakeholder groups may involve local residents, customers, employees, shareholders, banks and insurance companies, suppliers and other groups connected to the steel industry.

In order to engage and inspire stakeholders to take part in discussions on sustainability, there is a need to increase the possibilities for dialogue, a two-way communication. To change behaviour the communication is most successful in dialogue forums [4]. Information only, a one-way communication, is not sufficient. Stakeholders must have an opportunity to respond and to make their voices heard so their views can be incorporated into the industry's decision making. [5]

However, communication is not in it self sufficient for changing people’s behaviour. Attitudes including knowledge, social norms (expectations from others) and personal norms (individual demands), as well as habits and control (if people believe they can influence or not) are factors that influence peoples’ intentions to change behaviour and in turn their behaviour in practice [1, 2]. People are influenced by social norms, such as laws and agreements but also by other people’s opinions. Personal norms are demands that the individuals put on themselves (moral aspects). The link between the intention to act and the behaviour in practice is often weak. In a study made by Lindström in 2007 [6], it was concluded that knowledge (the cognitive part of an attitude) influenced the intention to act among environmental experts while personal norms and worry (the emotional part of the attitude) influenced the public’s intention to act. It is important to be aware of such background factors in order to develop strategies for information and communication aiming at increasing the environmental awareness and also making the work with environmental issues more efficient [4].

This project “Attitude and knowledge – a basis for an efficient environmental communication” has run over two project periods 2004-2007 and 2009-2012. The overall aim has been to study how stakeholder groups and individuals value environmental issues and also the role knowledge and personal concern play in environmental decisions.

Key issues through both phases of the project were:

- What are the preferences for the steel industry's environmental issues?
- What are the preferences of different stakeholders towards the steel industry's environmental issues?
- Is it possible to identify the underlying factors that influence preferences, both on an individual and group level?
- How can communication between the steel industry and various stakeholders improve?
- What is the impact from the individual's knowledge and personal concern on the environmental decisions made in the steel industry?

To investigate these issues, methods were needed that met the following criteria:

A method where the respondents made a trade-off between factors were sought since such a method had more similarities with the day to day decisions people make. Results from a study where the factors are evaluated one by one are less informative and not as useful as a basis for strategic decisions.

Thorough statistical analytical methods must comply in order to increase credibility and to make the results more eligible as a basis for strategic decisions. To further increase credibility, methods were sought that could be evaluated both quantitatively and qualitatively. In issues regarding preferences and attitudes the results cannot only be founded in quantitative analytical measures, they need to be complemented with qualitative analyses in order to make the picture complete.

Several methods for environmental valuation are currently being used to deal with this complexity; multiple-criteria analysis (including multiple objective decision support, multi-attribute decision making and multi-criteria decision analysis) [7], willingness to pay/willingness to accept [8], analytic hierarchy process [9], focus group discussion [10], cost-benefit analysis [11] and material flow analysis [12] to mention a few.

Conjoint analysis along with related methods (stated preference methods such as choice experiments, choice modelling, adaptive conjoint analysis and hierarchical conjoint analysis) have been widely used in marketing, health care and transportation. In the environmental evaluation segment, the method is not as widely applied, although the number of studies is increasing [13].

A similar method is the Q methodology [14, 15]. This method has been used extensively in social science, for example psychology [16-18]. Also the number of environmental valuation studies using Q methodology is steadily increasing [19, 20] although to this date the method has (to the best of our knowledge) never been tested within a manufacturing industry.

Conjoint analysis and Q methodology comply with the criteria stated above and were therefore chosen for this project.

In the initial project phase 2004-2007 a method for evaluating environmental factors, was adapted to the overall research issue of the project, different analytical methods were tested and a method to communicate and discuss the results was tested. In the second project phase, 2009-2012, the focus was on evaluating the preferences of different interest groups and to analyze if knowledge and personal concern (e.g. worry) had any influence on environmental decisions made in the steel industry.

2. OBJECTIVES

The main objectives of this research project was (2004-2012) to present a method for evaluation of environmental preferences within the steel industry as well as among it’s stakeholders [21, 22] and (2009-2012) to show how communication between stakeholders can be improved and to study how attitudes, norms and control could affect environmental decisions made within the steel industry [23].

2.1 Study I

The aim of study I, a literature review, was to provide an introduction to conjoint analysis and to present an overview of its application in the environmental field.

2.2 Study II

The aim of Study II was to assess environmental preferences for some sustainability attributes of the steel industry among different groups of people.

2.3 Study III

The aim of study III was to describe the preferences in different stakeholder groups for the four environmental objectives of the Steel Eco-Cycle research program (2004-2007), and to identify any gaps in preferences between industry representatives and different stakeholder groups.

2.4 Study IV

The aim of study V was to identify barriers to use new materials and specifically Advanced High Strength Steel (AHSS).

2.5 Study V

The aim of study IV was to identify how different stakeholder groups valued the characteristics of AHSS such as weight reduction and impact strength (durability) compared to factors such as price, scrap steel content and origin of the steel.

2.6 Study VI

The aim of study VI was to assess how knowledge influence environmental preferences.

2.7 Study VII

The aim of study VII was to assess if training influence environmental attitudes (preferences).

2.8 Study VIII

The aim of study VIII was to assess how attitudes including knowledge and worry influenced environmental decisions made in the steel industry. A supplementary aim was to study how responsibility for sustainability issues is viewed by people within the steel industry.

2.9 Study IX

The aim of Study IX was to assess the public’s risk perception, attitudes and concerns regarding the steel industry and its impact on the environment.

3. METHODS

3.1 Literature review (Study I)

A literature study was initially completed, and environmental applications of stated preference methods were reviewed [24].

3.2 Questionnaires (Study II, III, V- IX)

For most of the studies (all but Study I and Study IV) questionnaires were used for data collection.

3.3 Conjoint analysis (Study II, III and V)

Conjoint analysis is a stated preference method, which can be used to assess individual or group-level preferences for a specific product, service or situation. The method is used to evaluate specific attributes of the product/service/situation and thereby it is possible for researchers to determine which attribute is most important in the evaluated situation. Further information on the method can be found in [13, 24-27].

Traditional methods of environmental valuation determine preferences for each factor individually, while the main advantage of conjoint analysis is that the method uses the ability of the human mind to simultaneously make decisions based on multiple factors. The method creates a realistic research situation where both preferences and trade-offs for a set of factors – or attributes – are assessed. Conjoint analysis is a decompositional method [24], which means that the preferences are decomposed from the responses of the participants.

Green & Srinivasan [28] and Gustafsson [29] have stated a number of steps involved in the design of the survey. These involve selection of the data collection method, i.e. whether the valuation made by the respondents should be from a profile (full profile approach) or a two-factor comparison. The valuations can be made using either a full factorial experimental design or a fractional factorial design (reduced design). In order to keep the workload manageable for the respondents, the reduced design is often recommended. However, a fractional factorial design creates confounding effects, where it will not be possible to separate the interaction effects from the main effects.

The researcher must also decide in what manner the alternatives will be presented to the respondents: interview or questionnaire. In both cases visualization of the alternatives makes the task easier for the respondents as well as ensuring that all respondents access the same information on the alternatives. Yet another issue to consider is whether the respondents will be asked to rate, rank or choose from the alternatives. The elicitation method chosen will affect the way the data can be analysed.

Finally, the number of attributes must be limited since respondents will not be able to maintain the same level of concentration over a large evaluation set. Five to ten attributes are considered functional [24]. The number of attributes is dependent on the type of study and how the study is designed.

3.4 Analysis of data

Conjoint surveys can be analysed using a number of different methods. If the data set consists of ranked data and is linear, multiple linear regression or ANOVA are commonly used. In the studies reported here, a set of different approaches were used to analyse the data.

3.4.1 Effects from the factorial design

A rank order based conjoint analysis can be analysed through the main and interaction effects derived straight from the factorial design.

3.4.2 Multiple Linear Regression (MLR)

Multiple linear regression is a method that works well with rank-based conjoint analysis [30, 31]. The method assesses the relationship between several independent variables (the attributes) and one dependent variable (the ranking of the alternative). However, the method requires the variables to be independent (non-collinear) from each other; and using a statistical experimental design ensures this. The effects from the factorial design are equal to half of the regression coefficients from a MLR.

3.4.3 Principal Component Analysis (PCA)

Principal component analysis is a multivariate data analytical method that can be used to create a map of different correlating phenomena or variations in a data set. In this study, PCA was performed to evaluate how demographic data correlates to the preferences among the respondents.

PCA involves a linear transformation (projection) of the original variables into a smaller set of independent factors (components) describing as much as possible of the variance in the data matrix. The first principal components show the main co-variation within the data set. Version 9.2 of the Unscrambler software was used to perform the PCA [32].

3.4.4 Partial Least Squares Regression

Partial least squares regression (PLSR) is a multivariate regression method which can simultaneously handle several response variables. Similar to PCA, PLSR is based on a linear transformation of the original variables to a limited set of orthogonal factors, but now also attempting to maximize the covariance between the independent and dependent variables.

The main advantage of PLSR is that the results can be presented graphically with all individual responses visible. Another advantage is that PLSR is not restricted to non-correlating variables.

Further information on PLSR and PCA can be found in the textbook by Martens and Næs [33]. The Unscrambler software was used to perform the PLS regressions [32].

3.4.5 Cluster analysis

Cluster analysis has proven useful together with conjoint analysis in order to find segments among respondents [34-36]. The cluster analysis forms clusters of the respondents replies, by putting respondents (samples) that are similar to each other into groups, at the same time as respondents that differ in responses are kept apart [37, 38]. In this project, a hierarchical cluster analysis method was applied to the individual regression coefficients from the MLR analysis. The analysis was performed by the classification unit from the SPSS v. 15.0 software package [39].

3.5 Focus group discussions (Study IV)

Focus group discussions [40] are used when the aim is to scan a specific target group's (stakeholders) opinions in order to identify key issues or factors in a predetermined topic.

People from a certain stakeholder group are brought together in a room. Preferably the participants are chosen by random selection. The group of people are then given a topic to discuss during 45-60 minutes. A moderator is present, but she or he should not lead the discussion in any specific direction (unless it falls out from the predetermined topic), only listen and ask supportive questions if needed. An interview manual is used. The discussion is recorded and afterwards a transcription of the discussion is made. The transcription is processed through qualitative analysis and the text is analysed for key topics and key words.

The result can be used to associate the predetermined topic with the key issues (factors) that the participants thought were particularly interesting.

3.6 Q-methodology (Study VIII)

Q-methodology is similar to conjoint analysis in the meaning that the respondents are forced to make trade-offs between predefined factors. The method was first described by Stephenson [14] and has been used to assess subjective issues such as public response to climate change [41] and wind power [42] and leadership development [43]. To the best of our knowledge, this method has never been adopted to an industry specific issue such as environmental decisions in the steel industry.

Respondents are presented with a set of factors, in the form of statements, and asked to rank them in a fixed pattern.

A correlation matrix is estimated where the individuals' responses are correlated to each others. The aim is to measure to what extent the individuals are similar or differ from each other in their preferences. The correlation matrix is then run through a PCA where groups of respondents that respond alike become salient.

In the final step a typical sorting representative for the group is picked out for each of the groups, and this typical sorting is used to describe the preferences of the group in words.

4. STUDIES

The studies have been carried out during the periods of 2004-2007 and 2009-2012.

4.1 Study I: Literature review

Conjoint analysis is a relatively new approach for evaluating environmental values, and it was not until the mid-1990s that the method came into use. Since the middle of the 1990:s, conjoint analysis has been applied to a number of environmental issues such as energy, recreation, environmental valuation, ecosystem management, consumer preferences for environmentally certified products, public preferences regarding industrial projects, and environmental policy development and worked effectively in eliciting preferences on various environmental issues. In all 84 studies were found where conjoint analysis, or some closely related method, was used. Ecosystem management, environmental valuation, product evaluation and recreation are the areas where most conjoint studies have been carried out (Fig. 2) [24].

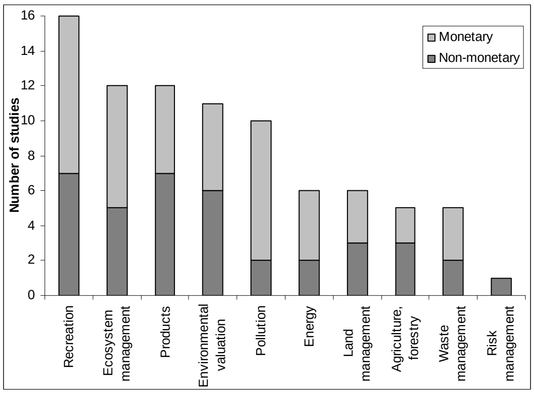


Fig. 2. Number of conjoint analyses in various environmental areas

4.2 Study II: Initial screening of environmental factors

4.2.1 Design of Study II

In the second study [44], the rank-based conjoint survey was designd. In order to use the most relevant attributes, a discussion was held with key persons from the "Steel Eco-Cycle" programme, similar to a focus group discussion. The attributes discussed initially were; acidification, chromium content, cost of production, emission of carbon dioxide, emission of dioxins, emissions of other toxic substances, environmental effects from production, eutrophication, life length of a product, price level of 1000 kg steel, proportion of ore, proportion of renewable resources used, recyclability, use of alloys, use of non-renewable energy, use of non-renewable resources, use of non-renewable resources containing energy and use of non-renewable resources not containing energy.

Three main requirements were defined for the attributes that were to be used in the study; the attributes should be of a kind which were useful for new product development, the attributes should guide decision makers, and finally the attributes should be relevant for the "Steel Eco-Cycle" research programme. The discussion resulted in five attributes for the second study:

- Use of non-renewable energy
- Use of non-renewable resources
- Emission of dioxins
- Emission of carbon dioxide
- Cost of production

For each attribute, figures from the Swedish steel industry were assigned on two levels. The figures used were collected from the steel industry and they represent actual emission and consumption levels [45]. The evaluation set was created by a fractional factorial design, including eight alternatives and one centre alternative creating a total of nine alternatives. The function of the centre sample was to diagnose the responses for non-linearities [46].

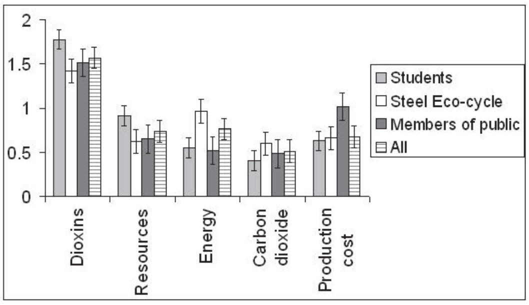


Fig. 3. MLR coefficients with confidence intervals for ranking data in the second study

The respondents were asked to rank nine different alternatives and thereafter rate the same alternatives. The aim of the rating process was to enable verification of the ranking results.

Three groups of respondents were included in the survey. The first group consisted of students from the University of Kalmar. The students had different major disciplines: environmental sciences, environmental engineering, and industrial organization and economics. The response rate for the students was 65%. The second group were participants in the “Steel Eco-Cycle” research programme. This group was asked to participate during a one-day conference held in Stockholm (May 31, 2006). The response rate was 82% (46 out of 56). The third group, members of the public, were asked to participate during an open house session at the University of Kalmar (20 Sept, 2006). Seventeen visitors completed the questionnaire.

The alternatives were presented in a questionnaire divided into four parts. The first five pages provided information on the survey, background information on the environmental issues covered by the survey, figures on the total Swedish load for the different attributes and emissions from the Swedish steel sector. The second part consisted of socioeconomic and demographic questions. In the third section respondents were asked to rank nine alternatives (attributes). After performing the ranking task, respondents were asked to rate the same alternatives on a scale of 1–10. In the rating task, the respondents were allowed to use the same rating for several alternatives.

Finally, the students were asked to evaluate the survey and answer a series of questions on the survey design and to state to what extent the ranking questions were easy to understand.

Presentation of the alternatives were both as figures and graphs, where the figures were recalculated as percentages of the upper level and presented as a bar graph for each alternative.

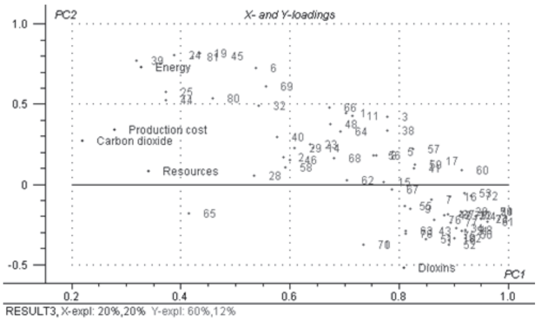


Fig. 4. PLSR regression loadings, linking individual preferences to the design variables in the second study

4.2.2 Study II: Results and discussion

The three original groups were analysed on average group level. When the MLR regression coefficients (equalling one half of the effects of the factorial design) were compared for the three groups, there was no significant difference (see Fig. 3). Emission of dioxin was perceived as most important for most of the participants. It was also noticeable that emission of carbon dioxide in this study received the lowest overall preference.

The individual results were illustrated using a PLSR loading, see Fig. 4. If an individual was placed close to an attribute in the plot, the specific respondent showed a strong preference for this attribute. Thus, any segmentation among the respondents was expected to be visible in this plot.

From the PLSR-plot it could be seen that the three original groups were not assembled, instead preferences were driven by other background factors than original group.

4.3 Study III: Environmental objectives of the Steel Eco-Cycle

The next study was designed to further study the differences of stakeholder groups [47]. To ensure that the whole industry was in focus, the environmental objectives of the research programme Steel Eco-Cycle was used as factors since they represent sustainability issues that are relevant to all operations of the trade.

4.3.1 Design of Study III

The four environmental objectives of the research programme the "Steel Eco-Cycle" were chosen to represent the major sustainability issues of the steel trade. The attributes were:

- Use of non-renewable energy,
- Use of non-renewable resources,
- Emissions of carbon dioxide and
- Weight reduction of steel products

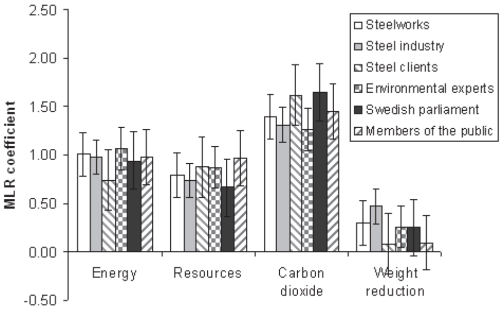


Fig 6. MLR coefficients with standard deviations for ranking data in the third study

Each attribute was presented at two levels. By using a fractional factorial design, eight alternatives were created. The alternatives were presented in a table where the respondents were asked to rank and rate the alternatives.

One objection to the choice of attributes in this study was that they interacted. Reduction in the use of non-renewable energy will lead to a reduction in emission of carbon dioxide. The same objection could be made for weight reduction of products, where use of non-renewable resources will decrease at the same time. However, the aim was to consider if the preference for the environmental objectives varied with different stakeholder groups, hence it was decided to use these environmental objectives despite the risk of confounding. They also held the advantage of being relevant to and understood by respondents across the trade.

A questionnaire consisting of four parts was used. First, a one page introductory letter described the overall research programme the "Steel Eco-Cycle". Next, two pages briefly described the four environmental objectives. The third part was the conjoint task with one page giving instructions on how to complete the task and then the actual conjoint task in a table. The last part was a set of questions on demographic and socio-economic information concerning the respondent. The respondents were also asked to freely mark important environmental issues from a list.

For those respondents that received their questionnaire by postal mail, a pre-franked return envelope was attached. Six groups of respondents were included;

- Steel works. SSAB in Borlänge, Outokumpu Stainless AB in Avesta and Sandvik AB in Sandviken participated.
- Steel clients. Four manufacturing industries – clients to the steel industry – participated.
- Steel industry (research institutes, steel traders, partners etc).

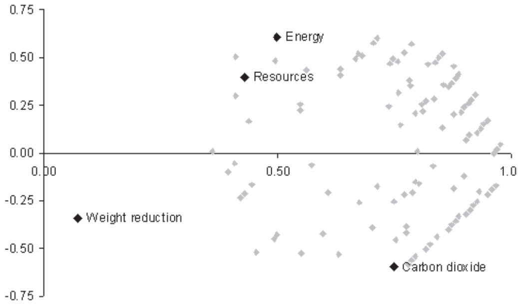


Fig. 7. PLSR regression loadings, linking individual preferences to the design variables in the third study

- Members of the public. Nine hundred addresses were randomly chosen from six different Swedish municipalities. Three of the municipalities held a large steel works, while the other three municipalities did not.
- Policy makers. Questionnaires were sent to the Swedish parliament.
- Environmental experts. The environmental experts were chosen from companies that are not specifically connected to any steel industry. In this category also persons working at county administrative boards were included.

4.3.2 Study III: Results and discussion

In the third study, six stakeholder groups were used; representatives from the steel industry (n=83), customers to the steel industry (n=18), steel research institutes (n=37), members of the public (n=176), decision makers (n=49) and environmental experts (n=25).

In Fig. 6, the MLR coefficients for the original stakeholder groups are presented. As in study II, the original stakeholder groups did not differ when the results were analysed as averages per group. Due to wide individual differences, the standard deviations were far too large to make the MLR coefficients an efficient way of presenting the results.

When the respondents were presented in a PLSR-plot (Fig. 7), no clear segmentation was visible although it is still obvious that there is a variation in the preferences of the respondents.

It was clear that carbon dioxide was the most preferred environmental objective and that weight reduction of products was the least preferred objective (the factor lies close to the center thus having little impact on the model). It was also interesting to note that use of non-renewable resources seemed to receive a lower priority than use of non-renewable energy. For 62% of the respondents, regardless of original group, the regression coefficient for weight reduction was zero or negative. A negavtive regression coefficient indicate that the factor had not played any role when the respondent ranked the alternatives, or even that the respondent actively left the factor out. Only 2% of respondents had a regression coefficient that was negative or zero for carbon dioxide. The figures for negative regression coefficients for use of non-renewable energy and non-renewable resources were 4% and 5% respectively.

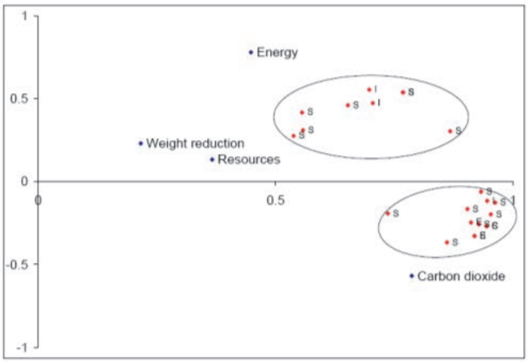


Fig. 9. PLS2 regression loadings showing respondents with quality issues as their occupation. The respondents are illustrated by letters; S=Steelwork, I=steel stakeholder, E=environmental expert, C=steel client, D=decision maker, P=public. 80 % of the Y-variance was explained on the first two latent variables.

When the results from the original groups were analysed, respondents from steelworks, environmental experts and the public followed the average. Steel stakeholders showed a wider variation concerning the weight reduction of products.

Respondents having environmental issues as their occupation prioritised the same environmental targets as the average respondent. Respondents whose jobs were related to quality control were divided into two groups, one focusing on carbon dioxide emissions (like the average respondent) and one focusing on non-renewable energy and weight reduction of products (Fig. 9.). Decision makers and steel clients focused more clearly on reduction of carbon dioxide emission, assigning weight reduction of products lower priority.

The group of respondents working in research and development were divided in a similar way (Fig. 10). The most important objectives was use of non-renewable energy and emission of carbon dioxide for one group and weight reduction for the other group. For these respondents use of non-renewable resources were the least important objective.

Validation

Siunce the alternatives in the conjoint task were hypothetical, there was a risk that they did not perfectly represent the respondents' preferences. Two validation questions were included that covered activities known to affect the environment and environmental effects. Use of non-renewable energy, use of non-renewable resources and emission of carbon dioxide (the greenhouse effect) were all present in the validation questions. Weight reduction of products was not included in the validation questions, since this would have revealed the aim of the last two questions to participants and may have led them to answer strategically.

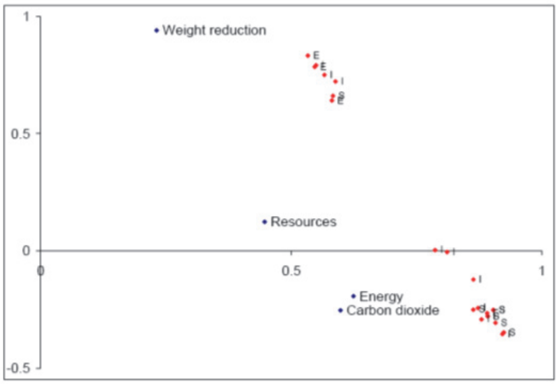


Fig. 10. PLS2 regression loadings showing respondents with research and development included in their occupation. Respondents are illustrated by letters; 85% of the Y-variance was explained on the first two latent variables

The main results are listed below. For each stakeholder group, the three environmental issues/effects marked by most stakeholder group members are presented (percentage in paranthesis)

- Steelworks: Greenhouse effect (83%), air pollution (56%), polluted drinking water (56%)

- Steel industry: Greenhouse effect (78%), polluted drinking water (75%), polluted air (59%)
- Steel clients: Greenhouse effect (76%), air pollution (71%), polluted drinking water (62%)
- Public: Greenhouse effect (80%), air pollution (78%), polluted drinking water (62%)
- Environmental experts: Greenhouse effect (78%), use of natural resources (57%), polluted drinking water (52%)
- Political decision makers (MPs): Greenhouse effect (100%), air pollution (69%), use of energy (58%)
- Average: Greenhouse effect (82%), air pollution (66%) and polluted drinking water (60%)

Fig. 11. shows the percentage of respondents in each stakeholder group that chose the environmental issues/effects correlated to the environmental objectives of the steel eco-cycle.

The figure can be compared to Fig. 6. Although the scales are different, the same pattern of response is seen.

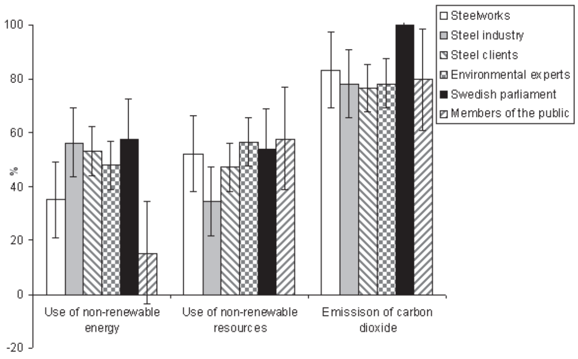


Fig. 11. Respondents in percent with standard errors that marked use of non-renewable energy, use of non-renewable resources and emission of carbon dioxide (green house effect) as one out of three most important when asked to chose freely from a set of environmental issues and environmental effect.

When the percentage of respondents that selected use of non-renewable resources, use of non-renewable energy and emission of carbon dioxide was compared to the average results from the conjoint task, we found a similarity in responses (see Fig. 12.).

It is therefore possible to presume that the attributes chosen for the conjoint task were relevant (or else the respondents would not have selected them when they were asked to choose freely) and that the responses are fairly consistent between the conjoint task and the validation questions.

4.4 Study IV: Barriers to the introduction of new materials - the case of high strength steels

4.4.1 Design of Study IV

Focus group discussions were held with three different groups, one in Kalmar and two in Stockholm [48]. The focus groups discussions concerned a container, e.g. the material used for producing a container and the use of containers in general. The group in Kalmar consisted of persons working with containers in different ways (transportation and logistics) while the two sessions in Stockholm held participants from the steel industry, researchers, representatives from the industry, consultants etc. In all, 24 persons participated in the focus group discussions.

An interview manual was used for the discussion. The discussions lasted for about one hour and in the end of the discussion a summary was made.

The discussions were transcribed and the discussion subjects were categorised. Finnally main barriers were identified from the material.

The results of the focus group discussions were validated through an open-end question in the conjoint questionnaire described below. The question was: ”Do you have any comments on the use of high strength steel from your perspective?” and 57 comments were given (43% of the respondents) [48]

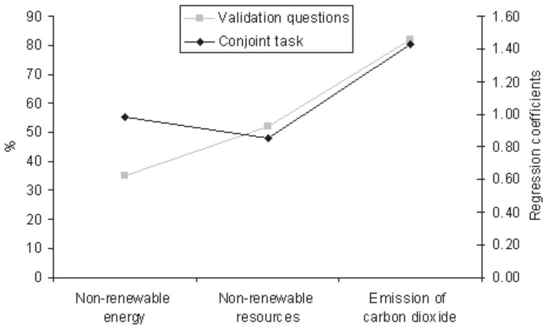


Fig. 12. Average results from the conjoint task (regression coefficients with confidence intervals) compared to validation questions (% of respondents).

4.4.2 Study IV: Results and discussion

The barriers were categorised as technical barriers, cost barriers, knowledge barriers, scrap management barriers and finally suitability barriers.

Technical barriers include factors such as **availability** of high strength steel and the **design process** where large changes in a design are much more rare than small changes. Also internal **standards and norms** may limit the use of new materials.

Cost barriers hold barriers such as **prices** for the steel and the **economy** of the buyers.

Knowledge barriers include **knowledge** of different steel grades. **Communication** was classified as a knowledge barrier as it is often unknown who will be the end user of the steel product. Therefore it could be difficult to inform the end user of the environmental benefits of different materials. **Herding** is a phenomena that is connected to knowledge and communication. Herding is when people tend to chose what others have chosen before them.

Scrap management barriers include **scrap management** where AHSS may become a barrier in an effective scrap management as it sometimes holds alloys that are not suitable for all steel grades. Also buyers of steel are sometimes unaware of what steel grade they use and therefore the **recyclability** is sometimes an obstacle.

Suitability barriers include the fact that there has to be a **need** for the high strength steel grades in order for someone to make a change in the design and shift towards a more expensive material. Also, advanced high strength steel is not **suitable** for all applications.

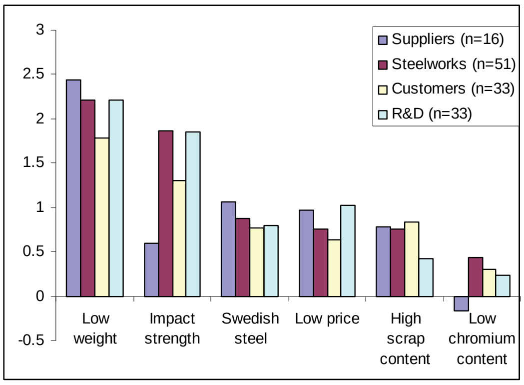


Fig. 14. Average main effects for each of the stakeholder groups

4.5 Study V: Preferences for new materials; high strength steel

A conjoint analysis was performed, based on factors derived from the focus group discussions in Study IV, where the respondents assessed six different steel characteristics [48].

4.5.1 Design of Study V

A conjoint analysis was performed in order to estimate the preferences for a set of steel characterristics. From the focus group discussions six factors were identified; impact strength, weight, chromium content, Swedish steel, scrap content and price. Eight hypothetical steel containers ("ISO-containers") were constructed through a fractional factorial design (resolution III, generators: D=AB, E=AC and F=BC). The container was chosen because it is a well known passive product without any brand or status issues connected to it.

A pilot test was performed including participants from the Linnaeus University. From the pilot test, a web-based questionnaire was designed and responses were collected.

The questionnaire included three parts, first the conjoint study where the respondents were asked to rank eight different containers. The second part consisted of a set of questions on background information (gender, age, educational level, training etc.). Finally the questionnaire included knowledge questions on steel and on the environment. The last part of the questionnaire aimed to compare the respondents' knowledge-level with their preferences, the results from the last part of the questionnaire are presented under "Study VI". The questionnaire was distributed through different networks, and in all 134 complete answers were collected.

4.5.2 Study V: Results and discussion

In all 134 responses were collected, all responses had been correctly filled out. Twenty-two percent of the respondents were women and the average respondent was 52 years old with a standard deviation of one year. Three participants did not report their age. Thirty-seven percent of the respondents had never worked in the steel industry while

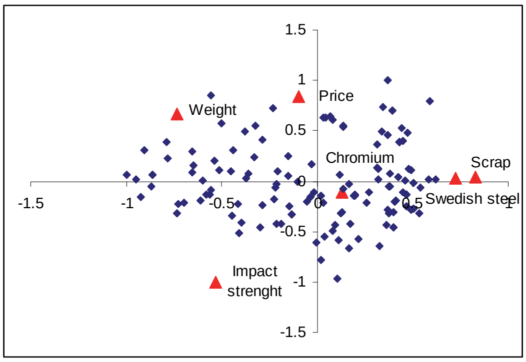


Fig. 15. PCA regression loadings, linking individual preferences to the design variables in the fourth study, 46% of the Y-variance was explained on the first two latent variables.

37% were working at a steel works at the time of the questionnaire and 25% had done so earlier.

The educational level showed that 83% of the respondents had a university degree, 16% had finished secondary school and 1% had finished primary school.

Generally, weight reduction of products was given the highest priority, followed by impact strength. Content of toxic substances, in this case chromium, was given the lowest priority. There was a significant difference in preferences for impact strength (ANOVA, p=0.006) among the original groups of respondents. Steelworks, customers and R&D were similar in their preferences while suppliers deviated from the three others by having lower preferences for impact strength and higher preferences for weight (see Fig. 14). Steel customers valued reduced weight and impact strength proportionally lower than the other groups. It is also interesting to note that steel customers value steel deriving from Sweden lower than the other groups and also that they stated that they were less sensitive to price.

4.6 Study VI: Influence of knowledge

Knowledge is one of the factors that may contribute to change peoples' behaviour. Knowledge is the cognitive part of the attitude. An attitude also includes an affective part (in this study "worry", see study VIII) and a behavioural part (not studied here). In order to study how knowledge affected the preferences of steel industry stakeholders, and in turn the way people intend to behave, two separate studies on knowledge were made, Study VI and Study VII. [49]

4.6.1 Design of Study VI

Study VI was carried out parallel to study IV. In the same questionnaire as the conjoint study in study IV, a set of knowledge questions were asked. Five questions on steel and five questions on the environment were included in the study. For each respondent the percentage of correct answers was estimated and this percentage was then compared to the preferences through a t-test. The method is also described in a conjoint study on base station siting made by Dohle, Keller and Siegrist [50].

4.6.2 Study VI: Results and discussion

When the percentage level of "knowledge", i.e. the correct answers to the knowledge questions, was compared to the respondents' preferences, no significant correlations could be found. Knowledge alone did not influence preferences in a study designed like the one reported here.

Each respondent was also asked to state what level of education and training he or she had. The training was divided in education (primary school, secondary school and university) and shorter training sessions (voluntary training outside of work, shorter training sessions provided by the employer concerning steel or the environment). The only significant correlation between training and preferences found was that university studies affected preferences even if specific knowledge did not. One possible reason may have been that university education influenced a person's way of sorting the statements and their way of analysing information. This could be the reason why a university degree affect preferences. No significant difference could be found that was based on major discipline, a degree in material science had the same effect as a degree in environmental science or economics.

4.7 Study VII: The effect of training

The connections between knowledge and other factors within the term attitude were also studied with a different approach. In connection to a one day seminar on environmental issues, participants were asked to respond to a questionnaire on their environmental attitudes before and after the seminar. [51]

4.7.1 Design of Study VII

A questionnaire was developed and distributed to the expected participants of a one-day environmental seminar, held at SSAB Borlänge for 31 persons in spring 2011. The questionnaire held questions on attitudes towards a set of environmental issues. The participants were not told that they would receive another questionnaire after the seminar. Approximately three weeks after the training session, another questionnaire was sent out. Ten questions were identical to the first questionnaire, but there were also new questions asked, indicating attitudes towards environmental issues.

The data was analysed with a t-test.

4.7.2 Study VII: Results and discussion

From the 31 participants in the seminar, twenty one persons responded to the first questionnaire and 14 to the second. From the 14 answers to the second questionnaires it was only possible to connect 10 of the responses to the respondents to the first questionnaire.

There was no significant difference in the responses to the ten questions before and after the seminar, except for a question that concerned natural disasters. The tragic events in Fukushima Japan took place in between the two questionnaires and the significant change in the results before and after the seminar can most likely be explained by this fact.

4.8 Study VIII: Knowledge and worry

A Q-methodology interview where five sorting tasks gave information on how environmental decision makers within the steel industry viewed important sustainability factors. Worry for environmental problems was studied as well as the sense of responsibility for environmental issues. [52]

4.8.1 Design of Study VIII

An interview concerning perceived risks of environmental problems, factors influencing environmental decisions, responsibility and worry was designed with five Q-sort questions and seventeen follow-up questions. The interview was pre-tested on a mechanical workshop/foundry. The results of the pilot study are not included in the results.

The Q-sort questions were designed to assess how connected the daily work with environmental issues were to worry and risk perception, what driving forces influence strategic environmental decisions and finally how the respondents perceived responsibility for environmental improvements.

Ten different facilities were visited of which seven were production facilities and three were facilities without production, see Table 4. In all 38 personal interviews were made.

Each interview was recorded and the comments and explanations made by the respondents were analysed qualitatively. Furthermore, the sorting tasks were analysed through a PCA.

4.8.2 Study VIII: Results and discussion

The respondents were given five sorting tasks. Three of those had the same set of response alternatives to different questions. The aim was to find out if there was any difference in how the participants perceived the environmental risk, the effort made by the company and finally the worry each respondent felt for the factors presented. The result is illustrated in Fig. 16. Use of non-renewable energy was perceived as a risk for the operation and also something that the individuals worried about, but this was in general not something that the companies worked actively with. The same result was given for the use of non-renewable resources.

Table 4. Steel companies that took part of the study.

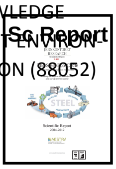
	City	Number of inter-views	Facility with production
Höganäs	Höganäs	5	Yes
Ovako	Smedje-backen	3	Yes
Outokumpu	Avesta	2	Yes
Outokumpu	Eskilstuna	3	No
Ruukki	Malmö	2	No
Rukki	Danderd	2	No
Sandvik (Kanthal)	Hallsta-hammar	5	Yes
Sandvik	Sandviken	4	Yes
SSAB	Luleå	5	Yes
SSAB	Borlänge	5	Yes
SSAB	Oxelösund	2	Yes

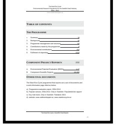
Emission of dust, metals, noise and recyclability were factors where the respondents perceived that their operations worked actively with while their own sense was that the risk was proportionally lower as was their personal worry. The only factor where personal worry was saliently stronger than perceived risk and active work from the operation, was worry for emission of dioxins. These results correspond well to the results found in Study II, where emission of dioxin received the highest attention out of five environmental factors.

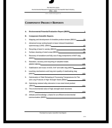
In Fig. 17 three groups of decision makers are visible. In the lower right corner of the plot, global sustainability issues are presented (green house effect, non-renewable resources and energy). In the upper right corner the local environmental problems are found, connected to local residents (noise, dust, transports, waste) and on the left hand side the emissions (emission of solvents, sulphur, nitrogen, metals, dioxins etc) are shown.

When the respondents were asked to sort driving forces in environmental decision making, personal worry were placed at the lower end of the sorting scale. Legislation, environmental policy, inspectors from authorities and local residents were considered top driving forces while suppliers, local politicians and environmental organisations (NGO's) were placed at the bottom of the sorting scale.

The decision makers were split in two groups depending on their views on responsibility for en-







vironmental improvements (see Fig 19.). On the left hand side, decision makers who feel that the res ponsibility is allocated the steel industry could be found, and on the right hand side decision makers that put the responsibility for environmental improvements outside of the steel industry are found.

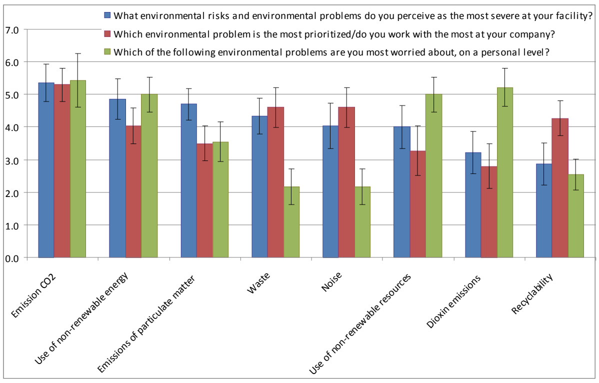


Fig. 16. Average responses on three questions on risks/work/worry with 95% confidence interval.

4.9 Study IX: Public risk perception of the steel industry

Study IX was made as a mirror to Study VIII, targeting the general public. [53]

4.9.1 Design of Study IX

In February 2012, a postal questionnaire was sent to 1000 randomly selected persons equally distributed in four municipalities in Sweden. In two municipalities, Luleå and Smedjebackan, a steelwork was located, and in two municipalities, Kalmar and Tingsryd, there was no connection to the steel industry. Kalmar and Tingsryd was chosen because they correspond well to Luleå and Smedjebacken in population size, area and density of population.

4.9.2 Study IX: Results and discussion

In all 428 responses were collected, 92 from the municipality of Kalmar, 114 responses from Luleå, 113 from Tingsryd and finally 109 from the municipality of Smedjebacken.

The respondents were asked to mark how well they perceived their own knowledge on the steel industry. Respondents from Luleå and Smedjebacken gave higher points than Kalmar and Tingsryd, indicating that the choice of municipalities had been correct. It could also be seen that respondents that had worked at a steel works themselves or hadclose family or friends working at a steel work gave them selves higher points than the average.

When the respondents were asked if they felt they had an interest in the steel industry, there was a difference, although not significant.

The respondents were asked to mark if they were satisfied with the information on environmental issues and risks that came from the steel industry. The average result was 2.4 on a 5 point scale indicating that in general the public was not satisfied. When the respondents were asked if they felt they could make their voices heard and contribute to environmental improvements for the steel industry the average response was 2.1.

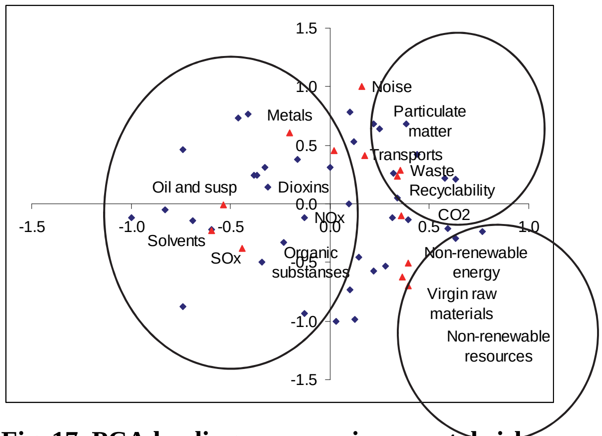


Fig. 17. PCA loadings over environmental risks. 43% of the X-variance was explained on the first two latent variables.

There was no significant difference between steel municipalities and non-steel municipalities.

The respondents were asked to rank nine environmental issues by their personal worry. On a falling scale the results were:

- Noise
- Use of non-renewable energy
- Waste
- Eutrophication
- Acidification
- Polluted land areas
- Dust
- Climate change
- Toxic substances

Finally, the respondents were asked to rank who they held responsible for environmental improvements within the steel industry. In Fig. 20 the results from Study IX is plotted (line) compared to the same question put to decision makers within the steel industry in Study VIII (bars).

5. DISCUSSION (comprehensive)

5.1 Comprehensive results

The nine studies presented in this subproject (88052) could improve knowledge in what preferences different stakeholders hold towards environmental issues. As in all stakeholder management activities, one of the first and most important steps is to identify the standpoint, or the preferences, of each stakeholder group before suggesting strategies for affecting people's preferences. In order to do so, traditional one-factor-at-a-time methods may not be sufficient, instead it was found necessary to use where the stakeholders were asked to evaluate their opinions in situations that mimic the day-to-day life where decisions and choices are made based on several factors at a time. Conjoint analysis and Q-methodology offer such methods. The results show that the methods can be highly valuable in identifying and analysing stakeholder preferences inside and outside the industry.

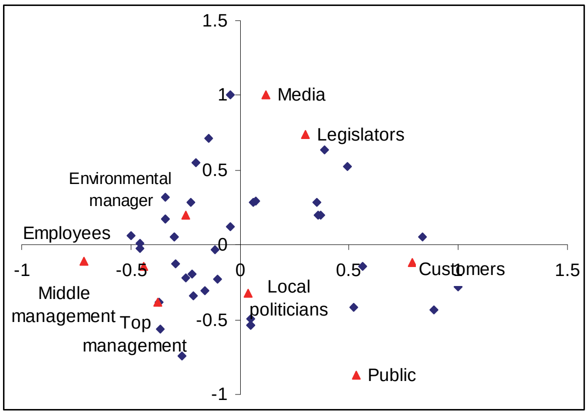


Fig. 19. PCA loadings showing who is perceived as responsible for environmental improvements within the Swedish steel industry. 53% of the X-variance was explained on the first two latent variables.

In order to compete with low cost countries, the Swedish steel industry have developed a product portfolio that holds more advanced steel grades. In Study III and V, weight reduction of products were studied from two different angles. In Study III weight reduction of products was included as one of the environmental objectives from the Steel Eco-Cycle research project. It was found that stakeholders both within and outside of the steel industry did not recognise the environmental benefits of weight reduction. In Study V weight reduction was set as one of the main areas of interest. When the selection of respondents held participants that worked closer to the steel industry, the level of understanding was higher. Still, the lack of understanding of weight reduction of products is an area where more effort needs to be made.

Another environmental issue that has been covered by two studies, is the emissions of dioxins. In Study II this factor was given the highest priority from a group of five factors. This finding was further examined in Study VIII where personal worry for toxic substances was examined. Results from Study II and Study VIII indicate that toxic substances is a cause or personal worry and when compared to other environmental factors personal worry may steer how the respondents respond and act. When compared, dioxins are perceived as more dangerous than chromium. The results from Study VIII indicate that personal worry is not a major driving force for environmental decisions, these are instead based on legislative requirements and requirements from top management.

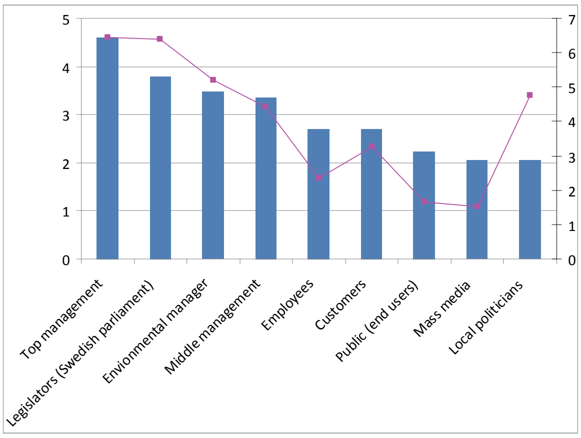


Fig. 20. View on responsibility for environmental improvements. Steel decision makers (n=38, bars) compared to the public (n=322, line). (Which of the following groups do you hold responsible for environmental improvements within the steel industry?)

5.2 Stakeholder acceptance of questionnaire: the paradox problem

The conjoint questionnaire is formulated using a full factorial experimental design or a fractional factorial design where all parameters are represented with fixed high and low values. This is necessary to get a statistically correct evaluation. However, if the factors (parameters) are not carefully chosen so that they are uncorrelated, the experimental design can results in combinations that respondents may see as paradoxes if they are compared to practical experience. This can result in decreased acceptance and decreased engagement in the effort when answering the questionnaire.

In order to avoid such irrelevant alternatives there are some important precautions to be taken:

- Carefully identify relevant factors to be included in the study and if possible avoid factors that are correlated

- In some cases paradox (irrelevant) alternatives cannot be fully avoided due to the characterristics of the factors and the demand of a statistically correct evaluation. It is possible to exclude the irrelevant alternatives, but to the cost of an increased number of alternatives, which in turn may cause fatigue effects.
- It is important to communicate and inform the respondents on how the study is designed: the background idea, why the questions have to be formulated as they are etc. As shown in Study II and Study III a thorough and personal introduction to the task lead to a high number of correctly filled out conjoint tasks.

5.3 The role of media and changes in attitudes over time

Media plays an important role in how people perceive environmental issues. Between Study II and III, the IPCC report on climate change [54] was published and the preferences for climate change among the respondents, changed from low to very high. When the results from studies made late in this project are analysed, the perceptions of climate change again start to decrease in importance (Study VIII and IX).

Another example of media attention changing preferences and environmental worries are the events in Fukoshima, in Japan 2011. In study VII one questionnaire was distributed before and one questionnaire after these events. The results showed a significant difference in worry among the respondents before and after the natural disaster.

5.4 Cross research and interaction between branches and methods

The output from the first half of the Steel Eco-Cycle research project gave inspiration to include a conjoint study in a process integration project that was carried out on a pulp and paper mill in northern Sweden. The project was carried out by Luleå Technical University in cooperation with Linnaeus University, Linköping University, Chalmers and Swerea MEFOS, and financed by the Swedish Energy Agency (Energimyndigheten) and the paper mill [55-57]. The scope was to study a possible extension with a bio refinery producing car fuel. The project included process integration using the reMIND tool, a macroeconomic study using a tool reCOM to investigate market and price mechanisms as well as a as a conjoint study to investigate stakeholder attitudes to the bio refinery. The conjoint study was designed using the experience from the studies in the Steel Eco-Cycle program. An additional scope was to study to use the conjoint result as input for the other tools. Preliminarily it was possible to use the tools to select starting parameters and cases for each other, whereas the direct use of the numerical output is a little more complicated. One possibility could be to combine conjoint analysis with economic theory and use it to derive Willingness To Pay (WTP), which can be used in the reCOM model. A conclusion was that such an extended conjoint in combination with the economic price model could be of interest for future studies.

6. CONCLUSIONS

6.1 Study I: Literature review

The literature review reveals that conjoint analysis as a method for evaluating environmental values is a relatively new and unknown method. Less than 100 studies were found although the number is steadily increasing. It is a promising method that allows for evaluation of several factors at a time and a method where the results are presented numerically and therefore are easy to interpret. This makes the method especially suitable for creating results that can serve as a basis for strategic decisions.

6.2 Study II: Initial screening of environmental factors

The first conclusion from this study is that the method works well. Conjoint analysis combined with multivariate data analysis (MLR, PLSR and cluster analysis) has proven successful in identifying stakeholder groups, as well as in assessing the composition of these groups and their respective preferences. The fact that the method may be used in identifying stakeholder groups confirms that the method may also be used to deliver information that is essential for strategic environmental decisions.

When environmental preferences of stakeholders are the subject of a study, the results shown here indicate that it is not sufficient to study the original groups solely, it is possible to find a new set of groups if the respondents are grouped by their preferences. Cluster analysis has proven to be a useful tool for this task.

Study II was performed in 2005, one year before report on climate change from IPCC [54]. It is worth noticing that emission of carbon dioxide in this study was perceived as the least interesting environmental factor from the five factors that were presented to the respondents. As shown in later studies, interest for emission of carbon dioxide increase drastically after 2006 when climate change was discussed extensively in media.

Emission of toxic substances, represented by dioxins, affect most respondents. The results indicated that personal worry direct the choices and decisions made by the respondents when the conjoint task is presented in a general manner.

6.3 Study III: Environmental objectives of the Steel Eco-Cycle

A clear result in Study III showed that as many as 62% of the respondents showed little or no interest in weight reduction of products. Reduced emission of carbon dioxide was the objective that received the most attention. The results showed that there was no difference in preference for weight reduction of products when the participants from production management and top management was studied as a group. This indicates that it is not clear that weight reduction of products is understood as an important environmental objective of the steel industry.

As in Study II the original groups were not the most advantageous way of clustering the respondents. In this study it was possible to show that preferences were more linked to occupation than original stakeholder group (steel works, steel industry, steel clients, environmental experts, members of public and Swedish parliament).

Study III was performed after the report on climate change by IPCC [54], and compared to study II, emission of carbon dioxide was given the highest priority. This is a good example of how media attention affects peoples preferences.

6.4 Study IV: Barriers to the introduction of new materials

Several barriers could be identified through the three focus group discussions; technical barriers (availability, the design process and standards and norms), cost barriers (price, economy), knowledge barriers (knowledge, communication, herding), scrap management barriers (scrap management, recyclability) and suitability barriers (need, suitable steel)

6.5 Study V: Preferences for new materials; high strength steel

From the six factors impact strength, weight, chromium content, Swedish steel, scrap content and price, weight reduction received the highest attention in Study V. Impact strength was the second highest preferred factor. There was a significant difference between the original groups on impact strength and the most likely explanation was that stakeholder groups outside of the steel industry were not as familiar with impact strength as stakeholder groups within the steel industry.

There is a difference in this study compared to study III is that emission of carbon dioxide is not included as a factor here. If it had been, the results would most likely had looked different.

As in study II a toxic substance, chromium, was included as a factor to see how the respondents perceived the risk of toxic substances in relation to the other steel features. In this study, chromium received much lower interest than dioxins did in study II.

6.6 Study VI: Influence of knowledge on preferences

Knowledge is a very important factor in order to change behaviour should towards a more sustainable behaviour. Knowledge is an important part of an attitude, and in order to change attitudes and in its prolongation the behaviour, knowledge on the environmental effects and the effects of ones own actions is necessary. However, knowledge level alone does not solely affect preferences, as shown in Study VI.

From Study VI (and study II, III and V) the results show that university education is correlated to preferences while shorter training sessions are not.

6.7 Study VII: The effect of training

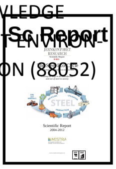
Preferences (attitudes) includes knowledge, social norms (expectations from others), personal norms (individual demands), habits and control (if people believe they can influence or not). In order to influence peoples' behaviour in practice all of these need to be affected. When the effect of attitudes from a one day seminar on sustainability issues was studied, no effect could be seen. The proper conclusion to draw is not that shorter training sessions are useless, instead the proper conclusion is that shorter training sessions cannot alone change the behaviour of people.

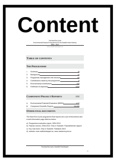
Continuous training is a good way of ensuring that the knowledge is kept at a high level. Continuous training may also affect the social norm if it is clear that the initiative comes from the top management. However, training alone will not affect preferences.

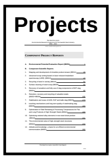
6.8 Study VIII: Knowledge and worry

There were two main conclusions from Study VIII. The first was that personal worry was given a low priority as a driving force on environmental decisions, while own knowledge was given a high priority. Compared to what issues the steel works worked actively with and what issues the decision makers felt personal worry for, it seems as personal worry is not a major driving force in strategic environmental decision.

The second important conclusion to draw was that there were three groups of decision makers who had different views on environmental topics. One group focused on local environmental problems such as noise, dust and waste, one group focused on emissions of metals, solvents, dioxins, nitrogen, sulphur







etc. and one group that focused on global environmental issues such as climate change, non-renewable energy and resources. Depending on what group of the decision maker belongs to there is a risk that the decision maker focuses on their own subjects of interest instead of the sustainability issues that are decided by top management, for example in the environmental or sustainability policy.

6.9 Study IX: Public risk perception of the steel industry

There was an over all agreement on what environmental factors that were found important by the general public (Study IX) and the ones that were prioritized by the decision makers of the steel industry (Study VIII). One factor that they disagreed on was emission of carbon dioxide/ climate change where the decision makers prioritised this factor as the most important factor (on average) while the general public left it as the second least important factor (on average).

The general public and steel decision makers also agreed on who should be held responsible for environmental improvements. The only difference were local politicians where the general public held them proportionally much more responsible than the steel decision makers did.

6.10 Comprehensive conclusions

The Steel Eco-Cycle research project has adopted a new and unique approach to study environmental attitudes. To the best of our knowledge, methods that study peoples attitudes and the affects attitudes have on the decisions made, have never before been applied on an entire branch of industry. Conjoint analysis as a method has been widely used in marketing and health care, but rarely based on individual results. Q-methodology has never been applied on an industry such as the steel industry.

In this project it has been shown that different groups consider environmental issues in different ways. This information is essential if the steel industry wants to market a new material or plan information campaigns or training sessions. First because the methods presented and developed in this project can be used to identify knowledge gaps and attitudes among target groups [58]. Second because the results from such studies can be used to tailor training sessions and information campaigns towards the targeted groups.

In most of the previous studies where conjoint analysis has been used to assess environmental issues, a specific product or situation has been evaluated [24]. This project show that the method also works with larger and more complex issues that apply to an entire manufacturing industry.

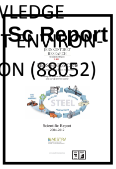
A potential pit fall is the choice of factors (attributes). The factors must be relevant and understood by the respondent. In Study II and V, the responses have been mostly correct in the sense that the conjoint task have been correctly evaluated. In Study III however, the conjoint task was misunderstood by several respondents, probably because the questionnaire in Study III was sent to the general public who were not familiar with the issues. Also, in Study II many of the respondents were visited in person and given a verbal explanation which helped them understand the task. In Study V all respondents were given a written explanation but here the questionnaire was only distributed to persons that were familiar with the steel industry.

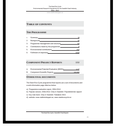
The factors must be uncorrelated to each other. Since the method is based on a factorial design, all factors and levels will be varied in the alternatives and if the factors are correlated, unrealistic alternatives will occur.

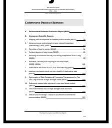
In this project the conjoint analysis method has been validated in several ways. In Study III there was an extra section to the questionnaire where the respondents were asked to freely choose the three most important environmental issues from a list. In the list the factors from the conjoint study was included. If the factors from the conjoint study had been wrongly selected and had not been representtative, they would not have be chosen. However, there was a good correlation between the results from the conjoint task and the validation task. The results were also validated through the discussions with the participants that followed Study II and Study III. In study V an open-end question followed the conjoint task so that the respondents could leave comments. There was no indication that the respondents were unsecure or hesitant to the factors in the conjoint task. Therefore a conclusion can be drawn that the method works well as long as representative factors are chosen.

The traditional method of analysing results from a conjoint analysis is by regression. The results will then show how different groups of people prioritise environmental issues. In this study, the combination of multivariate data analysis methods such as PLSR and cluster analysis was shown to add valuable information from the data analysis. Using PLSR, the results can be presented on an individual basis – which was rarely done in previous conjoint studies - and by using cluster analysis segments among the respondents could be identified.

Advanced high strength steels are relatively unknown to people outside the steel industry, and it can be discussed if the environmental benefits are well known even within the steel industry.







Respondents that were experienced with steel more often valued weight reduction as an important environmental quality, often even higher than other useful qualities such as low price and content of toxic substances.

The fact that AHSS is relatively unknown outside of the steel industry creates barriers that need to be overcome in order to establish the material on the market. There are technical barriers (availability, the design process and standards and norms), cost barriers (price, economy), knowledge barriers (knowledge, communication, herding), scrap management barriers (scrap management, recyclability) and suitability barriers (need, suitable steel). For each of these barriers an action plan can be established to further increase the possibility for potential clients to use this material.

Things that are unknown are often considered to be worrying. Toxic substances, such as dioxin, has proven to trigger worry among the respondents, but when toxic substances were presented in a wider concept (as in Study VIII) they are ranked proportionally lower. In communicating with stakeholders the steel industry has a delicate task in communicating about toxic substances in such a way that the public will not be allowed to focus solely on what scares them but instead get information that can help them assess the risk information with a natural science approach.

Worry is only one building block of attitudes [2], in Study VIII it was shown that worry alone does not guide environmental decisions. Worry can be provided against with knowledge through training. Knowledge is another important building block of attitudes. However, knowledge alone can not change behaviors [1], other factors such as how a person perceives the social pressure, the personal control over the situation and ethics of a certain behavior will affect the behavior.

In Study VIII three different views on environmental issues could be seen, one that focused on local environmental problems such as noise, dust and waste, one that focused on emissions of metals, solvents, dioxins, nitrogen, sulphur etc. and one that focused on global environmental issues such as climate change, non-renewable energy and resources. It would be interesting to make a future study to verify that the same viewpoints are represented among other groups. This division into three different viewpoints can become an important calibration issue. If an environmental policy with focus on global issues is set by the top management, it is important that the decisions made further down in the organisation complies with the policy.

Another interesting conclusion is that there are two ways to look at who is responsible for environmental improvements. In Study VIII two groups could be found, one group that put the responsibility for environmental improvement within the steel industry (employees, middle management, environmental manager and top management) and one group that put the responsibility outside of the industry (public, customers, local politicians, legislators and media). This is also an important issue to deal with. If a decision maker feels that it is the outside world that has the responsibility to make sure that the environmental work is improved, it may be difficult to gain support for the day to day work with environmental issues.

Future research should be directed to develop communication methods where discussions are stimulated between stakeholder groups. One possible way to go is to arrange focus group discussion after a conjoint or Q-sort study where representatives from different stakeholder groups can discuss their different views on the issue. The discussion can be analysed and the results can be used to develop the information flow between the organisation and its stakeholders. There is also a need to study the effect of tailored information campaigns towards the public and other stakeholders to see what environmental information is the most effective and trustworthy. The environmental benefits from AHSS need to be made better known and illustrated. An extended study on barriers for the introduction of new materials would benefit materials with lower environmental load. Finally there is a need to further study the three groups of decision makers that were found in study IX to see if and how environmental decisions are affected by what viewpoint the decision maker has.

7. Future utilisation

Conjoint analysis combined with multivariate methods such as multiple linear regression, partial least squares regression, principal component analysis and cluster analysis has proven to be a successful way of eliciting preferences of steel stakeholder groups. Q-methodology is a similar method that also works well in eliciting preferences of key individuals. Q-methodology cannot be used on a large group of people, as conjoint analysis can, but the extra value added by personal interviews compensate for that shortness.

The steel industry can use these methods to address attitudes influencing environmental and risk decisions. By identifying situations where attitudes and norms have more influence than knowledge, it will be possible to anticipate where training and information needs to be improved. At the same time the performers of the studies will be able to identify where lack of internal and external communication obstruct an efficient environmental and risk decision-making process.

A handbook has been written that explains the methods of conjoint analysis, Q-methodology and focus group discussions. [58]

8. Acknowledgements

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9. DISSEMINATION AND PUBLICATIONS WITHIN THE CURRENT PROJECT

Refereed publications

Alriksson, S and Öberg, T (2008). *Conjoint analysis – A useful tool for assessing preferences for environmental issues*. Environmental Science & Pollution Research, 15: 119.

Alriksson, S and Öberg, T (2008). *Conjoint analysis for environmental valuation – An overview of methods and applications*. Environmental Science & Pollution Research, 15: 237-250.

Alriksson, S and Grip CE (2012). *Steel industry environmental objectives: stakeholder preference assessment using conjoint analysis.* Steelmaking & Ironmaking. Accepted 12-10-05. DOI: 10.1179/1743281212Y.0000000087

Manuscripts

Alriksson, S and Henningsson M. *Perceived barriers for substituting materials and preferences for high strength steel characteristics*. Submitted.

Alriksson, S and Sahlin, U. *Analysing rank based conjoint analysis with multivariate methods*.

Filipsson, M and Alriksson, S. *The role of individuals' worries, knowledge and sense of responsibility in environmental decision making within the steel industry*

Academic dissertations

Alriksson S (2008). *Conjoint analysis as a tool for communication and corporate environmental decision-making.* Licentiate Thesis. University of Kalmar. ISBN 978-91-85993-08-6.

Conference publications, refereed

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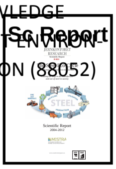

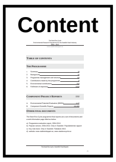

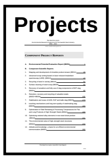

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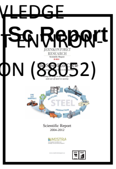

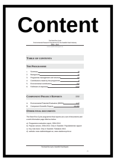

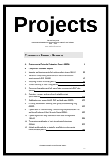

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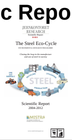

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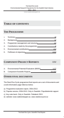

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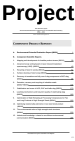

COMPONENT PROJECT REPORTS

THE SWEDISH FOUNDATION FOR STRATEGIC ENVIRONMENTAL RESEARCH- MISTRA

The foundation supports research of strategic importance for a good living environment and sustainable development. It seeks to promote the development of strong research environments of the highest international class and of importance for Sweden's future competitiveness. Opportunities to achieve industrial applications are to be pursued to the full.

THE SWEDISH STEEL PRODUCERS' ASSOCIATION

Since its foundation back in 1747, Jernkontoret has been owned jointly by the Swedish steel companies. Jernkontoret represents Sweden's steel industry on issues that relate to trade policy, research and education, standardisation, energy and the environment as well as taxes and levies. Jernkontoret also manages the joint Nordic research in the steel industry. In addition, Jernkontoret draws up statistical information relating to the industry and carries on research into the history of mining and metallurgy.

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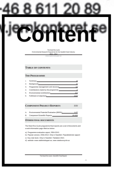

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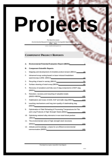


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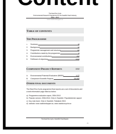
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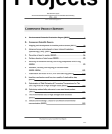
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