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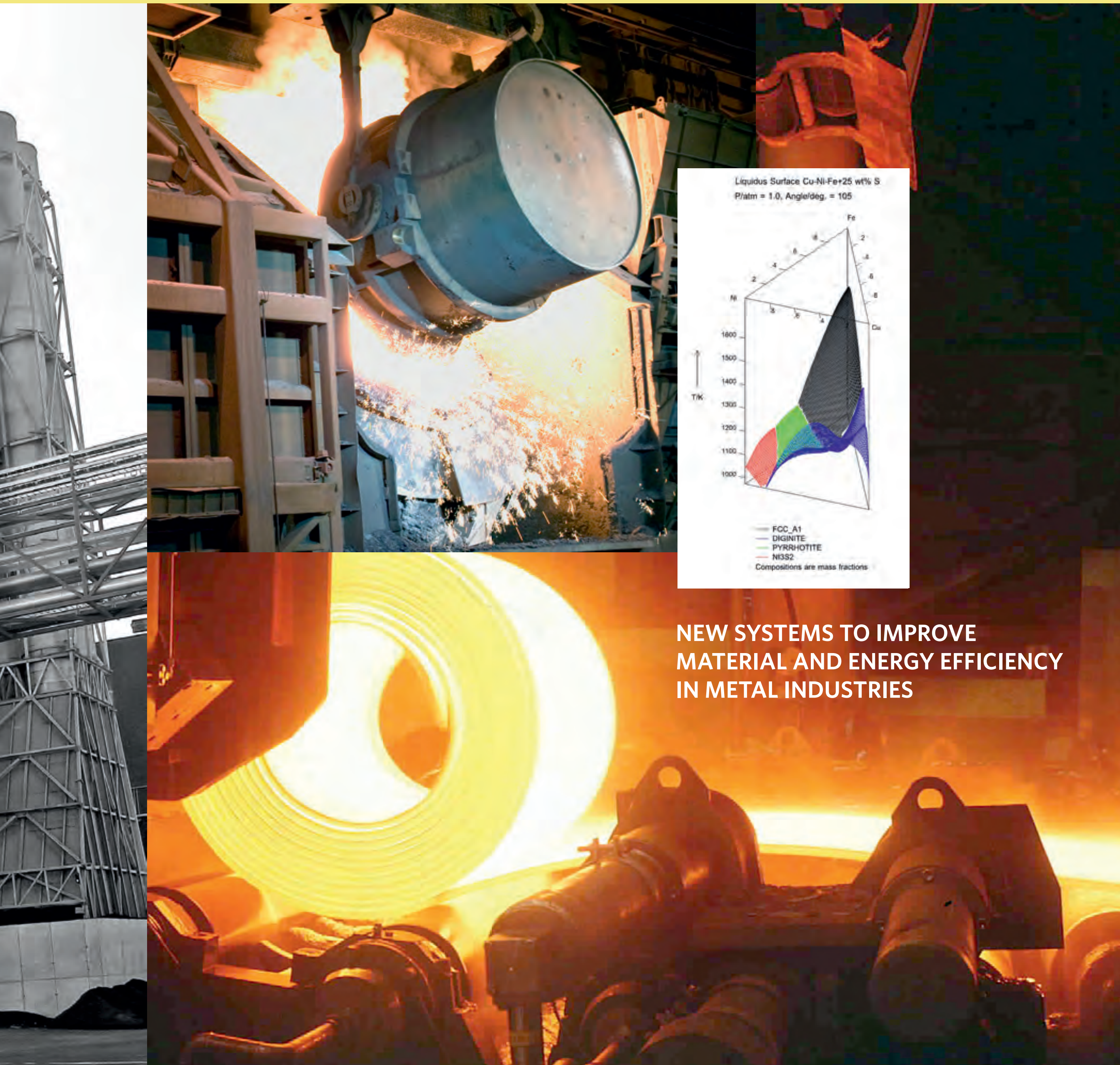
FINAL REPORT 5/2014

FIMECC
PUBLICATIONS
SERIES NO. 5

Energy and Lifecycle-efficient Metal Processes – ELEMET

2009-2014



NEW SYSTEMS TO IMPROVE MATERIAL AND ENERGY EFFICIENCY IN METAL INDUSTRIES

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Energy and Lifecycle-efficient Metal Processes

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CONTENTS

The Power of Joint Forces!

The uncovered things are often found to be fascinating but, because of their nature, impossible to reach. In industry, such problems are not only fascinating, but the sources of greatest business value and long-term competitive advantage. Though traditional methods are shown to be ineffective, these are problems worth cracking!.

Conquerors throughout history have chosen new ways and been ready to take risks, demonstrating a capacity to overcome unexpected challenges by partnering with others who share the same commitment and can offer something new towards the ultimate objective. This kind of effective, results-oriented co-creation lies at the core of FIMECC, and is part of our programme DNA, of which Energy- and Lifecycle-efficient Metal Processes (ELEMET) is a brilliant example.

FIMECC ELEMET is truly a programme in which the most challenging industrial programmes are solved through scientific method, and the novel results of research institutions cultivated into business opportunities for companies. All this has been achieved through dense co-operation involving industry, research institutions, Tekes and FIMECC. I wager these results would have been impossible without the joint forces of such a committed consortium.

FIMECC has promoted co-creations since its foundation, and its performance as an R&D&I platform has been recognised at both national and international level. FIMECC ELEMET's excellent results are once more a concrete testimony of the performance of FIMECC co-creation drives based on public-private partnership. Naturally, we in FIMECC are extremely proud of our R&D&I platform performance. We are proudest of all, however, of our consortium partners, who have challenged themselves, committed themselves to the shared targets, overcome the challenges together and made these results possible.

Together we are stronger than any of us alone!

Kalle Kantola
CTO
FIMECC Ltd

Substantial Improvements in Material and Energy Efficiency in Metal Industry

In 2009, metal industry companies in Finland, together with universities and research institutes, built a consortium with the purpose of realising a research programme that would seek to improve the material and energy efficiency of metal production plants. The consortium joined together all the significant players in Finnish metals production and metallurgical research to participate in the programme on Energy- and Lifecycle-efficient Metal Processes (ELEMET).

The FIMECC ELEMET programme focused on processes relevant to the Finnish metals industry, in both steel and base-metal production. The key research areas were metallurgy and thermodynamics, the results being applied to production processes through modelling and simulation.

It was stated at launch of the programme that the research was to find broad and substantial improvements in energy and material efficiency, and thereby improve the economic competitiveness of companies. To achieve the defined goals it was mandatory to build a critical mass of knowledge, with model platforms and databases that could be used in further development work and in practical application at the mills.

Now, after five years of programme implementation, we can see that the given targets have been reached. The co-operation among consortium partners has been highly successful, while fruitful collaboration with a number of selected international companies and universities has also produced important results.

The programme comprised six work packages with 11 research projects, and had a total budget of EUR 37 million.

The work packages and projects are described briefly here:

Radically Improved Material and Energy Efficiency in Ferrous Industry

Projects:
- Material-efficient Blast Furnace (MEBF)
- Efficient Electric Arc Metallurgy (Effarc)

The goal was to introduce new research and modelling methods in understanding the major unit processes for carbon and stainless steels, and use them to reduce energy consumption and greenhouse gas emissions. Special focus was laid on blast furnace and electric arc metallurgy processes.

New Opportunities in Base Metals Industry

Projects:
- Improved Sulphide Smelting (ISS)
- Ion Exchange Technologies for Hydrometallurgy (IX-Hydro)
- Process Alternatives for Low-grade Ores (Lowgrade)
- Water-saving Mineral Concentration Technologies (Procedy)

The focus was on efficiency in the entire production chain, from ore to final metal. Broad international co-operation revealed new experimental data on thermodynamic properties of metal-sulphide substances for advanced modelling of copper and nickel smelting. Various hydrometallurgical unit processes, especially leaching and ion-exchange, were studied and modelled to find new options for using low-grade ores and meeting environmental and product-quality challenges. Study of the physico-chemical particle-bubble processes, coupled with advanced fluid dynamics modelling, aimed to gain water savings in flotation processes.

Towards Zero-waste Plant

Project:
- New Metallurgical Solutions for Ferrous Dust Treatment (Metdust)

New concepts for zero waste metals production were studied, with the focus on new metallurgical solutions for the treatment and use of dusts.

Lifecycle Management and Environmental Footprint

Project:
- Metrics of Environmental Efficiency for Metal Production Technologies (Metric)

A sustainability index for process industry was developed, comprising three different aspects of sustainability: environmental, economic and social. The index facilitates transparent knowledge exchange between industry and society.

Innovative Simulation Tools for Metallurgical Processes

Projects:
- Modelling of Microstructure and Properties of Materials from Casting to Rolling Process (Mocastro)
- Development of Hot and Cold Rolling Processes by Novel Process Modelling Methods (Nopromo)

New advanced modelling platforms were developed that allow coupling of chemical reactions and physical transport phenomena in metallurgical processes, and predicting the evolution of structure and material properties from liquid to solid state and during subsequent processing until rolling and thermo-mechanical processing.

Development of Production Technology for Future Ultra-clean Steel

Project: • Advanced Melt Metallurgy (AMMe)

Dominating physical and chemical phenomena were studied, and new process-oriented models generated for the secondary metallurgical processes, as well as for ladle treatments, casting area and solidification stages. The research has given a solid scientific basis for the development of advanced ultra-clean steel grades.

It has been a great privilege for me to serve the consortium during this time, and in living up to the enthusiasm and devotion of the researchers as world-class scientific knowledge was created and top-level research was carried out in the projects. 400 reports were published during the programme, of which 120 were peer-reviewed international journal papers and 130 conference papers. The programme also witnessed the accomplishment of 19 doctoral or licentiate theses and 50 master's degree theses.

I would like to extend my warmest thanks to Kari Keskinen from Tekes for his excellent guidance and support at every stage of programme implementation. I would also like to express my fullest gratitude to the members of the Programme Management Committee for keeping the programme on a constant and steady course, to the entire staff at FIMECC for making every effort in their power to support me and the programme, and finally to my programme manager colleagues for their most inspiring meetings and the help they gave whenever it was needed.

Jarmo Söderman
Programme Manager
FIMECC ELEMET Programme

PROGRAMME FACTS SHEET

Programme name:

Energy- and Lifecycle-efficient Metal Processes

Contact persons:

Kalle Kantola, FIMECC Oy, CTO, Chairman of ELEMET Programme Management Committee (PMC)

Jarmo Söderman, FIMECC Oy, ELEMET Programme Manager

Participants:

Industrial partners

Ruukki Metals Oy
Outokumpu Stainless Oy, Outokumpu Oyj
Outotec (Finland) Oy, Outotec Oyj
Boliden Harjavalta Oy
Boliden Kokkola Oy
Norilsk Nickel Harjavalta Oy
Finex Oy
Freeport Cobalt Oy
Talvivaara Mining Company

Universities and research institutes

Aalto University
University of Oulu
Lappeenranta University of Technology
VTT Technical Research Centre of Finland
Åbo Akademi University
Tampere University of Technology
University of Helsinki
Geological Survey of Finland (GTK)

International collaborators

University of New South Wales, Laboratory for Simulation and Modelling of Particulate Systems/Australia
Osaka University, Division of Materials and Manufacturing Science/Japan
Max-lab, Lund/Sweden
University Stellenbosch/RSA

National Physical Laboratory/UK

Max Planck Institute Magdeburg/Germany

TU Kosice, Department of Non-ferrous Metallurgy/Slovakia

Centre of Excellence on Soft Computation in Material Science and Engineering, Bengal Engineering & Science University (BESUS)/India

GTT Technologies/Germany

University of Illinois, Urbana-Champaign/USA

University of Rio Grande do Sol/Brasil

Labein-Tecnalia/Spain

Programme duration: 2009–2014

Programme value (EUR): 37 million

Main targets and motivation

The FIMECC ELEMET research programme addressed the research objective of intelligent production, manufacturing and metal industry process development, with a view to low energy consumption and minimised environmental impact. The means to achieve the given objectives were modelling and simulation, starting from the underlying physical phenomena in the metallurgical processes. These were successfully applied for adoption of new enhanced production technologies and discovery of new process routes.

The FIMECC ELEMET programme gathered a powerful and top-level group of researchers for world-class metallurgical research and for industrial applied technology development. The programme was a combination of strategic platform research, using the leading academic resources, and the industrial applied research of the participating companies.

Results

The 11 research projects of the FIMECC ELEMET programme achieved substantial improvements in material and energy efficiency in the metals industry. The results are presented in the following pages, in the Project Highlights and Facts for each project.

Publications and theses

400 publications and reports, of which 120 peer-reviewed international journal papers and 130 conference papers.

Number of Doctoral and Licentiate Theses: 19

Number of Master’s Theses: 50

STAKEHOLDERS' PERSPECTIVES

Industrial Review

Competition on the global market is getting tighter all the time. It is vital for metals industry to develop and make use of the very latest technologies and innovations. Finland is a small country with limited resources, making it essential to find ways of ensuring that all available knowledge and know-how is taken up.

While universities and research institutes possess expertise, the contact to field may sometimes be weak. By the same token, though small enterprises may have good ideas and even prototypes, difficulty in creating the necessary connection to heavy industry may deprive innovations of the necessary practical tests and final use. Industry is under continuous pressure to improve processes in order to produce sustainable products with better yield, better energy efficiency, better properties and better quality. Some resources are available, but these are needed for the core business.

The FIMECC ELEMET programme has offered long-term public funding enabling the gathering together of skilled resources for specific development projects – projects that involved universities, research institutes, small enterprises and metals industry in a concerted drive towards energy efficiency, improved use of raw materials, increased yield and reduction of waste.

The result of this combined effort with industrial and academic partners has seen the advance of new production technologies and new competences for the benefit of Finnish metals and engineering industry. Simulation tools have demonstrated their value for the development of new special steel grades in steel companies, while several new products were developed and launched during the funding period. The enhanced properties of these products improve end product energy and material efficiency, and extend useful life, thereby promoting sustainability.

Co-operation with over 20 partners has facilitated industrial-scale tests, among others using laser-illuminating and video techniques, stereoscopic technique, carbon dioxide snow, and laser for line dimension measurements. Services such as analysis, material preparation and calculations for chemical reactions were used in support of the trials in progress.

Partners have expanded their knowledge of solidification phenomena and effected an improvement in the inner quality of slabs, with a greater understanding of hydrogen removal and the effect of hydrogen content on the crack susceptibility of heavy plates. Innovations in tools for rapid process and product development have produced advanced steels and ferroalloys with secondary metallurgy units, and simulate processing variables in case-specific studies.

At the Tornio Works there has been a significant increase in strategically important ferritic grades. Development of the processing of these grades has been bolstered by the long funding period.

Reduction of material and energy consumption has been realised by using the new recycling methods and technologies in Finnish industrial companies such as Ruukki Metals Raahe Steelworks. Economic and environmental sustainability has been improved through success in decreasing CO_2 emissions.

Paavo Hooli
Outokumpu Stainless Oy

Risto Pietola
Ruukki Metals Oy

Erkki Pisilä
Ruukki Metals Oy

Research Institutes' Review

The FIMECC ELEMET programme for 2009–2014 was the first SHOK effort by the Finnish metallurgical industry to generate a common R&D platform, its purpose being to facilitate fundamental and applied research in process and equipment development according to the needs and requirements of industry. The topics covered were 'hard issues' in iron, steel and non-ferrous metal-making processes, as well as 'soft issues' dealing with metal-making sustainability and environmental impact. A wide range of Finnish and selected overseas universities and research institutes were involved in the programme development stages, offering their skills and resources for achieving the various goals described in the 2008 programme plan.

The unusually long-term (five-year) funding scheme allowed the participating university partners an excellent opportunity to focus their best scientific resources and intellectual skills on the clear, well-defined and industrially significant targets and milestones of the project plan. This enabled the successful execution of sub-tasks as solid PhD theses and scientific publications.

Action in the field of iron and steel metallurgy focused on key improvements in material and energy efficiency in unit processes throughout the process chain – from raw-material handling to the final steel product – and on the development of new production technologies for the future ultra-clean steels. In various pyrometallurgical unit processes in the area of non-ferrous metals, the focal point was essentially divided equally between aqueous processing and refining environments and phenomena at high temperatures, with clear emphasis on fundamental scientific research rather than short-term troubleshooting. The size and volume of the FIMECC ELEMET programme plan allowed the linking together of several research groups in Finnish universities and foreign institutes, either as partner or sub-contractor. This feature is relatively new in Tekes-funded programmes, and will create further possibilities in future R&D environments. Networking with foreign research groups, in particular, requires a long time span in view of the different funding principles in other countries.

The scientific impact of the FIMECC ELEMET programme is significant, also from the point of view of the universities. The current trend of accomplishing PhD theses as compendia – a collection of scientific papers published in journals and conferences – has extended the target duration of doctoral studies from three to four years. This new funding scheme has allowed PhD theses to be accomplished without the desperate need to compile short-term funding sources, such as foundations and industrial part-time projects. As a result, by the end of the programme a total of 17 PhD theses will have been completed or examined.

The large fraction of fundamental and applied research carried out in FIMECC ELEMET is, on the one hand, an excellent indication of the focus and understanding of the Finnish base metals industry concerning the importance of knowledge-based skills required for hard global competence. On the other, it serves as a clear demonstration of the strengths of networking: take away the close national and international relations, and the scientific outcome would have been far less than now appears in the Final Report and its list of publications. A total of 300 publications in international journals, conference proceedings and presentations amounts to a clear indication of scientific excellence. The examples of international co-operation on the scientific level also include a number of MSc and PhD theses finalised in foreign universities as a result of their scientific activities and educational outcome, and not only of foreign students graduating in Finnish universities.

An important impact of the FIMECC ELEMET programme has been its support for fundamental and academic research in the areas of metal making. Not only has this been crucial in several niche topics, such as reduction (oxide) metallurgy, hydrometallurgy, phase equilibria and thermodynamic simulations, but equally in other simulation and modelling techniques and methodologies. Close linking enabled the metallurgy research groups in Finnish universities to profile their activities and avoid overlapping, thus maximising their skills coverage at the national level.

Pekka Taskinen
Aalto University

Timo Fabritius
University of Oulu

WORK PACKAGE 1:
Radically Improved Material and Energy Efficiency in Ferrous Industry

The goal was to introduce new research and modelling methods in understanding the major unit processes for carbon and stainless steels, and use them to reduce energy consumption and greenhouse gas emissions. Study was made particularly of blast furnace and electric arc metallurgy processes.

PROJECTS:

- Material-efficient Blast Furnace (MEBF)
- Efficient Electric Arc Metallurgy (EffArc)

PROJECT NAME

WP 1 Radically Improved Material and Energy Efficiency in Ferrous Industry

MEBF

Material-efficient Blast Furnace

Material efficiency of the blast furnace processes was dramatically improved at Raahe as a result of the MEBF project: 35 shiploads of primary raw materials are saved annually

Material efficiency in blast-furnace-based iron-making is vital to the cost efficiency and sustainability of hot metal production. Cost-efficient hot metal production, on the other hand, is a precondition for profitable manufacturing of modern hot-rolled steel grades. In addition, increased efficiency in iron-making processes brings environmental benefits, such as decreased CO_2 emissions, decreased amount of solid wastes and lower primary fossil fuel consumption, leading to more sustainable steel production. .

The improvement in raw material efficiency can be achieved in the following ways:

1. Highly optimised operation of the blast furnace process,
2. Effective recycling of iron- and carbon-bearing materials and flux substituting materials,
3. Use of high-quality raw materials.

As the overall outcome of the MEBF project, the material efficiency in iron-making was dramatically improved, which can be seen in Figure 1.

The improvement in raw material efficiency was achieved through intensive joint research work covering the topics of:

- Development of residual material briquetting to substitute primary raw materials
- Physical and numerical modelling of raw material charging, layer formation and descending in the blast furnace process
- Numerical modelling of mass and heat transfer requirements for effective burning of auxiliary reducing agents in the blast furnace raceway, and
- Research of burden material behaviour in simulated blast furnace conditions.

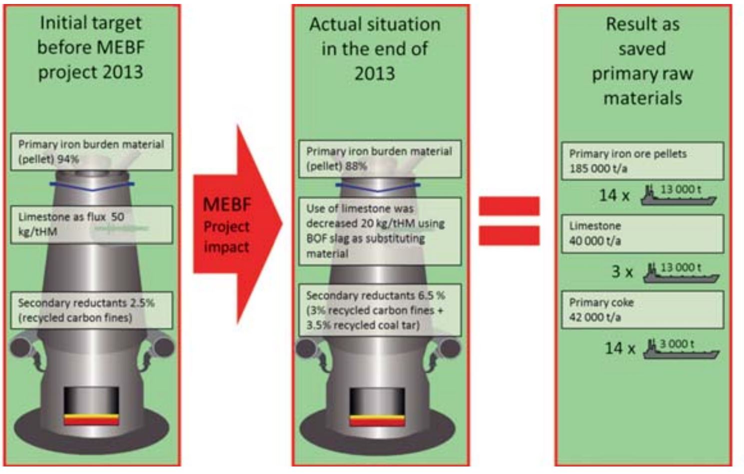

Figure 1. **The overall outcome of the Material-efficient Blast Furnace project as saved primary raw materials**

The key parameter in achieving the results was excellent communication and co-operation between various research parties and the industry. The research carried out in laboratory scale was scaled up step-by-step, leading to industrial trials and later to day-to-day practice in hot metal production. The results achieved in this project have been vital for the cost efficiency of iron-making, and therefore for the business profit of the Ruukki company. An overview of the blast-furnace-related research activities is shown in Figure 2.

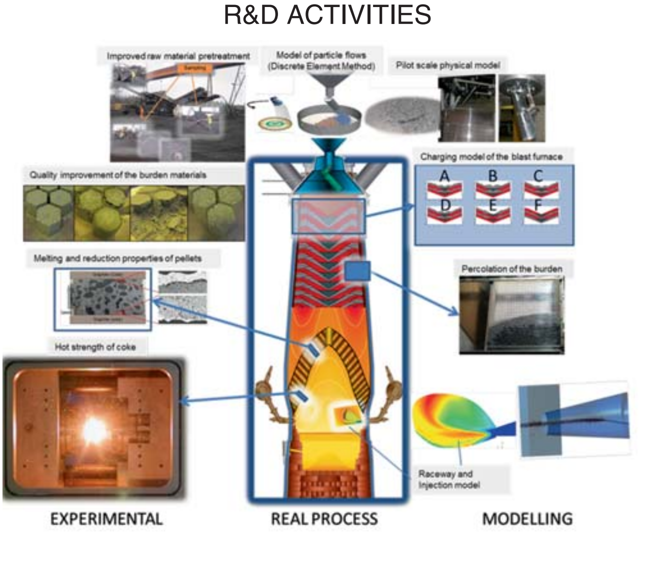

Figure 2. **An overview of the blast-furnace-related research activities**

PROJECT NAME

WP 1 Radically Improved Material and Energy Efficiency in Ferrous Industry

MEBF

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION
TIMO FABRITIUS UNIVERSITY OF OULU **JARMO LILJA** RUUKKI METALS OY	**UNIVERSITY OF OULU** • LABORATORY OF PROCESS METALLURGY • LABORATORY OF MASS AND HEAT TRANSFER **ÅBO AKADEMI UNIVERSITY** • LABORATORY OF THERMAL AND FLOW ENGINEERING **AALTO UNIVERSITY** • CLEANTECH GROUP **RUUKKI METALS OY** **OUTOTEC (FINLAND) OY**	**2009 – 2014** PROJECT VALUE (EUR) **3.561 MILLION**

Material-efficient Blast Furnace

Main targets & motivation

Steel is one of the most important construction materials in the world today. The major share (roughly 70%) of steel is produced from virgin raw materials with the integrated blast furnace (BF)–basic oxygen furnace (BOF) route. Raw-material efficiency plays a key role in the profitability and sustainability of steel-making.

The main goal of the MEBF project was substantial improvement in the material and energy efficiency of the blast furnace process in the Finnish metallurgical industry. This goal was to be achieved through both novel numerical modelling and experimental methods, and most importantly through co-operation and information exchange between various research parties and the industry.

The main goal of the project was divided into four sub-goals:

1. Development of a novel blast furnace briquetting recipe. The goal of the new briquette formula was to obtain savings in primary raw materials and to enable the use of various feed material sources, by-products of different industry branches.
2. Improved control of blast furnace burden charging by modelling and simulation. This goal was to be obtained with numerical modelling of the charging of raw materials, layer formation and descending of the charge in the blast furnace.

3. CFD (Computational Fluid Dynamics) modelling of the injection process of auxiliary fuels. The goal was to produce information on the optimal heat and mass transfer conditions in the raceway and tuyere area with the current rate of oil injection, and also to determine criteria for possible ultra-high injection levels in the future.
4. Research of raw material behaviour in blast furnace conditions. This section included a wide array of research including pellets (reducibility, swelling), briquettes (reducibility, swelling), auxiliary fuels (gasification, volatile matter composition) as well as blast furnace coke (strength, reactivity). It also included developing a new method to evaluate coke strength at lower blast furnace temperatures. The overall goal of this section was to optimise the blast furnace raw material palette from an efficiency standpoint.

In addition to blast furnace and iron-making research, goals were set on increasing knowledge of pelletising and sintering processes used for ferroalloy production. The main focus was on investigating the behaviour of sintered pellets in smelting furnace conditions, reduction and oxidation reactions. Another goal was to minimise the environmental effects: reducing emissions (NOx, carbon credit, etc.); improving gas cleaning processes and sintering of new raw materials and by-products.

Tests were set for oxide- and carbonate-type manganese ores to find out the optimal combination of raw material type and form (lumpy ore, sinter and pellet) for high-carbon ferromanganese (HCFeMn) production. An optimised sintering furnace control system was also to be developed with new on-line measurements for higher-level automation.

Results

The main result of the MEBF project was the development and successful implementation in industrial use of a novel blast furnace briquette recipe. Use of the new briquette formula led to significant savings in primary raw materials at Ruukki Raahe steel works. The raw-material savings are roughly equal to 35 shiploads annually, and have significantly improved the profitability of steelmaking at Ruukki.

A significant amount of new information was also obtained during the project on raw material properties and their behaviour in blast furnace conditions: briquettes (19 publications), coke (5 publications), pellets (5 publications) and auxiliary fuels (6 publications). A new method was developed for evaluating the hot strength of blast furnace coke, and statistically reliable results of the strength of various coke grades at operational temperatures was obtained for the first time.

A novel charging simulation tool was also introduced at the Ruukki works. The tool was developed to model blast furnace charging and layer formation. Fundamentally new insights were obtained regarding the behaviour of pellets during charging and burden descent in the blast furnace process through DEM (Discrete Element Method) modelling of layer descent in the blast furnace.

A CFD model was developed to simulate hydro-carbon injection at the tuyere level. This model was used to identify the limiting factors of auxiliary fuel injection and to optimise combustion in the blast furnace raceway and tuyere area. The model can be applied for alternative auxiliary fuel injection.

Experimental research work was conducted on pelletising and sintering of various manganese ore fines. Batch pelletising and sintering tests were performed for two different kinds of South African manganese ores. Solid state reduction mechanisms of manganese-bearing raw materials were investigated in laboratory and pilot scale in electric furnace conditions. This thermodynamic study showed that agglomerated manganese concentrate fines (both from pellet and sinter feed) need less external energy for electric smelting compared to lumpy ore.

This is due to the fact that pretreated material excludes volatiles that vaporise at lower temperatures.

Novel material and energy balance calculations were made for a steel belt sintering furnace using an HSC-SIM tool. HSC Chemistry is a software for process simulation, reactions equations, heat and material balances, equilibrium calculations, electrochemical cell equilibriums, Eh-pH Diagrams and Pourbaix diagram. HSC-SIM in turn is an extension of the HSC software, a module that supports process simulation with several process units and streams. This model is easier to use and has now replaced the old heavy Excel models in practice. The tool provides a large database behind the calculations and is also used as the basis for energy calculations.

Key publications

1. Mäkelä, M., Paananen, T., Heino, J., Kokkonen, T., Huttunen, S., Makkonen, H. & Dahl, O. (2012), Influence of fly ash and ground granulated blast furnace slag on the mechanical properties and reduction behavior of cold-agglomerated blast furnace briquettes, ISIJ International, Vol. 52, No. 6, pp.1101–1108.

2. Yu ,Y. (2013), Experimental and discrete element simulation studies of bell-less charging of blast furnace, Doctoral Theses, Åbo Akademi University, 2013. (Includes 6 publications).
3. Vuokila, A., Riihimäki, M. & Muurinen, E. (2014), CFD-modeling of heavy oil injection into blast furnace – Atomization and mixing in raceway-tuyere area, Steel Research International, 85, (4), 1–8.
4. Haapakangas, J., Uusitalo, J., Mattila, O., Kokkonen, T., Porter, D. & Fabritius, T. (2013), A method for evaluating coke hot strength, Steel Research International, Vol. 84, No. 1,pp. 65–71.
5. Kemppainen, A., Alatarvas, T., Iljana, M., Haapakangas, J., Mattila, O., Paananen, T. & Fabritius, T. (2014), The water-gas shift reaction in an olivine pellet layer in the upper part of blast furnace shaft, ISIJ International, Vol. 54, No. 4, pp. 801–809.

Number of publications:	68
Number of Doctoral Theses:	3
Number of Master's Theses:	12

Networks and international co-operation

International co-operation:

- As a co-operation effort between Åbo Akademi University and Tohoku University, Japan, Dr Rikio Soda of Tohoku University acted as a visiting researcher in Turku during the period June–August 2012.
- Tamoghna Mitra visited Tohoku University, Japan, during the period January–June 2013 for work on modelling of pellet reduction and DEM modelling.
- Yaowei Yu visited Clarkson University, New York, for research on numerical modelling of fluid and particulate flow during a period of 2.5 months (October–December 2012).
- Testing of blast furnace briquettes was performed in an experimental blast furnace in Sweden as co-operation between Ruukki, LKAB and MEFOS.
- Pilot-scale trials of sludge treatment were carried out at Luleå and Skelleftehamn by Ruukki and Swerea MEFOS.
- Ruukki and the University of Oulu participated in the Process Integration Forum (PRISMA) together with SSAB, LKAB and others regarding co-operation and knowledge exchange on process integration.

Presentations in international conferences:

- 5th International Conference on Discrete Elements Methods, August 25–26 2010, London, England.
- METEC InSteelCon 2011, 27th June– 1st July 2011, Düsseldorf, Germany.
- Scanmet IV – 4th International Conference on Process Development in Iron and Steelmaking, 10–13 June 2012, Luleå, Sweden.
- AISTech 2012 – The Iron and Steel Technology Conference and Exposition, 7–10 May 2012, Atlanta, GA, USA.
- Asia Steel International Conference 2012, 24–26 September 2012, Beijing, China.
- Particles 2013 – 3rd International Conference on Particle-Based Methods, 18–20 September 2013, Stuttgart, Germany.
- ISIJ-VDEh-Jernkontoret Joint Symposium – The 14th ISIJ-VDEh Seminar and The 8th Japan-Nordic Countries Joint Symposium on Science and Technology of Process Metallurgy, 15–17 April 2013, Osaka Japan.
- Carbon 2012 – Annual World Conference on Carbon, 17–22 June, 2012, Krakow, Poland
- KomPlasTech 2013 – The 20th Conference Computer Methods in Materials Technology, 13–16 January 2013, Zakopane, Poland.

Applications & impact

The improvement in the material efficiency of the blast furnace process was achieved by improving the industrial operating practices and methods at Ruukki. The project also had a significant impact on material efficiency from a scientific and knowledge standpoint. Here are some examples of the impact and applications:

- A novel briquetting formula was developed, which allowed the increase of briquette usage, higher recycling of carbon- and iron-bearing wastes, and partial replacement of the binder material with secondary raw materials.
- A tool simulating blast furnace charging was developed and used for evaluation and development of charging programmes at the Ruukki blast furnaces.
- A new analysis method for the study of coke hot strength was developed allowing coke to be tested at operational temperatures. The method is also applicable for evaluation of new materials such as biocoke.

- A model was developed for the injection process of residual oil into the blast furnace. Results of the modelling of oil injection applicable in optimisation of the combustion process and future use of higher injection rates of auxiliary fuels.
- The research work on manganese ores has expanded the markets for steel belt sintering technology to include manganese raw materials. (Traditionally manganese ore fines have been agglomerated and sintered to sinter product – not pelletised.)
- The simple and user-friendly HSC-SIM tool that was developed enables faster performance of material and energy balance calculations for the steel belt sintering process.

PROJECT NAME

WP 1 Radically Improved Material and Energy Efficiency in Ferrous Industry

EffArc

Better understanding of phenomena in electric arcs. More efficient production of ferroalloys.

Efficient Electric Arc Metallurgy

Results obtained from the EffArc project show a way to a new and effective process control method using optical emission. The new method enables the gaining of essential information on different phenomena taking place inside a furnace during the process at very high temperatures. Until now there has been no way of obtaining such data from furnaces. Process data is gathered only after smelting, and is therefore impossible to use for process control.

The new method with fluorescence spectrometer is suitable for on-line control of the smelting processes, for instance in electric arc furnaces (EAF) widely used in the production of stainless steel. The EAF melts and heats recycled steel scrap to the required process temperatures, Figure 1. Figure 2 shows the new on-line measurement system.

The optical emission method allows a direct view into the heart of an operational EAF in real time. Materials charged to electric arcs are excited and emit intense light and heat. The light emission profile carries element-specific wavelengths of light and provides information about the substances present in the furnace. Changes in emission profile are extremely valuable to the operators in improving process efficiency.

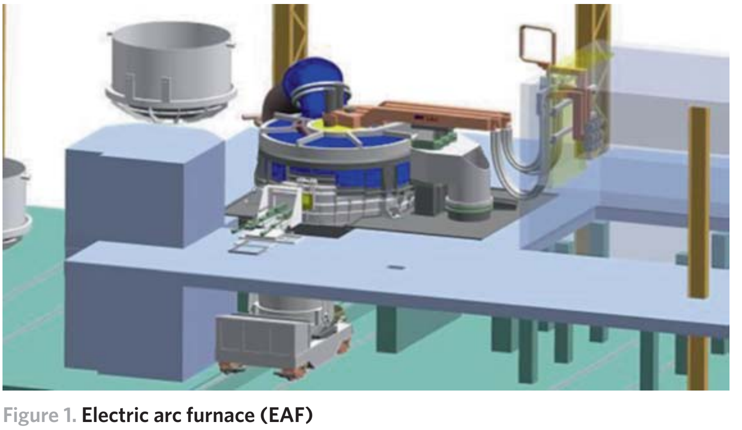

Figure 1. **Electric arc furnace (EAF)**

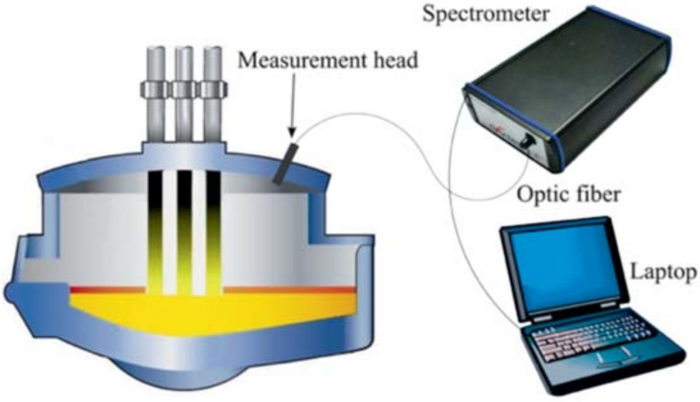

Figure 2. **Schematic picture of a fluorescence spectrometer in an EAF**

The fluorescence spectrometry method is also suitable for other furnace types, such as direct current (DC) furnaces. Successful pilot test runs were carried out at a new pilot-scale DC furnace (capacity 600 kVA) specifically developed and built at the Outotec Research Centre in Pori. These runs increased Outotec's competence (theoretical knowledge and operational skills) in DC furnace technology substantially, Figure 3.

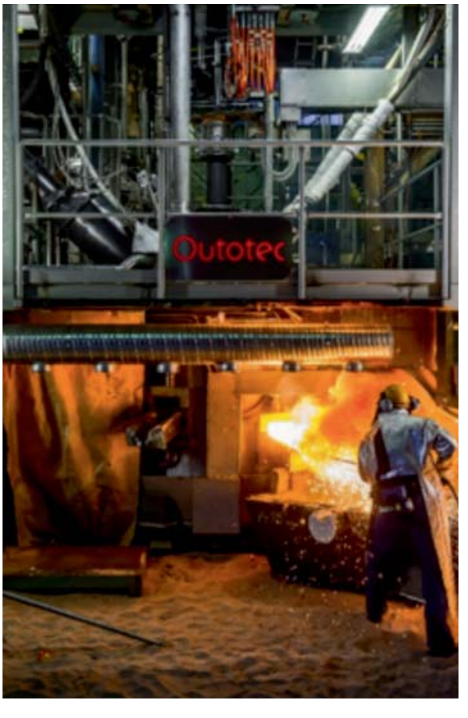

Figure 3.
Tapping from the DC pilot furnace at the Outotec Research Centre in Pori
(Copyright © Outotec)

Laboratory instrumentation was built to support the development of the optical emission method, Figure 4. Laboratory instruments provided valuable reference information for emission profiles of different compositions of steel and slag. This information can be used to improve furnace efficiency in industrial-scale EAFs, effectively in combination with other process monitoring, such as off-gas analyses.

The devices built enabled laboratory-scale experiments of fluctuating arc emission from an EAF. Knowledge of arc emission characteristics was obtained from different components of stainless steel and slag oxides. The emission was found to be highly element-specific and to contain information about the composition and state of the matter in the arc.

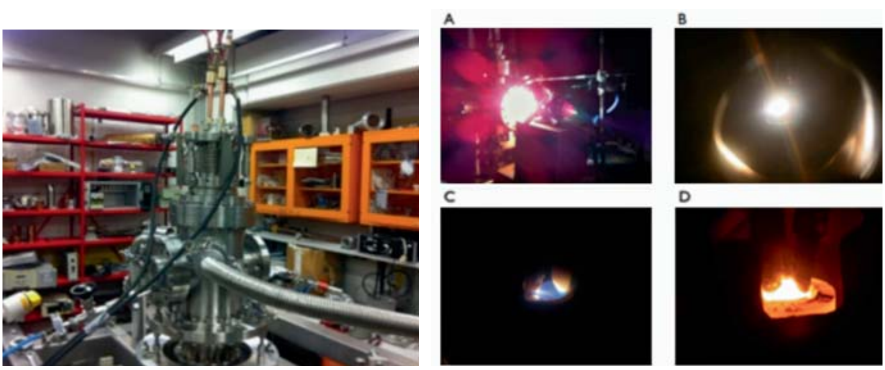

Figure 4. **A laboratory-scale EAF. Specific views: A. Light collection. B. Electric arc, C. Filtered image of the arc. D. The view after melting of a metal sample (University of Oulu).**

Laboratory-scale tests were carried out with chromite smelting, and good quality ferrochrome produced using different reductants: metallurgical coke, anthracite and coal. The reductants had closely similar behaviour when the same, fixed carbon amount was used, although metallurgical coke proved slightly better than the others. Tests were also performed successfully with ilmenite and titanomagnetite, and will be continued with other materials such as calcium carbide and steel mill dusts.

fimecc
FINAL REPORT 5/2014

PROJECT NAME

WP 1 Radically Improved Material and Energy Efficiency in Ferrous Industry

EffArc

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OUTOKUMPU STAINLESS OY
OUTOTEC (FINLAND) OY
RUUKKI METALS OY

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

4.141 MILLION

Efficient Electric Arc Metallurgy

Main targets & motivation

Gaining information on radiation characteristics emitted from an electric arc, and its effects on the stabilities of oxides in the furnace, is essential in order to improve understanding of the influence of electric heating on slag-metal reactions.

In metallurgy, electric arcs provide energy for the process. Heat and light can both contribute in breaking the bonds between the atoms in metallic compounds. The starting point for an understanding of the photochemical reactions is characterisation of the arc light. Further understanding of the processes in the area of extreme temperatures also helps to gain long-term improvement in process stability and an increase in energy efficiency.

Electric heating has a clear effect on the reaction kinetics between molten metal and slag in various metallurgical unit operations. Phenomena in metallurgical electric arc furnaces have been neglected mainly on account of their complexity, even though they use up a major portion of the electrical energy needed in the metallurgical industry. Smelting of ferrochrome, and scrap melting and ladle station in stainless and carbon steel making, are the relevant processes in Finland. Novel sampling methods and supporting models are necessary in order to improve energy and material efficiency. Naturally it was important to improve the monitoring and analysis techniques in electric furnaces, and to attempt to use the theoretical findings in the development of electric furnace applications.

A new online analysis method based on emission spectrum analysis was developed for the electric arc furnace (EAF).

Electric arcs are also present in the submerged arc furnace (SAF). The electrical behaviour of the charge has a great influence on how the furnace functions. It is important to gain more information not only on the arc itself but on the charge (coke, lumpy ore, pellets and fluxes) and its electrical behaviour. One possibility here is to make use of the drill sampling technique used in blast furnaces.

An important objective of the project was to expand knowledge of DC (direct current) furnace technology in ferroalloy process metallurgy. Use of a DC furnace carries certain benefits when compared to the more conventional AC (alternating current) furnace. The DC furnace is more flexible with raw materials with regard to their type and form, and with reducers. Concentrate fines of lower quality can be fed directly to a DC furnace without agglomeration, producing energy and cost savings. Even with smaller production capacities, the DC furnace is highly cost-efficient.

Results A fluorescence spectrometer was used in the laboratory to record spectra of several samples, with the purpose of investigating its capacity for developing the metallurgy process in real time. Positive results, supported by actual measurements at Outokumpu, made it possible to prepare an announcement of a new invention notice.

Two models of the electric arc furnace (EAF) process have been developed with ChemSheet software. In the first model the entire EAF process was regarded as one balance area (gas + slag + metal bath) or equilibrium stage. The second model modelled the gas phase, the formed slag layer on top of the metal bath and the metal bath itself as separate equilibrium stages. Validation showed that mass transfer between gas phase, slag layer and metal bath plays an important role, and thus revealed the inability of the first model to simulate slag and metal bath compositions accurately for all main elements. The second model gives better results which will allow for customised EAF simulation with adjusted process parameters.

The purpose of the SAF part of the project was to find out if the position and movement of the electrodes can be detected in the magnetic fields around the furnace. A one-month test period was held in May 2010, during which the magnetic fields around the SAF2 were measured. No correlation between the position of the electrodes and the magnetic field was found in the analysis of the data. This is mainly because of a strong variation in the magnetic flux density.

A material management model was created to optimise the melt shop processes, i.e. from materials to end product. The model tells how much, where and when the materials should be introduced, and gives a preliminary price for the material cost. Every heat can be evaluated as many times as needed, with differing material limitations, leading to optimal material processing. This optimisation system has been found extremely useful. Its effectiveness in controlling valuable material flows helps to make best possible use of the available materials for each individual heat, of which more than 10,000 are conducted every year.

Experiments were carried out on the behaviour of the submerged arc furnace (SAF) charge both at room temperature and in simulated SAF conditions. It was found that the reduction degree of pellets and graphitisation of coke affected electrical behaviour, while a different effect was produced by selective gasification of coke.

A DC furnace literature survey (S. Pisilä OU, 2010) was prepared to in order to obtain solid background information of the topic. A major outcome of the project was the pilot scale DC furnace (capacity 600 kVA) that Outotec developed and built at the Outotec Research Center facilities in Pori. This is an important milestone for the company. After the successful DC pilot test runs Outotec has good competence (theoretical knowledge and skills) in DC furnace technology. In addition, the company has broadened its product portfolio by introducing a new furnace product to the global ferroalloys market and thus significantly increased its competitiveness in the market.

Key publications

1. Liukkonen, M., Penttilä, K. & Koukkari, P. (2012), A Compilation of Slag Foaming Phenomenon Research - Theoretical Studies, Industrial Experiments and Modelling, VTT, Espoo.
2. Mäkinen, A., Niskanen, J. & Aksela, H. (2012), Relative photoionization cross section of Cr atoms in the valence region, PHYSICAL REVIEW A 85, 053411.
3. Mäkinen, A., Patanen,M., Aksela, S. & Aksela, H. (2012), Atom-solid 3p level binding energy shift of transition metals Cr, Mn, Fe, Co, and Ni, Journal of Electron Spectroscopy and Related Phenomena, Volume 185, Issue 12, pp. 573–577.
4. Rousu, A., Mattila, O. & Tanskanen, P. (2010), A laboratory investigation of influence of electric current on the burden reactions in a submerged arc furnace, Twelfth International Ferro Alloy Congress, INFACON XII, Helsinki.

5. Heikkilä, A., Pussinen, J., Mattila, O. & Fabritius T. (2014), About Electrical Properties of Chromite Pellets – Effect of Reduction Degree, Steel Research Int. 85 No. 9999.

Number of publications: 16
Number of Doctoral Theses: 1
Number of Master's Theses: 6
Number of patent applications/patents: 1

Networks and international co-operation

OU-MTG has been networking with Aachen RWTH to study phenomena occurring EAF.

OU- ESG has been working with MAX-lab research facility at University of Lund, Sweden.

Outotec has been developing DC furnace technology in co-operation with AFC (Alied Furnace Consultants Ltd), MDM Technical Africa (Pty) Ltd. and Pöyry.

Applications & impact

Basic research and device development of optical emission spectroscopy of laboratory scale electric arc furnace (EAF) has provided foundation for application of the method as well as provided new information about elemental components of stainless steel. EAF's new dynamic online-model for operators is under evaluation and but it is not yet ready. Present version is available for R&D personnel and for operators. Now model is ready to use in operation but education for operators is not ready and model needs more evaluation.

The novel method of fluorescence spectrometer is further researched in a spinoff-project. On-line measurement device for control of electric arc furnace has been developed and it is being implemented at Outokumpu Stainless, Tornio Works.

During the pilot period Wedge is being used in analyzing data of FeCr -plant for sophisticated process control. An experimental data based Electrode Management System (EMS) for electrode slipping procedure was developed.

An expert system type Advisor program was developed to support furnace operator in decision making (batch calculation).

A new lining monitoring system was built to optimize the lifetime of the smelting furnace refractory. Furnace temperature profile was simulated according to actual thermocouple readings. The system is available for use and it enables extending the refractory lifetime.

WORK PACKAGE 2:
New Opportunities in Base Metals Industry

Here focus was on efficiency in the whole production chain, from ore to final metal. New experimental data on thermodynamic properties of metal sulphide substances for advanced modelling of copper and nickel smelting were revealed in a broad international co-operation. Various hydrometallurgical unit processes, especially leaching and ion exchange, were studied and modelled to find new options for using low-grade ores and meeting environmental and product quality challenges. In order to gain water savings in flotation processes, study was made of the physico-chemical particle-bubble processes, coupled with advanced fluid dynamics modelling.

PROJECTS:

- Improved Sulphide Smelting
  (ISS)
- Ion Exchange Technologies for Hydrometallurgy
  (IX-Hydro)
- Process Alternatives for Low-grade Ores
  (Lowgrade)
- Water-saving Mineral Concentration Technologies
  (Procedy)

PROJECT NAME

WP 2 New Opportunities in Base Metals Industry

ISS

A world-class research group has been established at Aalto University, focused on experimental and computational thermodynamics in alloys, slag chemistry and sulphide systems

Improved Sulphide Smelting

The overall target of the project was to gain new experimental data concerning lead alloys and sulphide systems of industrial interest, and to use the data obtained, together with the literature values for modelling, in order to derive their thermodynamic properties for process simulation purposes at high temperatures.

Results Based on the experimental results, the thermodynamic descriptions of e.g. the Ni-Pb, Fe-Pb, Cu-Pb and Fe-Ni-Pb systems have been improved. By combining the observed results with the available literature information, phase diagrams of these systems have been modelled mathematically.

Phase relations in selected metal sulphide systems have been studied experimentally. By combining the observed results with the available literature information, phase diagrams of these systems have been modelled mathematically using the Calphad technique, see Figure 1.

Thermodynamic properties of several tellurides, selenides and sulphosalts have been studied by an improved experimental technique. Based on the experimental results, accurate thermodynamic functions were determined for about 40 selected equilibrium reactions. The thermodynamic data obtained were largely unknown prior to the ISS project.

The *ab initio* method has been successfully applied to alloys and intermetallics, and properties of binary alloys in the Cu-Ni-Pd system have been modelled.

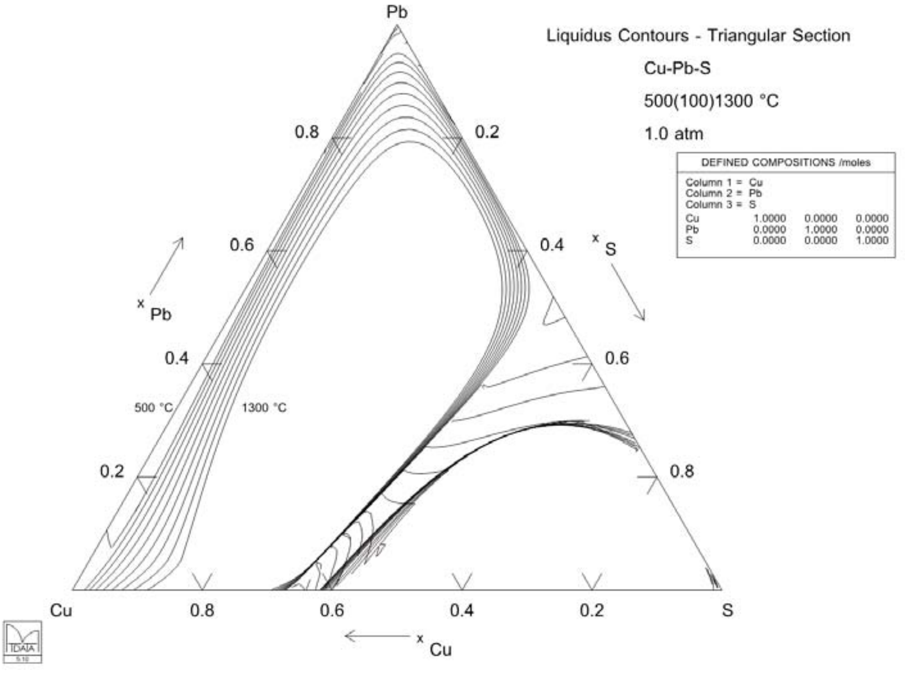

Figure 1. Cu-Pb-S ternary system with temperature contours from 500 to 1300 °C modelled in ISS

Figure 2. Tapping of sulphide matte from a Flash Smelting Furnace after primary smelting (Boliden Harjavalta Oy)

Applications & impact

Despite the fact that, by nature, all the sub-tasks conducted in ISS are fundamental research, the results obtained have a great potential for practical sulphide smelting applications. Some of these end uses and application areas are outlined below:

1) The results concerning properties of lead alloys could be applied in the development of lead-free solder alloys, Generation IV nuclear power plants, recycling of metals and impurity removal from steel scrap. The quantitative phase equilibrium information and thermodynamic assessments of the selected metal sulphide systems can be used to evaluate different pyrometallurgical steps of base metals production including, for example, formation of molten phases in the fluidised bed zinc roasting and metal value distributions in various copper smelting technologies, see Figure 2.

2) Available sulphide ores are showing poor grades and becoming increasingly complex. The thermodynamic properties of phases and phase assemblages that have been determined can therefore be used in various missions, such as modifications of operating flow sheets and outlining strategies in the processing of complex raw materials. The by-products in the base metals production process, for example anode slimes and flue dusts, are further processed for valuable metals and selenium recoveries. These also involve complex phase relations of unknown nature. The results obtained in this project can thus also be used in the optimisation of the extractive metallurgy of noble metals and platinum group metals. Furthermore, the results can be applied for improved manufacture of novel functional materials incorporating the chalcogenides studied.

3) The first-ever introduction to Finnish metallurgical industry and development of the ab initio method for thermodynamic properties of alloys and compounds will enable establishment of databases for alloys of interest. The databases will be established for fast data mining of properties of novel alloys without the need for costly and time-consuming experimental procedures. The results obtained – so far for the binary alloys of the Cu-Ni-Pd system – can be used to address the pyrometallurgical challenges in platinum-group metals extraction.

PROJECT NAME

WP 2 New Opportunities in Base Metals Industry

ISS

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BOLIDEN KOKKOLA OY
NORILSK NICKEL HARJAVALTA OY
OUTOTEC (FINLAND) OY

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

2.925 MILLION

Improved Sulphide Smelting

Main targets & motivation

Objectives:

1) To gain new experimental data concerning lead alloy and sulphide systems of interest, and to use the data together with the literature values in order to derive their thermodynamic properties.

2) To perform experimentation and improved methods in order to obtain accurate thermodynamic functions of selected equilibrium reactions. The thermodynamic properties of the selected phases were either poorly studied or not known before.

3) To develop methods for using ab initio techniques to model properties of alloys and compounds. This new method developed under the ISS project was the first of its kind to be introduced to the Finnish metallurgical industry.

Novelty:

New, improved experimental techniques (EMF and isothermal equilibration-quenching methods) and modelling tool applications (ab initio) have been developed. Several novel experimental data sets on phase equilibria and thermodynamics of alloys and compounds were obtained. For several lead-based and selected metal sulphide systems, the own results together with the critically selected literature data were used to optimize their thermodynamic properties using advanced thermochemical software.

Key publications

1. Vaajamo. I. (2013), Developing a Thermodynamic Database for Lead-Based Alloys. Department of Materials Science and Engineering. Aalto University Publication Series DOCTORAL DISSERTATIONS 173/2013.
2. Johto, H. (2014), Phase Equilibria of Selected Sulfide Impurity Systems at Elevated Temperatures. Aalto University Publication Series, DOCTORAL DISSERTATIONS 52/2014.
3. Tesfaye, F. (2014),Thermodynamic Stabilities of Complex Phases and Phase Assemblages in Ag-Te and Ag-(Bi,Cu)-S Systems. Aalto University Publication Series DOCTORAL DISSERTATIONS 100/2014.
4. Feng, D. (2014), Thermodynamic Investigation of Ag-Au-Se and Ag-Pd Systems. Aalto University Publication Series DOCTORAL DISSERTATIONS 2014.
5. Johto, H., Henao, H., Jak, E. & Taskinen, P. (2013) Experimental Study on the Phase Equilibria of the Fe-O-S System, Metall. Mater. Trans. B, 44B (6), pp. 1364–1370.

Number of publications: 76
Number of Doctoral (Licentiate) Theses: 5 (1)
Number of Master's Theses: 4.

Networks and international co-operation

Several scientific links and tangible joint research activities have been established during the ISS project. A close co-operation with the National Physical Laboratory (NPL, UK) in developing thermodynamic databases (MTDATA-Mtox), and joint seminars, thesis works and researcher exchange with Stellenbosch University (RSA) are the most remarkable examples. Overall, international co-operation initiated during the programme involved six different countries, as outlined below:

- National Physical Laboratory (UK): scientific co-operation, MTDATA-Mtox development and visits
- Stellenbosch University (RSA): scientific co-operation, joint theses, joint seminars and MSc and PhD exchange, incl. sabbatical leave for Professor Guven Akdogan at Aalto, July–December 2013
- University of Witwatersrand/Mintek (RSA): scientific co-operation, joint seminars and visits (a joint FiDiPro project developed together with Oulu University for 2014–2015)

- Central South University (PRC): student/scientists' exchange, guest lectures and joint seminars – two doctoral students/post-docs to be sent by CSU to Aalto University and its TDM group for in-depth studies in non-ferrous pyrometallurgy in 2014–2015
- University of Queensland (Australia): scientists' exchange, joint project (ARC) and visits – will continue in FIMECC's forthcoming SIMP programme 2014–2018
- University of Ghent (Belgium): scientific co-operation (e.g. EPMA, FIB), thesis projects and visits
- Hassan 1st University, Settat (Morocco): modelling and experimental studies in concentrated aqueous systems.

PROJECT NAME

WP 2 New Opportunities in Base Metals Industry

IX-Hydro

Ion Exchange Technology for Hydrometallurgy

A platform for designing and validating novel ion exchange processes was developed and applied in industrially relevant cases

The major outcome of the IX-Hydro project was a continuous ion exchange workstation suitable for early-stage experimental validation of process configurations and operation procedures. The unit was constructed at Lappeenranta University of Technology. Continuous operation was achieved by connecting up to 10 ion exchange columns in series or parallel through a computer-driven motor valve system.

Thanks to the versatile design of the unit, it was possible to investigate both counter-current and cross-current operations. The unit was also used to speed up process development by running multiple batch column experiments in parallel.

It was found that the recovery yield of fast-eluting target species, such as the major metal in concentrated metal sulphate purification and silver (Ag) in silver chloride (AgCl) solution purification, could be improved by introducing an additional eluent inlet, upstream from the feed position. Moreover, it was found that the resin preconditioning technique invented in IX-Hydro can be implemented both in continuous counter-current and cross-current operation. Results of the scientific cobalt sulphate ($CoSO_4$) purification work were used successfully in the project when developing a new product line. The line was taken into use during the project.

Several mathematical modelling and simulation tools were developed to facilitate the ion exchange (IX) process development and optimisation. Tools pertaining to the fundamental phenomena (ion exchange and adsorption phase equilibrium, mass transfer kinetics), as well as batch and continuous operation of fixed bed IX systems, were bundled together into a simulation toolbox. Development of the tools also produced a systematic approach to acquire basic data needed for simulation of unit operations, as well as better understanding and new applications of advanced numerical methods.

A novel preconditioning technique for ion exchange resins was developed to eliminate possible precipitation of metals in the column. The method is in principle applicable to any chelating ion exchange resin that would normally be neutralised after regeneration with mineral acids. In IX-Hydro, it was applied to removal of divalent impurity metals, such as lead (Pb), zinc (Zn), calcium (Ca), and magnesium (Mg) from AgCl. An amount of AgCl up to six times higher could be processed during a cycle when the new pretreatment method was applied. Moreover, it was shown experimentally that the method can also be implemented easily in a continuous ion exchange process by introducing an additional zone into the multicolumn ion exchange unit.

Development and application of inorganic ion exchange materials were also successfully accomplished in the project. Various manganese oxide materials (MOM) were prepared for the removal of TENORM (i.e., Radon (Ra) and its progeny) from synthetic ground waters. One of the materials was prepared from synthetic ore leaching solution containing a high amount of manganese (Mn). MOM materials showed a very high uptake of TENORM studied, removing at best 99.9 % of alpha and beta activity from the solution. In addition to much higher removal efficiency compared to conventional materials, MOM materials produce 10–100 times less waste volume.

Results with collaboration

The IX-Hydro project brought together expertise from industrial technology solutions providers and mining and metals processing industry, as well as researchers from academia. The project effected a substantial increase in the level of infrastructure and tools for the development of ion exchange processes for the Finnish industry. From the perspective of the industrial partners it was deemed crucial that the developed mathematical models are applied to selected industrially relevant applications.

Three types of purification applications were carried out in the project. The first investigated final purification of concentrated aqueous metal solutions by removing relatively small amounts of impurity metals. The second type of separation problem involved recovery and purification of aqueous precious metal solutions by eliminating divalent impurity metals. Synthetic polymeric ion exchange resins were employed for both these applications. The third type of purification applied inorganic ion exchange materials to remove technologically enhanced naturally occurring radionuclei from aqueous solutions.

Ion exchange in hydrometallurgy

Sustainable mining and metals processing requires environmentally benign process technology. Hydrometallurgical processes operate at low temperature and in aqueous solutions, the main benefits being low gas emissions and negligible dust formation, together with high selectivity and high recovery. On the other hand, these processes use chemicals, whose consumption and environmental impact must be minimised.

Ion exchange technology has great potential, especially in preparation of high purity metals and purification of process and mine waters. Because of the high selectivity and the use of solid separation materials, it can offer a safe and environmentally friendly alternative to other hydrometallurgical methods such as solvent extraction and precipitation. Although a wide range of ion exchange materials for metals separation are commercially available, a lack of simulation methodology and tools for the design and experimental validation of continuous ion-exchange processes means that the full potential of ion exchange technology has yet to be realised.

Figure 1. **Continuous ion exchange workstation at Lappeenranta University of Technology**

PROJECT NAME

WP 2 New Opportunities in Base Metals Industry

IX-Hydro

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION
TUOMO SAINIO LAPPEENRANTA UNIVERSITY OF TECHNOLOGY **ERKKI PAATERO** OUTOTEC OYJ	**OUTOTEC (FINLAND) OY** **NORILSK NICKEL HARJAVALTA OY** **TALVIVAARA OYJ** **FINEX OY** **FREEPORT COBALT OY** **LAPPEENRANTA UNIVERSITY OF TECHNOLOGY** **UNIVERSITY OF HELSINKI**	**2009 – 2014** PROJECT VALUE (EUR) **1.606 MILLION**

Ion Exchange Technology for Hydrometallurgy

Main targets & motivation

The IX-Hydro project was part of the work package "New opportunities in base metals industry". Ion exchange (IX) is generally recognised as a safe and environmentally acceptable method for the recovery and purification of metals in aqueous solutions. The technology has potential especially in preparation of high purity metals and in the purification of process and mine waters. However, the full potential of IX technology has yet to be realised because of a lack of simulation methodology and tools for the design and experimental validation of continuous ion-exchange processes. The purpose of the IX Hydro project is to fill in these gaps.

The motivation for the project was the participants' view that new ion exchange technologies can help the Finnish metallurgical industry and mining companies to solve environmental and product quality challenges. It was also seen that research results may open new business opportunities for engineering companies and manufacturing industry.

The main technical and scientific research problems addressed in IX-Hydro were 1) how continuous ion exchange processes should be operated in hydrometallurgy, 2) what mathematical models should be used to balance complexity and accuracy in ion exchange process simulation, 3) how to remove radionuclides in waste streams selectively and control TENORM using ion exchange materials.

Results An automated continuous ion exchange workstation was constructed to fill a gap in Finland's research infrastructure. The unit includes up to ten columns that can be divided into up to five zones. With multiple zones, different kinds of operations such as loading, washing, or regeneration can be conducted continuously and simultaneously. The constructed unit was tested in various cases and found useful in development and laboratory scale validation of new ion exchange process schemes. Specific examples include a new process scheme for purifying a concentrated electrolyte solution in an industrial application, as well as a new process scheme for purifying silver from divalent impurity metals in a concentrated sodium chloride medium using ion exchange.

A comprehensive ion exchange modelling and process simulation software, ResMod, was written. A large number of empirical and physical models for ion exchange equilibrium and kinetics were reviewed, and a library of carefully selected mathematical models made available. Moreover, the new software is capable of simulating a wide range of ion exchange unit operations, including counter-current or cross-current type simulated moving bed processes. The simulation software and the ion exchange workstation together form a platform for development of novel ion exchange processes.

A novel method was developed for improving ion exchange process performance by controlled neutralisation of the separation material. The method eliminates pH variations that often occur with chelating ion exchange materials containing nitrogen or oxygen donor atoms. Elimination of pH fluctuations reduces the risk of precipitation in the column, and therefore widens the range of applications of chelating resins in hydrometallurgical processing of neutral or near neutral feed solutions.

Various manganese oxide materials (MOM) were prepared for the removal of TENORM (Technologically Enhanced Naturally Occurring Radioactive Materials) from synthetic ground waters. In particular, attention was paid to Ra and its progeny. One of the materials was prepared from synthetic ore leaching solution containing a high amount of Mn. Very high uptake of TENORM was reached with the MOM studied, removing at best 99.9% of alpha and beta activity from the solution. In addition to much higher removal of TENORM species, the MOM materials were found to produce 10–100 times less waste volume than conventional elimination methods.

Key publications

1) Virolainen, S., Suppula, I. & Sainio, T. (2014), Continuous ion exchange for hydrometallurgy: purification of Ag-NaCl using counter-current and cross-current operation, Hydrometallurgy, 142C, pp. 84–93.
2) Virolainen, S., Suppula, I. & Sainio, T. (2013), Controlled partial neutralization of Amphoteric Ion Exchange Resin for Improved Metals Separation, React. Funct. Polym, 73, pp. 647–652.
3) Virolainen, S., Heinonen, H. & Paatero, E. (2013), Selective recovery of germanium with N-methylglucamine functional resin from sulfate solutions, Sep. Purif. Technol. 104, pp. 193–199.
4) Laatikainen, M. & Sainio, T. (2012), Sorption of Ampholytes in Weakly Acidic Ion Exchangers, Solvent Extraction and Ion Exchange, 30, pp. 388–397.
5) Laatikainen, M., Laatikainen, K., Sainio, T. & Siren, H.(2011), Removal of Very Small Amount of Nickel from Concentrated Zinc Sulfate Solutions – Modeling Approach, 1st International Conference on Methods and Materials for Separation Processes, 5.–9.6.2011, Kudowa Zdroj, Poland.

Number of publications:	18
Number of Doctoral Theses:	2
Number of Master's Theses:	2

Networks and international co-operation

A network between the participating universities and industry was built by combining the expertise areas of the research groups and departments. Researcher exchange visits (in total 6 months) to Wroclaw University of Technology (Poland) and the University of Toulon (France) were made in 2011 and 2013. So-called double degree collaboration between Lappeenranta University of Technology and St. Petersburg University of Natural Resources (Mining Institute) resulted in one MSc thesis in the field of continuous ion exchange within this project.

Applications & impact A new product line employing ion exchange for a specific purification task was developed and taken into use in industry during this project. The scientific results can be considered very significant, as continuous ion exchange was not previously well established in Finnish metals processing industry. The tools developed in the project offer a platform for development and testing of novel ion-exchange-based hydrometallurgical process schemes.

Process Alternatives for Low-grade Ores

New decision-support tools through more effective use of expert knowledge – improved metals extraction processes with lower environmental load

A gold process development tool named *Auric Adviser* was created, the tool having two knowledge models. The first holds the knowledge needed to recommend whole processing chains derived from existing gold extraction operations. With proper knowledge formalisation, this can be used for initial selection of the processing method. The second knowledge model can be used to develop a better processing chain using the unit processes available for the ore. This model uses input-output models derived both from literature and based on own experimental data.

Two process selection methodologies, Decision trees and Case-based Reasoning (CBR), were compared. The CBR method was selected for building the first process development tool prototype because it can also operate with incomplete data. The availability of knowledge is no longer a challenge for today's process designer, who is now concerned with remembering, classifying and performing comparative analysis for the information that already exists. The key result of the project was to show how to make use of artificial intelligence to help capture and re-use existing knowledge. Gold and nickel ores were selected as test materials, and special attention was paid to refractory gold and lateritic nickel ores. The results with the process development tools provided new ways of handling expert knowledge.

The task of the CBR process development tool is to retrieve a selection of descriptions of existing gold extraction operation that best match the ore and mineralogical context described in a query to the tool. The cases retrieved provide the planner of a potential mining operation, and the subsequent ore refinement process chain, with a first draft of the treatments involved in exploiting the site. The planner would also obtain insight into the potential arrangement of these treatments within the process chain in order to achieve the most efficient means of refining the ore at the prospective site.

The ability of the prototype tool – developed using myCBR – to operate with similarities of incomplete data, introduces a fundamentally new approach in the field of hydrometallurgy. No comparable tools were found in the literature, the closest example being rule-based *Intelligold* software dating from 1990 but not since developed.

The method of knowledge formalisation and retrieval can be expanded to other application areas. The main differences will be the selection of important attributes, their grouping, and data collection to form the case base. The case base structure allows use of whole processes starting from raw material description, or use of unit processes using input-output models. Experimental results can be used to increase the unit process database.

In addition to process development tools, several potential methods for improving metals extraction processes and decreasing the environmental load of metals extraction were identified and tested. Chloride heap leaching of copper-containing ore was scoped in the means of cost evaluation. The main parameters affecting utility, energy and chemical costs were evaluated and a sensitivity analysis of energy cost carried out. One of the main challenges in chloride heap leaching may be its relatively high utility and chemical cost. In particular, maintaining the heap at elevated temperature was considered challenging, together with acid consumption.

Development of the gold cyanide leaching process included analysis methods for cyanide, gold and silver, as well as leaching tests and adsorption experiments using the carbon-in-leach (CIL) method. The CIL method, however, was found to be sensitive to carbon attrition – gold associated with fine carbon particles reported to leach residue along with them and was lost. While the CIL method can significantly improve gold extraction, this improvement is counteracted by the carbon attrition.

Iron removal is an essential process in hydrometallurgical production, and creates a large volume of iron precipitate residues known to contain hazardous elements. Greater environmental awareness has increased the attraction of precipitating iron as hematite, rather than the more common jarosite or goethite.

The focus in iron removal was on potential applications for hematite precipitates, and on the requirements for use of hematite in different industries. Environmental classification of the precipitates was also determined, along with requirements for long-term storage at waste disposal sites. The demand for low-cost raw materials in earthworks and construction can be considered almost “unlimited”. The use of hematite as a raw material in steel production necessitates a purification process, and treated hematite can be diluted with iron ore.

Due to its high recovery of valuable metals and encouraging potential for commercial applications, the hematite process is a feasible alternative for hydrometallurgical iron removal, for example in zinc production. With proper processing and purifying of hematite, a major waste stream could be turned into a marketable product, and environmental benefits achieved. Changes in the waste storage legislation of toxic iron wastes, or increased taxes, would change the cost structure, increasing the competiveness of the hematite process.

All the process cases – chloride-based metallurgy, the carbon-in-leach method for gold extraction, and iron removal as hematite – are techniques that can be applied in industrial scale.

Figure 1. **Gold bars and silver grains (Courtesy of Boliden Harjavalta Oy)**

The target of the Lowgrade project was to produce process development tools for the utilisation of low-grade ores and ores that cannot economically be handled by conventional technologies. Process development takes time and requires extensive resources. Providing decision-making methods based on development tools results in more efficient use of the resources needed for experimental work and testing.

The specific targets of the research included description of the unit processes, development of unit process selection tools, and testing of the process selection methodology using real raw material sources. Specific industrial cases were carried out to enable sustainable chloride heap leaching of copper-containing sources, recovery of silver from zinc production residues, improvement of gold extraction using the carbon-in-leach method, and environmentally friendly technology for removal of iron as hematite from hydrometallurgical process streams.

PROJECT NAME

WP 2 New Opportunities in Base Metals Industry

Lowgrade

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION
OLOF FORSÉN AALTO UNIVERSITY	**OUTOTEC (FINLAND) OY** **AALTO UNIVERSITY** **UNIVERSITY OF OULU** **TAMPERE UNIVERSITY OF TECHNOLOGY**	**2009 – 2014** PROJECT VALUE (EUR) **2.029 MILLION**

Process Alternatives for Low-grade Ores

Main targets & motivation

The Lowgrade project was part of the work package "New opportunities in base metals industry". Efficiency was sought in the whole production chain from ore to final metal. Various hydrometallurgical unit processes were studied and modelled to find new options for utilising low-grade ores and meeting environmental and product quality challenges.

The project had both large-scale and small-scale objectives, the latter aiming to improve several specific production methods for the hydrometallurgical industry. The large-scale objective was development of a decision-support methodology to assist in the development of new processes. An efficient decision-support tool will allow better use of existing knowledge, thereby decreasing time and costs in process development and design.

The decision-support methodology will contain tools for different stages of process and unit process selection, focusing on gold and lateritic nickel. Such methodology has only been used once for these test materials, in a gold processing application in the 1990s. The tools will include mineralogical characterisation of low-grade ores, to facilitate selection of processing methods, selection and modification of pre-treatment and leaching methods for different types of ores, selection and development of solution purification methods based on pregnant solution properties, and selection and development of product recovery methods as metals or compounds based on purified solution properties.

Results Decision-support methodology founded on case-based reasoning (CBR) was developed with regard to process selection and development for gold ores and lateritic nickel ores. Designing a CBR system involves identification of the important factors related to processing of a particular raw material type and formalisation of the knowledge used in cases. Rapid prototyping tools for CBR development were evaluated and the benefits of a decision-support methodology demonstrated in test runs.

A comparison was made of methods for pre-treating and leaching refractory gold ores. A sulfide refractory gold concentrate was broken using oxidative autoclave leaching, bacterial leaching and electrochemically assisted leaching to break a sulphide refractory gold concentrate. All these methods produced comparable results because the system is based on the effect of ferric iron as oxidant.

Carbon-in-leach (CIL) extraction was tested to improve gold recovery, and the critical factor was identified to be carbon attrition causing fine carbon particles and the associated gold to report to leach residue.

Chloride hydrometallurgy was developed for primary base metal production and for recovery of noble metals from secondary sources. Heap leaching was found to be sensitive to energy and chemical costs, and perhaps suitable for warm climates. Chloride leaching of noble metals is technically possible using acid chloride solutions with an oxidant.

Iron removal is an essential process in many hydrometallurgical processes. Increased environmental awareness has increased the attraction of precipitating iron as hematite, rather than the more common jarosite or goethite. Potential applications for hematite were identified, along with requirements for its use in different industries.

Key publications

1. Rintala, L., Lillkung, K. & Aromaa, J. (2011) The use of decision and optimization methods in selection of hydrometallurgical unit process alternatives. Physicochemical Problems of Mineral Processing 46, pp. 229–242.
2. Rusanen, L., Aromaa, J. & Forsén, O. (2013), Pressure oxidation of pyrite-arsenopyrite refractory gold concentrate. Physicochemical Problems of Mineral Processing 49, pp. 101–109.
3. Forsén, O. & Aromaa, J. (2013) The use of hydrometallurgy in treatment of secondary raw materials and low-grade ores. Acta Metallurgica Slovaca 19, pp. 184–195.

4. Rintala, L., Aromaa, J. & Forsén, O. (2012) Use of published data in the development of hydrometallurgical flow sheet for gold using decision-support tools. XXVI International Mineral Processing Congress. 24–28 September 2012. New Delhi, India.
5. Sauer, C.S., Rintala, L. & Roth-Berghofer, T. (2013), Knowledge formalisation for hydrometallurgical gold ore processing. Proceedings of AI-2013, The Thirty-third SGAI International Conference on Innovative Techniques and Applications of Artificial Intelligence, 10–12 December, Cambridge, pp. 291–304.

Number of publications:	14
Number of Doctoral Theses:	1
Number of Master's Theses:	5

Networks and international co-operation

A decision-support tool, *Auric Adviser*, (a java-based workflow recommender software prototype) was developed in co-operation with the School of Computing at the University of West London (UWL). Researcher exchange took place during 2013–2014. The UWL research group, Centre for Intelligent Computing, assisted in the respective knowledge modelling and programming tasks, and with study of the means of formally representing cases in the domain of gold extraction using myCBR Workbench (an open-source similarity-based retrieval tool), and of effective retrieval of relevant cases.

Applications & impact

The project developed the methodology for a decision-support tool founded on case-base reasoning. Such a tool will assist in the use of existing knowledge by providing alternative starting points for process development from its case base that may contain hundreds of documented examples. The decision-support tool is in prototype scale, but can also be enlarged and modified for raw material types other than those used in this project.

The Lowgrade project raised the level of technological knowledge among the participating companies. Several specific hydrometallurgical cases were tested and technological and economical boundary conditions defined. Cases included methods for treating low-grade materials, and for lowering the environmental load of metals production. The process cases tested are metal production methods that can be used in production scale.
The scientific significance of the research on decision support is clear. One of the publications produced by this research was selected as best application-oriented paper at the 33rd SGAI conference of 2013.

Water-saving Mineral Concentration Technologies

Water savings in mineral separation processes by advanced modelling of particle-bubble interactions

New insights were gained during the project into the effect of different surfactants, salts and combinations of surfactants and salts on the air/liquid boundary layer and its implication on the bubble formation, coalescence, break-up and bubble deformation. Both laminar and turbulent conditions were investigated. The results clearly showed that the old theories and models developed for static conditions are not valid when turbulence is present. It was shown that there is a sharp difference between the mechanisms by which the frothers control the bubble size. The strongly surface-active frothers have a better bubble stabilisation capability than those weakly surface active, and therefore prevent bubble breakup more effectively. From the results it also became clear that there is a difference in the bubble breakup mechanism between the strong and weak frothers.

Industrial relevance

"Understanding the mechanisms affecting bubble size in turbulent conditions is essential to enable reliable modelling of the behaviour in industrial flotation cells."

Comment of the industry representative

A unique, computational modelling framework was also developed to permit exploration of the physical and physico-chemical aspects of bubble-particle interactions. This is a highly significant contribution as it allows the modelling of three-phase phenomena taking place in flotation, and opens up new avenues for flotation research.

Industrial relevance

"This new approach may in future reduce the need for expensive and time-consuming experimental testing of flotation of different ores."

Comment of the industry representative

Computational fluid dynamic (CFD) and multiblock models were also developed specifically for high-density slurries in flotation. The focus was on practical models with reasonably short computation times, allowing the use of modelling in engineering design. Dense suspensions are typically non-Newtonian, implying a viscosity depending on the shear rate. This can have a significant effect on the flow pattern and the behaviour of gas bubbles. Models that take into account the effects of turbulent eddies and the movement of the bubbles on the shear rate and fluid viscosity were implemented in both the CFD and multiblock models. The multiblock solver is an effective tool in modelling situations where CFD is excessively time-consuming. In the case of bubble movement in a highly viscous slurry, the multiblock model was 1000 times faster than CFD.

Industrial relevance

"Traditional multiphase CFD simulation is impractical in everyday engineering so this kind of tool is very useful."

Comment of the industry representative

Challenges in flotation

Flotation is the most widely used mineral beneficiation technology. With the depletion of high-grade ore reserves, low-grade ores became the primary source of metals, and flotation the only feasible method of processing these ores.

Flotation is a highly complex, three-phase physico-chemical separation process used to separate valuable minerals from gangue. The ore is first ground in order to liberate the valuable minerals from the gangue, after which it is mixed with water to form slurry. Chemicals that render hydrophobic ("air-loving") the surface of the minerals to be separated are also added to the system. When air is introduced in the form of bubbles into the tanks containing the slurry, the hydrophobic particles attach to these bubbles and rise to the top of the tank, where a mineralised froth is formed. The froth containing the valuable minerals is collected and processed further in order to obtain the metals. These include copper, lead, zinc, etc. or industrial minerals glass sand, kaolin, bentonite, and others.

One of the major challenges faced by the mineral processing industry in the modern world is the transformation of water into a precious commodity. Reduced consumption in the mineral recovery process is therefore important, not only from the financial point of view, but because water resources in most mining areas are becoming scarce. Tightening environmental regulations and pressure from civil organisations also put serious stress on mining operations to decrease their energy and water consumption. Finding new ways of achieving this is therefore a primary challenge, requiring a significant research effort from industry and academia.

The general objective of the project was to develop more water-efficient flotation technologies. The aim was to reduce the use of water by 20–25%, an aim that in part was reached.

Understanding the boundary phenomena that take place at the gas/liquid/solid interfaces is of key importance in optimising existing processes, and designing new processes that are more water-, energy- and cost-efficient. The performance of the flotation process is governed by particle-bubble interactions and the behaviour of the particle-bubble aggregates. These are influenced both by the interaction of reagents with the solid/liquid and gas/liquid interfaces and by the hydrodynamics inside the flotation cell. The project focused on both these aspects.

Model verification

The models were verified using a laboratory-size flotation cell as a test platform. Simulations with both single-phase flow and flow with air feed were carried out using power law and Bingham plastic models for the rheology. The turbulent effect on shear rate, and therefore on the viscosity, was found to be considerable. The flow pattern in both pseudoplastic and Bingham plastic cases was substantially affected by including the eddy shear rate in the viscosity expression. The effect due to bubble movement was significant in the top part of the tank.

Industrial relevance

"Understanding of these phenomena and the ability to model them is beneficial in the dimensioning of flotation equipment."

Comment of the industry representative

A model including all three phases (water, solids, air) was developed and implemented in CFD to obtain a more realistic picture of the flow pattern in true flotation process conditions. The model makes no attempt to predict the recovery of the desired mineral, but uses the amount of recovery as an input value. The new approach is a notable improvement in the modelling of flow conditions in the flotation cell when compared to single- or two-phase simulations.

Industrial relevance

"The three-phase CFD model is a superior tool in the development of large scale industrial flotation cells."

Comment of the industry representative

One cubic meter modifiable pilot scale flotation cell was constructed and commissioned in this project. The cell has been used for evaluation of physical and metallurgical performance of novel mixing mechanisms.

In field tests higher solids suspension and air feed capacity were obtained with same metallurgical performance in pilot cell with a new mixing mechanism. Thus higher solid contents could be utilized in order to reduce the use of water in flotation.

Figure 1. **Industrial flotation plant (Copyright © Outotec)**

PROJECT NAME

WP 2 New Opportunities in Base Metals Industry

PROCEDY

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION
KARI HEISKANEN AALTO UNIVERSITY, SCHOOL OF CHEMICAL TECHNOLOGY **MARKO LATVA-KOKKO** OUTOTEC (FINLAND) OY	**AALTO UNIVERSITY** LAB. OF MECHANICAL PROCESSING & RECYCLING **AALTO UNIVERSITY** LAB. OF CHEMICAL ENGINEERING **VTT TECHNOLOGICAL RESEARCH CENTRE OF FINLAND** FLOW DYNAMICS **OUTOTEC (FINLAND) OY**	**2009 – 2014** PROJECT VALUE (EUR) **2.941 MILLION**

Water-saving Mineral Concentration Technologies

Main targets & motivation

The general objective of the project was to develop more water efficient concentration technologies. The main emphasis was on the most utilised beneficiation technology, flotation. The aim was to reduce the use of water with 20–25%.

Flotation is a very complex physico-chemical separation process involving solid, liquid and gas phases interacting with each other. Understanding the boundary phenomena that takes place at the gas/liquid/solid interfaces has a key importance in optimizing existing processes and designing new, more water, energy and cost efficient processes. Particle-bubble interactions and behavior of the particle-bubble aggregates are governing the performance of the process. They are influenced both, by the interaction of reagents with the solid/liquid and gas/liquid interfaces and by the hydrodynamics inside the flotation cell. The project focused on both of these aspects.

The bubble formation in flotation is dependent on the mechanism used to create the bubbles, the hydrodynamic conditions and the surface-active agents present in the system. It is well know from literature, that frothers decrease bubble size by preventing coalescence, and help to create a relatively stable froth phase. The action mechanism of different frothers nonetheless remains unclear, and systematic research efforts are needed to clarify these mechanisms.

Measurement of the detailed flow conditions in a flotation tank is compromised by the opaqueness of the slurry and the presence of air bubbles. This is especially true where the goal is to use slurries with as high a consistency as possible in order to save water and energy. To understand the flow and turbulence in flotation cells, the aim was to develop models usable in high-density, non-Newtonian slurries. The target was to obtain practical models for use in the analysis and design of flotation equipment.

The objectives of the project can be summarised as follows:

- Improve knowledge of the gas/liquid boundary phenomena in flotation through the study of the effect of frothers, collectors (amines) and salts and drawing conclusions on the mechanism of frother action from a novel, holistic approach involving systematic investigation of gas/liquid interfaces in micro/nano-, meso- and macro-size scales
- Gain deeper understanding of bubble formation
- Improve modelling capabilities for multiphase systems
- Develop a computational framework for the exploration of physical and physico-chemical aspects of bubble-particle interactions.

Results

New insights were gained into the effect of different surfactants, salts and combinations of surfactants and salts on the air/liquid boundary layer, and its implication for bubble formation, coalescence, break-up and bubble deformation. Both laminar and turbulent conditions were investigated. The results clearly showed that the old theories and models developed for static conditions are not valid when turbulence is present.

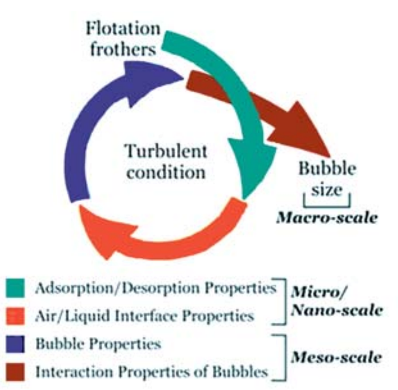

Figure 1. **Interactions affecting bubble size in flotation**

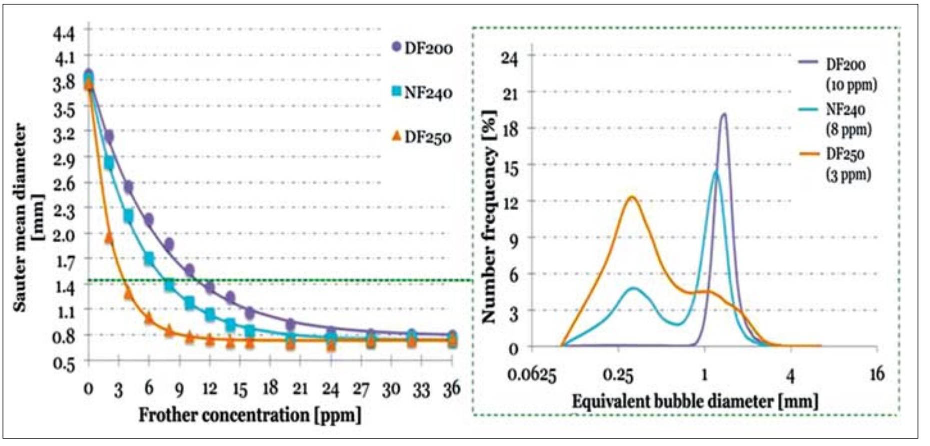

Figure 2. **Effect of different frother types on Sauter mean diameter and bubble size distribution**

It was shown that there is a sharp difference between the mechanisms by which the frothers control bubble size. The strongly surface-active frothers have a better bubble stabilisation capability than those weakly surface-active, and therefore prevent bubble breakup more effectively.

- The research has shown that there is a difference in the bubble breakup mechanism between strong and weak frothers.
- Development of a unique computational modelling framework in which the physical and physico-chemical aspects of bubble-particle interactions can be explored. This is highly relevant to e.g. minerals flotation.
- Development and implementation of a simplified three-phase model in CFD. The model is based on particle attachment in a prescribed region in the flotation.
- In dense slurries with high viscosity the bubble slip velocities can be small, making the CFD simulations very slow. The existing multiblock model at VTT was therefore improved to allow a large number of blocks (thousands) and to include the same non-Newtonian models as in CFD. Using the multiblock model, the gas holdup in the tank can be predicted quickly even with complex rheology.

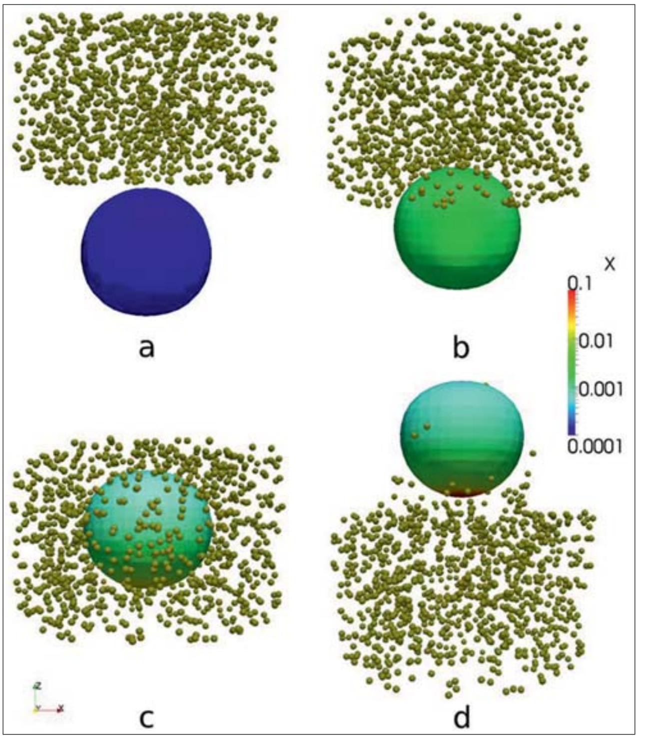

Figure 3. **A 1-mm air bubble rising through a cloud of settling solid particles. The bubble is depicted by the 0.5 phase fraction contour (α=0.5). The colour on the surface of the bubble represents normalised surface surfactant concentration. The snapshots are taken after 0 (a), 5 (b), 10 (c), 15 (d) ms.**

Key publications

1. Heiskanen, K., Javo, Z., Wierink. G., Omelka, B. & Schreithofer, N. (2012), Effect of Frother Mobility on the Bubble Behaviour in Bubble Rise Velocity Measurements at the Initial Stages of Bubble Formation. In: Separation technologies for minerals, coal, and earth resources (ed. Young, C.A. & Luttrell, G.H.), SME, Engelwood, USA, pp. 1–5.

2. Jávor, Z., Schreithofer, N. & Heiskanen, K. (2012), "The effect of bubble release techniques on their behaviour at the initial stages of rise". Minerals Engineering 36–38, pp. 254–261.

3. Jávor, Z., Schreithofer, N., Gomez, C.O., Finch, J.A. & Heiskanen, K. (2013), Effect of scale dependent dynamic properties on bubble size. In: Proceedings of Materials Science & Technology 2013, Montreal, Canada, pp. 2024–2033.

4. Jávor, Z., Schreithofer, N. & Heiskanen, K. (2014), Validity of critical coalescence concentration in dynamic condition. International Journal of Mineral Processing 127, pp. 16–22.

5. Jávor, Z., Schreithofer, N. & Heiskanen, K. (2015), Micro- and nano-scale phenomena effect on bubble size in mechanical flotation cell. Minerals Engineering 70, pp. 109–118.

Number of publications: 17
Number of Doctoral Theses: 1 accepted, 1 in preparation
Number of Master's Theses: 1

Networks and international co-operation

One Ph.D. student spend 6 months during the project at McGill University in Montreal, Canada, working together with Prof. J. Finch and his research group on the study of the effect of frothers on bubble formation and behaviour.
One M.Sc. student from the University of British Columbia, Vancouver, Canada spent 6 months at Aalto University conducting research on the interaction of amine type collectors, frothers and salts at the gas/liquid interfaces.

Applications & impact

Bubble formation and size distribution is a key parameter controlling the minerals flotation process. An understanding of the factors affecting bubble size, such as the type of frother and the presence of different ions, contributes significantly to the knowledge base needed to design technologies that use less water than existing processes. While there may be various options for achieving this goal, there is a need for clear comprehension of the implications of the accumulation of ions and surfactants when, for example, the water circuits are closed and process water is fully re-circulated, or when saline water is used for processing. The results of the project contribute significantly to this understanding.

The importance of the modelling framework is that it describes for the first time a possibility of incorporating full momentum coupling, including the momentum induced from chemical potentials. It also includes the possibility of modelling surface property changes due to reagent adsorption.

The modelling developments are necessary in the simulation of new flotation concepts because water saving obviously implies higher density and more viscous slurries, with more complex rheology. Incorporating all three phases in the flow modelling gives more accurate prediction of the process conditions. Multi-block modelling offers a practical way of modelling mixing, bubble behaviour, and residence times much faster than CFD. Design process equipment for water- and energy-saving mining processes needs to make use of all of these.

The models and knowledge generated within this project will be used to optimise process performance of existing devices and to develop new equipment for more water- and energy-efficient concentration technologies. This will significantly improve the environmental sustainability of mining.

WORK PACKAGE 3:
Towards Zero-waste Plant

New concepts for zero-waste metals production were studied. The focus was on new metallurgical solutions for treatment and utilisation of dusts.

PROJECT:

- New Metallurgical Solutions for Ferrous Dust Treatment (METDUST)

Methods for decreasing the amount of dust and recycling of metal-containing wastes were developed on the way towards a zero-waste steel plant

New Metallurgical Solutions for Ferrous Dust Treatment

Methods for recycling stainless steel production dust were developed using selective removal of zinc by leaching. Methods for the recovery of dissolved metals from dusts after leaching were created based on solvent extraction and precipitation. In many previous attempts the solid-liquid separation after leaching had been found unfeasible. In this project, however, the filtration of residues after alkaline or acid leaching was mostly successful. In cases where hot and concentrated leaching solutions produced crystallised salts after cooling, the filtering was made by hot slurries and any problems were avoided.

The effective pre-treatment for improving metal recovery was to roast the dust with excess alkali. Roasting with 3:1 weight ratio NaOH to dust at 500 °C for one hour converts franklinite to soluble form. After the roasting almost all the dust can be leached using strong acid.

The choice of an effective hydrometallurgical dust treatment process is influenced by the multitude of possible combinations of unit operations. Experimental investigation of all options is obviously impossible, so the use of simple process synthesis methods was also investigated. A stochastic optimisation method known as Ant Colony Optimisation was found suitable for simultaneous construction of a sequence of hydrometallurgical unit operations (leaching, precipitation, solvent extraction, back extraction) and selection of the best operating conditions (pH in particular) for each of them. The presence of iron in solvent extraction is undesirable, and so selective leaching of compounds other than iron from the dusts was preferred. While this is difficult to achieve in direct acid leaching, good results were obtained with pH-controlled leaching.

The project developed products, practices and ideas for reducing the amount of waste and reusing certain waste streams. The methods for decreasing the amount of dust included screening of the lime and modifications to the blowing and tapping practices. The screening of the small fraction (20–35%) decreased bag filter dust in the argon-oxygen decarburisation converter (AOD). Modifying top lance operation decreased the amount of dust by a third, and dry ice (solid CO_2) in tapping resulted in a visible decrease in dust.

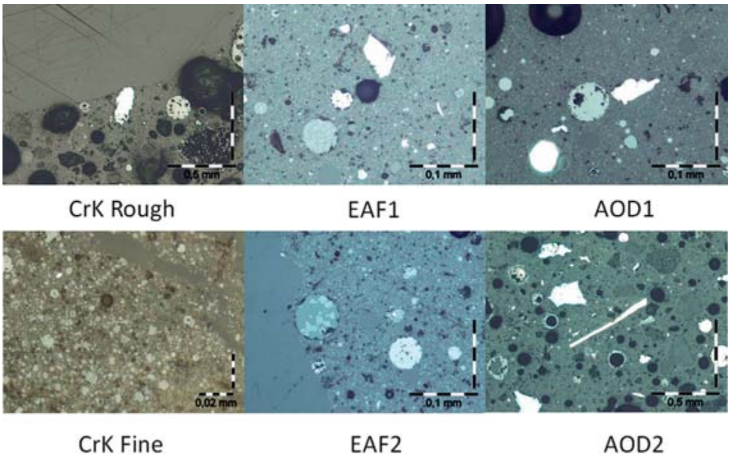

Figure 1. **Microscope views of metal process dusts: from chromium converter (CrK, rough and fine filter), electric arc furnaces (EAF1 and EAF2) and argon-oxygen decarburisation converters (AOD1 and AOD2) (TU Kosice, Slovakia; dust samples from Outokumpu Stainless Oy, Tornio)**

The new treatments for metal-rich waste included heap leach of regeneration sludge and AOD slag. The smelting of sludgy wastes in a dust smelter became a daily operation. Pilot tests for treating cold rolling oily sludges showed that it is possible to feed oily sludges with solid feed into the plasma furnace. Hot rolling water treatment sludge, continuous casting sludge and many cold rolling oily sludge fractions can now be treated, which is a great improvement on the earlier landfilling. Smelting of metal oxide waste briquettes resulted in slag foaming, which improved energy efficiency and chromium recovery. Hydrometallurgical treatment of regeneration sludge to separate metals as hydroxides looked promising. After diluting sludge with water the metals can be precipitated by pH-selective precipitation.

The dust treatment plant was designed by Outokumpu and Outotec, and the feasibility study finalised for investing in their own dust smelting plant.

Lower energy consumption and a reduced amount of waste are a necessity for the future metals industry. The metallurgical industry is facing demands concerning economic competitiveness, growth and environmental acceptability. New production technologies are required in the move towards zero-waste plants.

The Metdust project developed methods for decreasing the amount of waste produced in stainless steel production, recycling the waste in order to recover valuable metals, and removing hazardous materials and treating them for conversion to a non-reactive form. Production of stainless steel using ferrochrome, electric arc furnace melting and argon-oxygen decarburisation creates 10–20 kg of dusts per ton of steel. The final rolling and pickling stages also produce significant amounts of metal-rich wastes and acid sludge.

The specific result of the research was the development of new hydrometallurgical processing methods for baghouse dusts, sludge and metal-rich wastes. The stainless steel dusts have widely varying particle sizes (<1 μ to 50 μm) that provided a challenge in leaching and solid-liquid separation. While the main elements in the dusts were iron, chromium, nickel, zinc, silicon and calcium, they also contained some molybdenum, manganese and magnesium. Each dust was unique, the properties varied from batch to batch, and composition was affected by the alloying and melting processes. The main compounds were iron, nickel, chromium and zinc oxides, their combinations and various silicates. Encapsulation by molten and solidified phases hindered dissolution with, specifically, the mineralogy of zinc found to affect recovery. Zinc was present as soluble zincite (ZnO) and insoluble zinc ferrite (franklinite, $ZnFe_2O_4$) in electric arc furnace (EAF) dusts, and the insoluble franklinite was a major obstacle in leaching.

Three main lines were defined in the process development. Two lines aimed at selective removal of zinc, leaving zinc-free oxides as residue. This was done using either strong bases or dilute acids. Neither system was capable of reaching zinc levels below 0.1% without alkaline roasting to break the zinc ferrite. The third line was hot, strong acid leach, which was efficient in dissolving most of the metals.

The project resulted in the following factors being defined for consideration in the design of a dust treatment plant:

- Chromium-containing materials and glassy phases that may surround other compounds dissolve with difficulty, if at all;
- Dissolution of zinc from all the dusts studied occurs in 10–20 minutes. All dusts can be leached in the same step;

- To obtain high zinc recovery, franklinite ($ZnFe_2O_4$) must be decomposed before leaching;
- Molybdenum dissolves easily, even in water;
- Acid leaching without roasting dissolves max. 75% of the charge, the residue being iron-chromium and zinc-iron oxides. Recovery of metals from acid solution can be done by solvent extraction, ion exchange and precipitation;
- The acid pickling regeneration salts can be used in preparation of leaching acid;
- Alkaline leaching dissolves zincite (ZnO) and part of ferrite, other oxides remain in residue. Molybdenum dissolves in alkali. Roasting is needed to break franklinite. Recovery of zinc from alkaline solution can be done using electrowinning, but selective molybdenum recovery is still open.

Figure 2. **The demanding ferrochrome smelter process (Outokumpu Stainless Oy, Tornio)**

PROJECT NAME

WP 3 Towards Zero-waste Plant

METDUST

CONTACT PERSON

OLOF FORSÉN
AALTO UNIVERSITY

PARTICIPANTS (ORGANISATIONS)

OUTOKUMPU STAINLESS OY
BOLIDEN KOKKOLA OY
OUTOTEC (FINLAND) OY
AALTO UNIVERSITY
UNIVERSITY OF OULU
LAPPEENRANTA UNIVERSITY OF TECHNOLOGY

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

4.424 MILLION

New Metallurgical Solutions for Ferrous Dust Treatment

Main targets & motivation

The Metdust project was part of the work package "Towards zero-waste plant". The aim of the project was to reduce the costs and environmental load of stainless steel production by developing new processes and technologies for steel mill dust and sludge treatment. The target was to recover valuable metals in suitable form for use as raw materials, and to remove harmful materials and treat them for conversion into a non-hazardous form. The various solid wastes in the form of dusts and sludge in steel plants include chrome converter (CRC) dust, electric arc furnace (EAF) dust, argon-oxygen decarburisation converter (AOD) dust, mill scale, mill sludge, etc.

The specific project targets included methods for decreasing the amount of dust, development of new methods for treating metal-rich waste, initial design and planning of a pyrometallurgical dust treatment plant, and development of hydrometallurgical processes for utilisation of dusts and sludge. The hydrometallurgical process development included waste-material characterisation, selective and complete leaching methods, solid-liquid separation and product recovery.

The technical and scientific goals included recovery of valuable elements, capture of economically uninteresting and environmentally critical elements, integration of the developed processes and production methods into existing plants, and development of economically viable operation of the new methods.

Results

Methods for decreasing dust formation included lime screening and modification of blowing practices. The trials showed that fine lime can be screened off from the lime feed, although it remains unclear how this affects the amount of dust. The amount of bag filter dust decreased by approximately one third after modification of blowing practices, and further developments will take place in the melt shop.

Development of new methods for treating metal-rich wastes resulted in one product, one practice and two possible methods for recovering nickel. Stainless steel slag was treated with a new product called OKTO sand, used as a replacement for burnt lime in the melt shop. The energy efficiency of melting and chromium recovery were improved by using briquettes to increase slag foaming. Two different approaches for recovering nickel from regeneration sludge were proposed, and carried forward to practical testing.

The dust treatment plant was designed with Outotec, and a feasibility study finalised for investing in their own dust smelting plant.

Hydrometallurgical zinc removal can be done using acids and alkalis, but alkaline roasting is needed for high zinc yield. After a strong acid leach, 0.1–0.2% zinc remains in residue. Filtration and iron precipitation produce a solution after acid leaching that can be treated using solvent extraction or ion exchange for nickel, zinc and molybdenum recovery. Zinc-free iron-chromium oxides can be recycled to melting.

Key publications

1. Kekki, A., Aromaa, J. & Forsén, O. (2012), Leaching Characteristics of EAF and AOD Stainless Steel Production Dusts. Physicochemical Problems of Mineral Processing, 48(2), pp. 509–606.
2. Stefanova, A., Aromaa, J. & Forsén, O. (2013), Alkaline leaching of zinc from argon-oxygen decarburization dust from stainless steel production. Physicochemical Problems of Mineral Processing, 49(1), pp. 37–46.
3. Hietanen, E., Kekki, A., Sainio, T. & Häkkinen, A. (2012), Solid/liquid separation of suspensions obtained from selective leaching of metal dust generated in the stainless steel industry, 11th World Filtration Congress, Graz, Austria, 16–20 April.
4. Kukurugya, F., Havlik, T., Kekki, A. & Forsén, O. (2013), Characterization of dusts from three types of stainless steel production equipment. Metall 2013, 67(4), pp. 154–159.
5. Virolainen, S., Salmimies, R., Hasan, M., Häkkinen, A. & Sainio, T. (2013), Recovery of valuable metals from argon-oxygen decarburization (AOD) dusts by leaching, filtration and solvent extraction. Hydrometallurgy, Vol. 140, pp. 181–189.

Number of publications: 18
Number of Doctoral and Licentiate Theses: 2
Number of Master's Theses: 4

Networks and international co-operation

A working network between the participating universities was built by combining expertise areas of the three research groups. Materials characterised by the University of Oulu were used as raw materials for leaching tests performed by Aalto University and Lappeenranta University of Technology (LUT). Aalto developed leaching procedures that LUT was able to use for recovery tests. Aalto in turn gained knowledge from LUT that was needed in product recovery tests.

International cooperation was executed during 2011–2013 between Aalto University and the Technical University of Kosice in Slovakia. Research exchange was used to conduct parts of various experiment series at both universities, resulting in joint publications. Professors of both universities gave guest lectures in postgraduate seminars. In addition, double-degree collaboration between LUT and St. Petersburg State Mining Institute in Russia resulted in a M.Sc. degree in 2013.

Applications & impact

Methods for decreasing the amount of dust and for recycling metal-rich wastes have been developed by Outokumpu Stainless. New methods were developed for treating metal-rich wastes using existing plasma treatment. Methods were developed for feeding treated dusts back to melting. Outokumpu Stainless and Outotec designed and made a feasibility analysis for a dust treatment plant. Various plant practices were adopted at Outokumpu Stainless for decreasing the amount of dust and recycling certain materials.

Flowsheets were developed for the hydrometallurgical processes. Pretreatment by alkaline roasting is needed to achieve the target values of zinc for recycling, and this has a negative effect on feasibility.

The procedures developed by Outokumpu Stainless have a direct effect on plant operation, and decrease the amount of waste produced.

The results of the research work opened a new technological field for utilisation of stainless steel production wastes. Hardly any publications concerning the processing of stainless steel dusts existed before this project, even though much research had been performed on unalloyed steel. Both acid and alkaline leaching systems were shown to operate. The generally accepted truth that solid-liquid separation will not work was shown to be false. The use of solvent extraction and ion exchange for solution purification was also shown to be feasible in the recovery of valuable metals.

WORK PACKAGE 4:
Life-cycle Management and Environmental Footprint

A sustainability index was developed for process industry, comprising three different aspects of sustainability: environmental, economic and social. The index facilitates transparent knowledge exchange between industry and society.

PROJECT:

- Metrics of Environmental Efficiency for Metal Production Technologies (METRIC)

PROJECT NAME

WP 4 Life-cycle Management and Environmental Footprint

METRIC

Metrics of Environmental Efficiency for Metal Production Technologies

The novel index promotes sustainability and supports decision-making in process industry by integrating all the relevant dimensions of sustainability – environmental, social and economic – in a single tool

The Metric project created a sustainability index that comprehensively and reliably captures the environmental, economic and social sustainability at an industrial plant (Figure 1). The novel index supports decision-making by integrating all the relevant dimensions of sustainability into a single tool. The index can also be used as a communication tool for stakeholders such as environmental authorities and local communities.

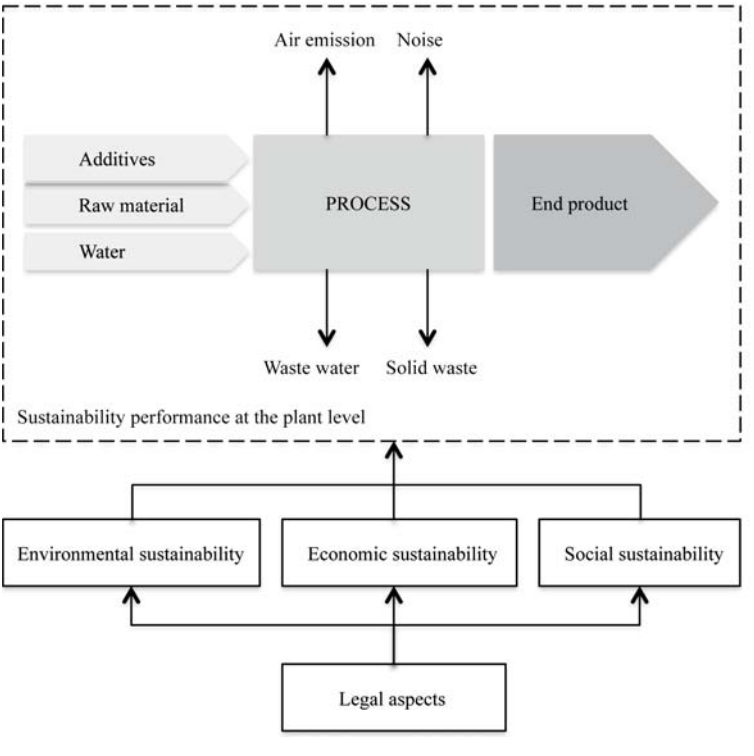

Figure 1. **Sustainability aspects at an industrial plant**

The novel index was created in intensive collaboration between the university and participating industries, involving company personnel from both operations and environmental management. Collaboration with the industry was arranged through workshops run by industry and academia. The purpose of these workshops was to achieve a better understanding of the main challenges and needs regarding sustainability assessment in the metal production industry, with special emphasis on activities at the level of an operational plant. The development work for the index was based on literature research and the results of university–industry collaboration through the workshops. The development work structure is shown in Figure 2.

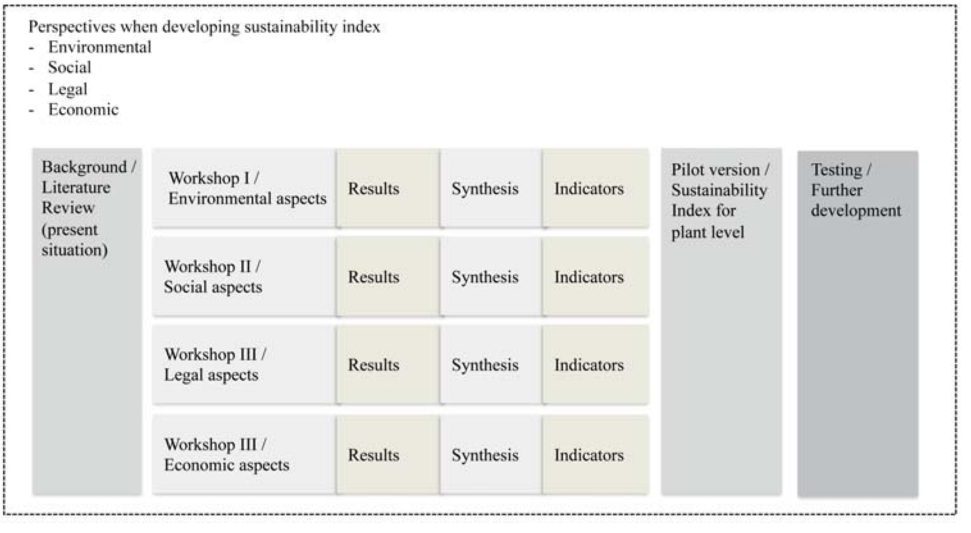

Figure 2. **Structure of the development work for the sustainability index**

The novel index is the right answer to the pronounced demand for a sustainability performance measurement tool supporting both strategic and operational management at plant level. The index also supports the internal and external communication needed for customers, local communities, authorities, shareholders, investors, media, and others. Combining both broader sustainability performance assessment and traditional environmental control methodology, the new tool opens a highway for further research and development work. By encompassing all associated impacts, the index captures the full environmental, economic and social sustainability performance of an industrial plant. Index structure is presented in Figure 3.

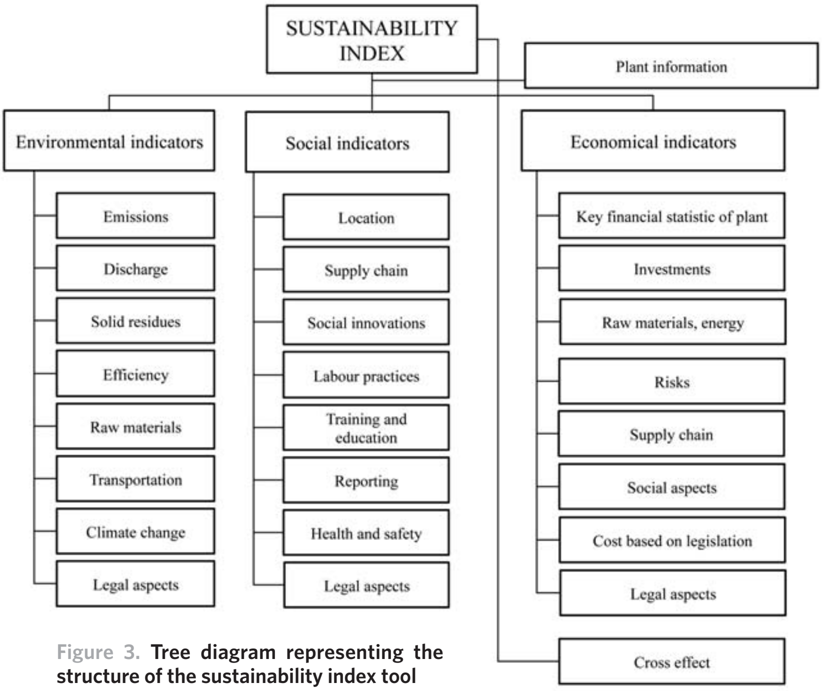

Figure 3. **Tree diagram representing the structure of the sustainability index tool**

The project underlines the importance of comprehensive industrial sustainability evaluation. It was shown that by integrating the concept of sustainability into companies' decision-making processes, the stakeholders are able to achieve a deep understanding of the effects of different actions on a broad scale. Besides providing information for the plant's internal use, plant-level evaluation also covers environmental, social and economic impacts on the surrounding society and, in the broadest perspective, its own contribution to global sustainability challenges.

Figure 4. **Concentrator plant (Copyright © Outotec)**

PROJECT NAME

WP 4 Life-cycle Management and Environmental Footprint

METRIC

CONTACT PERSON	PARTICIPANTS (ORGANISATIONS)	PROJECT DURATION	PROJECT VALUE (EUR)
OLLI DAHL AALTO UNIVERSITY **ILKKA KOJO** OUTOTEC OYJ	**AALTO UNIVERSITY** **OUTOTEC OYJ** **OUTOKUMPU OYJ** **RAUTARUUKKI OYJ**	**2009 – 2014**	**1.095 MILLION**

Metrics of Environmental Efficiency for Metal Production Technologies

Main targets & motivation

Many sustainability assessment methods have been developed over recent decades for evaluating the sustainability of companies and their processes. The metal production industry is facing growing demands for improvement in its environmental and social performance while sustaining economic competitiveness. There is also extensive focus on sustainability measurement at the EU level. These and similar developments in the overall operational environment, coupled with customer demand, constitute significant drivers for industry towards continuous improvement and better control of operations in this field. Greater awareness of overall sustainability issues is therefore needed in order to address the on-going and emerging challenges in this branch of industry.

In recent years sustainability has played an important role in every kind of policy, and there has been increasing public awareness of the limits of the environment. Nowadays, however, the indicators of industrial sustainability primarily satisfy the needs of corporate management and global investors. The information is often broad and non-specific, and sometimes even gives a false impression. Contradictions between environmental, economical and social aspects also point out the unreliability of existing sustainability indexes. This state of affairs serves the interests of neither industry nor the policy makers concerned with industry.

Current corporate sustainability indexes and indicator systems need to be assessed using scientific methods, and their strengths and weaknesses identified. This requires quantitative and qualitative assessment and synthesis of existing indexes and indicator systems. This assessment and synthesis provides new data on the functionality of existing corporate sustainability indicators and lays the foundation for the development of a new, more balanced sustainability index.

The overall goal of the research project was to develop an assessment tool for plant-level operations based on a sustainability metric. This would take into account all sustainability dimensions, including the costs of different intertwined options. The tool would support informed decision-making within industry by assessing the sustainability of plant-level operations and integrating the concept of sustainability into industrial decision-making processes. Typically, sustainability assessment methods tend to focus on company-level assessment. The assessment in this project focused instead on plant level, and was broadened to cover the impacts of the supply chain. The adoption of this approach enables a comprehensive assessment of the causes of different actions, one that takes account of the impacts outside the plant boundaries.

Results

The scientific steps taken in the project were a search of the literature on sustainability in heavy industry and on sustainability indexes, creation of a sustainability index model, testing of the sustainability index in selected plants, and publication of the research results in scientific journals. The project's technical goal was to develop a sustainability index tool (as simple and workable as possible) for metal processing industry.

The index that was developed consists of main indicators, each main indicator containing several sub-indicators formed by comparing actual process values to average BAT-values or other verified sources. Evaluation of the environmental performance of the plant is therefore based on the objective numerical data.

The legal and policy research was treated inclusively and covered the project's technical, social and economic sectors. Legislative evaluation used EU legislation as its framework.

Company representative's comments

Today there is an increasing need for producing enterprises to report their activities transparently within a sustainability framework. This arises from needing not only official permission to operate, but the social licence to do so. Beyond financial and environmental performance, it is increasingly important for enterprises to report on social aspects related to their operations. With continuous improvement lying at the heart of sustainability, it is essential to find representative indicators. These should not only measure something with real meaning to the enterprise, but, most importantly, create the opportunity to set new targets in the sustainability context – in other words, to aim for a better level of operations within the environmental, social and economic dimensions.

The measurement of sustainability is an area that is developing continuously. To give an example, as I am writing this, in 2014, there is a large pilot campaign under way in the European Union. The aim of the campaign is to develop rules for use in measuring the environmental footprint of products and industrial operation based on LCA methodology. This shows that both the methodologies and the science behind measuring the influence of a product or an operation (for example metals production) are still in the development phase.

The main target in this project was a more thorough study of the indicators used to measure sustainability, coupled with development of a set of indicators that, despite having a clear scientific background, would be relatively easy to measure on the basis of the operational data. Legal aspects were also very much in focus. Rather than enterprises simply complying with the stipulated legal minimum, the sustainability perspective demands a focus beyond the regulations towards continuous improvement in operations. This cross-fertilisation of the different sciences served to make the work in this project highly interesting and fruitful.

The sustainability index tool developed here may still need some further work. The reasoning and background for the indices selected in the tool is nevertheless much clearer now than before. The motivation for use in reporting – and especially in finding the most relevant targets for continuous development of the processes – is high.

Director **Ilkka Kojo**, Outotec Oyj

Key publications

1. Husgafvel, R., Pajunen, N., Virtanen, K., Paavola, I-L., Päällysaho, M., Inkinen, V., Heiskanen, K., Dahl, O. & Ekroos, A. (2014), Social sustainability performance indicators – experiences from process industry. International Journal of Sustainable Engineering. www.tandfonline.com/doi/full/10.1080/19397038.2014.898711 #.UzMb4ijR3wz [accessed 27.3.2014].
2. Päällysaho, M., Pajunen, N., Husgafvel, R., Wierink, M., Paavola, I.-L., Heiskanen, K., Dahl, O. & Ekroos, A. (2012), Metrics for Sustainable Production in Process Industry. Conference article. XXVI International Mineral Processing Congress, IMPC 2012 "Innovative Processing for Sustainable Growth" New Delhi, India, 24–28 September 2012.
3. Virtanen, K. (2013), The Use of Sustainability Indicators in Industrial Applications. Master's thesis, Aalto University.
4. Husgafvel R., Pajunen N., Päällysaho M., Paavola I-L., Inkinen V., Heiskanen K., Dahl O. & Ekroos A. (2013), Social metrics in the process industry – background, theory and development work. International Journal of Sustainable Engineering, published online 14 June 2013. www.tandfonline.com/doi/full/10.1080/19397038.2013.800166
5. Päällysaho, M. (2011), Exergy as an environmental efficiency metric - opportunities and challenges. Master's thesis, Aalto University.

Number of publications: 19

Number of conference publications/presentations: 23

Number of Doctoral and Licentiate Theses: 1

Number of Master's Theses: 3

Networks and international co-operation

The results of the METRIC project were presented at many international conferences during the ELEMET programme period (2009–2014).

Applications & impact

Sustainability index tool, pilot version.

The results of the project are directly applicable to the development of sustainability control methodology within process industry through process-integrated intelligence. The implications of existing global sustainability indices and standards for the development of process industry sustainability control methodology are demonstrated. The results will contribute to 1) the modernisation of process industry decision-making and strategic planning, with special emphasis on sustainability control and energy and material efficient processes, 2) informed decision-making and strategic planning within process industry through novel control methods that cover multiple aspects in an integrated manner, and 3) advancement of the sustainable use of natural resources and clean technologies as key elements of the future competitive advantage of process industry. The new sustainability tool will improve mutual trust among different stakeholders, and facilitate transparent knowledge exchange between the corporation and the surrounding society, including interest groups and individual citizens. It will also improve the quality of information needed in the assessment of the ethics of investment.

The development of sustainability metrics for process industry is based on a thorough literature research, including review of existent sustainability indices. A regulative and policy approach was included as a background to the project, being one of the drivers towards sustainability, in academic research in articles and certainly in the index.

The project witnessed two Master's theses published on exergy analysis, and one on the sustainability index that had been developed under the project.

WORK PACKAGE 5:
Innovative Simulation Tools for Metallurgical Processes

New advanced modelling platforms were developed that allow coupling of chemical reactions and physical transport phenomena in metallurgical processes, and predicting of the evolution of structure and material properties from liquid to solid state and during subsequent processing until rolling and thermo-mechanical processing.

PROJECTS:

- Modelling of Microstructure and Properties of Materials from Casting to Rolling Process (MOCASTRO)
- Development of Hot and Cold Rolling Processes by Novel Process Modelling Methods (NoProMo)

PROJECT NAME

WP5 Innovative Simulation Tools for Metallurgical Processes

MOCASTRO

Modelling of Microstructure and Properties of Materials from Casting to Rolling Process

"Seeing inside steel" – improving steelmaking with new simulators

Novel comprehensive simulators were constructed in the MOCASTRO project to describe different process stages in steelmaking industry – from liquid through the solidification, cooling and solid stages to reheating. The development work made use of multiphysical models with advanced mathematics and optimising algorithms. The models have been developed in Finnish universities in cooperation with international universities and research facilities. Based on the laws of physics, these can be used in a wide range of applications. The models are accepted and validated by a large group of researchers worldwide.

Figure 1. **Teamwork to achieve top results in steelmaking**

Figure 2. **New simulators using several physical models offer tools for analysing existing and new steel grades to enhance quality and cost efficiency**

The simulators that have been developed make it possible to "see inside" the products and find explanations and answers to important phenomena in each process stage. Simulators also decrease significantly the time needed to bring new or 'new-for-the-plant' products into production. This is because all the critical process parameters can be determined beforehand, dispensing with time-consuming laboratory and production trials.

Where they understand the phenomena and are able to control them in different process stages, simulators can be used as powerful new tools for improving internal and external quality and material properties, and for designing new products. Improved quality decreases quality costs and increases productivity as products can be made 'right first time'. With enhanced material properties, the products can be used in a wider range of applications. With new products, the steel mill can take market share from more expensive materials.

Industrial relevance

"Simulation t*ools are useful for us in developing new special steel grades. Several new products were developed and launched during the project. The enhanced properties of these products improve end-product energy and material efficiency, and extend their useful life, thereby promoting sustainability."*

Kari Ojala*, Vice President Hot rolled plate and strip products, Ruukki Metals Oy*

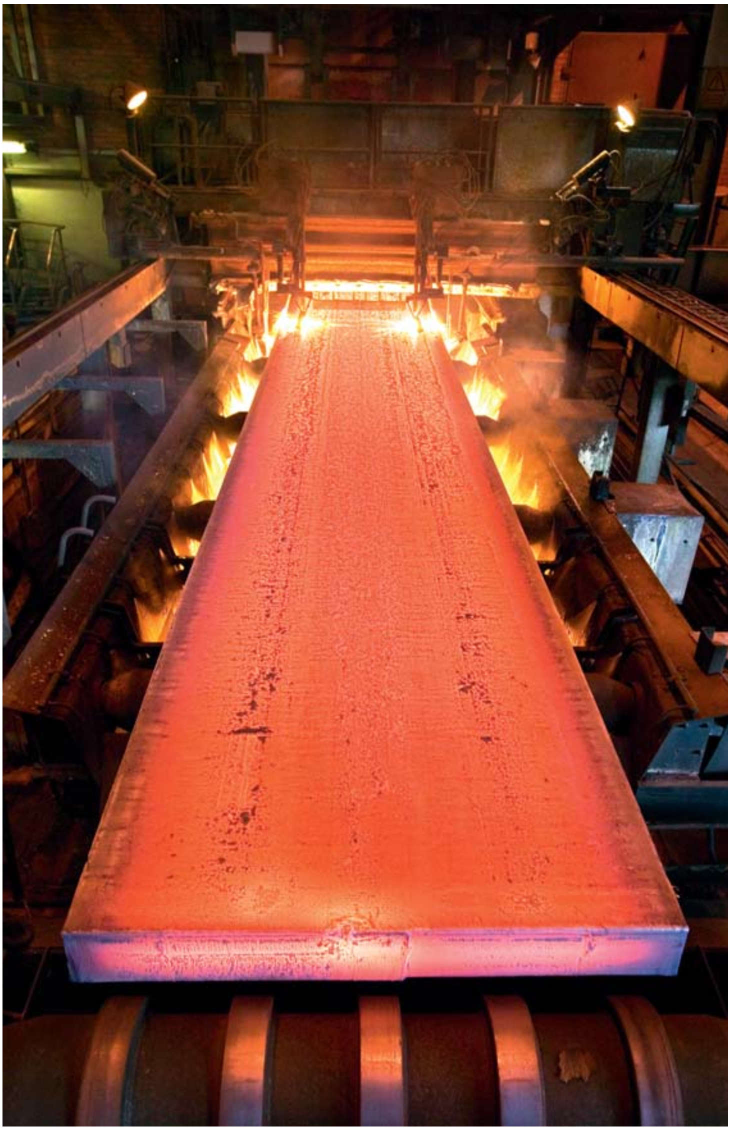

Figure 3. **Right first time! – slab-cutting after successful casting of a new steel grade (Ruukki Metals, Raahe)**

PROJECT NAME

WP5 Innovative Simulation Tools for Metallurgical Processes

MOCASTRO

CONTACT PERSON

SEPPO LOUHENKILPI
AALTO UNIVERSITY, SCHOOL OF CHEMICAL TECHNOLOGY

MERVI LEINONEN
RUUKKI METALS OY

MARKO PETÄJÄJÄRVI
OUTOKUMPU STAINLESS OY

PARTICIPANTS (ORGANISATIONS)

AALTO UNIVERSITY
UNIVERSITY OF OULU
RUUKKI METALS OY
OUTOKUMPU STAINLESS OY

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

6.348 MILLION

Modelling of Microstructure and Properties of Materials from Casting to Rolling Process

Main targets & motivation

The aim of the project was to develop models for predicting the evolution of microstructure and properties of the material from liquid to solid state and during subsequent processing steps: cooling, heating, rolling and heat treatment. The models include simulation of solidification, phase transformations and formation of non-metallic inclusions and precipitated phases.

The developed models will be coupled with the process models in the industrial MOCASTRO project. The longer-term objective is to improve process control and steel quality in the Finnish steel industry, but also to increase the knowledge of the phenomena in the studied processes. One challenging goal is to apply the models in developing and manufacturing new advanced steel grades.

The project is of great strategic and operational importance for Finnish steel producers in that it provides a novel simulation platform that results in less defects and stricter control of material properties. This means improved quality and increased productivity and yield. It will also open superb potential for development of new value-added products by applying simulation tools and by searching for optimal production methods and routes to achieving the desired structure and properties for materials.

Results

- CastManager; Continuous casting simulator calculates strand temperatures, cooling conditions and quality of steel based on casting machine construction and process parameters.
- SlabManager; Slab simulator tracks each slab after cutting in the casting machine and calculates slab temperatures, hydrogen removal and defect probabilities.
- IDS (InterDendritic Solidification); Model package for the simulation of solidification phenomena of steels from liquid state to room temperature including microstructure and material properties.

Key publications

1. Barcellos, V. K., Gschwenter, V. L. S., Kytönen, H., Santos, C. A., Spim, J. A., Louhenkilpi, S. & Miettinen, J. (2010), Modelling of Heat Transfer, Dendrite Microstructure and Grain Size in Continuous Casting of Steels, Steel Research Int., 81 (6), pp. 461–471.
2. Louhenkilpi, S., Laine, J., Miettinen, J. & Vesanen R. (2013), New Continuous Casting and Slab Tracking Simulators for Steel Industry, Materials Science Forum Vol. 762.
3. Miettinen, J., Louhenkilpi, S., Kytönen, H. & Laine, J. (2010), IDS: Thermodynamic–kinetic–empirical tool for modelling of solidification, microstructure and material properties, Mathematics and Computers in Simulation, 80 (7), pp.1536–1550.
4. Miettinen, J., Louhenkilpi, S., Wang, S., Kytönen, H., Laine, J., Hätönen, T., Petäjäjärvi, M. & Hooli, P. (2010), Modelling of microstructure in steel continuous casting: overview and presentation of the IDS tool, Int. J. Mechatronics and Manufacturing Systems, Vol. 3, Nos. 1/2.
5. Petäjäjärvi, M., Klug, J. L., Hooli, P., Heller, H. P. & Scheller, P. R. (2012), Industrial mould slags for continuous casting of stainless steel – analysis of the crystallisation behaviour using the Single Hot Thermocouple Technique, Molten12, Peking, China.

Number of publications: 53
Number of Master's Theses: 5

Networks and international co-operation

1. Centre of Excellence on Soft Computation in Material Science and Engineering / Bengal Engineering & Science University, India (BESUS).
2. GTT Technologies, Germany (GTT).
3. University of Illinois, Urbana-Champaign (UIUC).
4. University of Rio Grande do Sol (Brasil) (URGS).

Applications and impact

Benefits of the MOCASTRO project are increased knowledge of solidification phenomena, improved inner quality of slabs, increased knowledge of hydrogen removal, and the effect of hydrogen content on the crack susceptibility of heavy plates. Thanks to the developed simulators, post-simulation of casting and slab handling processes is now possible in cases where certain defects have been observed. It is also possible to simulate new steel grades before casting. Improved inner quality has enabled the manufacture of new special steels and thickness ranges, while yield and cost-efficiency have also been improved.

PROJECT NAME

WP5 Innovative Simulation Tools for Metallurgical Processes

NoProMo

Development of Hot and Cold Rolling Processes by Novel Process Modelling Methods

Developed approaches enable the development and production of steels for demanding applications in terms of microstructure evolution during hot rolling and dimensional ranges during cold rolling

Significant results in steelmaking were produced in all three of NoProMo's sub-projects. In "Numerical modelling of the slab reheating process", the main achievement was to obtain 4% lower energy consumption in hot rolling. The key outcome in "Modelling of microstructure evolution during hot plate rolling" was a substantial increase in toughness through modifications in the rolling pass schedule, while thanks to "Prediction model for tailor-made cold rolling" the steel mill can now use larger dimensional ranges in terms of steel thickness and width, and produce new and better steel products. Other major achievements could also be mentioned.

The common factor uniting these sub-projects lay in satisfying the ever-increasing requirements set for the dimensional and mechanical properties of low-carbon ultra-high-strength steels. Modelling of steel production processes makes use of the development work for new steel products and of dimensions with the desired micro- and macroproperties. This shortens the time from inquiry to customer delivery and minimises energy consumption.

Figure 1. **A coil of cold-rolled steel (Ruukki Hämeenlinna Works, Finland)**

Sub-project "Numerical modelling of the slab reheating process"

Slab reheating prior to strip or plate hot rolling is an energy-consuming process. It is thus vitally important to reduce energy consumption while at the same time enhancing furnace operating performance. The key results of this project are given as follows:

- Improvement of the energy efficiency of one of the reheating furnaces at Ruukki's Raahe Works. A 4% drop in energy consumption has been realised against the original target of 2%.
- Development of a CFD model to simulate combustion and flow characteristics inside the furnace, together with a sound understanding of the thermal behaviour of a steel slab.
- The CFD model has been used to help minimise temperature differences between furnace rows.
- Reliable measured slab temperature data from the pusher-type reheating furnace.
- Decrease in target temperatures for slabs.
- Reduced austenite grain sizes prior to hot rolling. Abnormal grain growth has taken place at the previously used higher reheating temperatures (Figure 2), and can now be avoided (Figure 3).

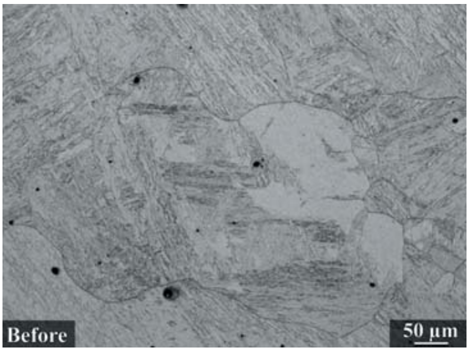

Figure 2. **Reheated austenite grain sizes before the project (magnification x 10)**

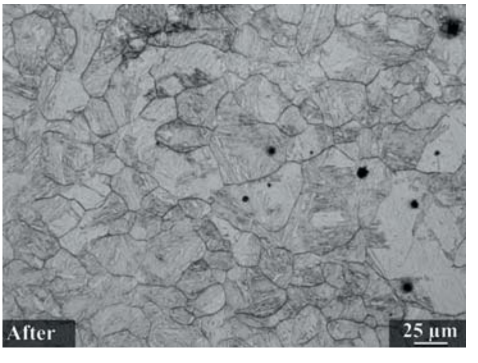

Figure 3. **Reheated austenite grain sizes after the project. Austenite grain size is 27 microns (magnification x 20)**

Sub-project "Modelling of microstructure evolution during hot plate rolling"

While model predictions regarding rolling force and torque are frequently built on simplified calculations for the sake of computational time, predictions for grain size distribution require local values for important deformation variables such as strain, strain rate and temperature. The strain and strain rate distribution over the plate thickness direction has been described by means of a Finite Element Method (FEM) study consisting of a large range of plate thicknesses and pass reductions. Finally, the kinetics of restoration and the austenite grain size evolution are described by a comprehensive set of semi-empirical formulations.

Results summary:

- Development of a microstructural model that predicts austenite grain structure evolution in hot rolling process.
- The key outcome of the methodology is illustrated in Figure 4, showing the measured impact energy behaviour at –40 °C using two different industrial rolling pass schedules. This result confirms that the new approach enables the development of quenched and tempered structural steels for demanding applications at low temperatures.
- Industrial scale validation tests showed good accuracy of the predicted austenite grain sizes compared to actual measurements.
- The novelty feature of the project is the offline microstructural model for novel ultra-high strength steels. The main added value was successful application of the model in development work for heavy gauge structural steel family for demanding applications.

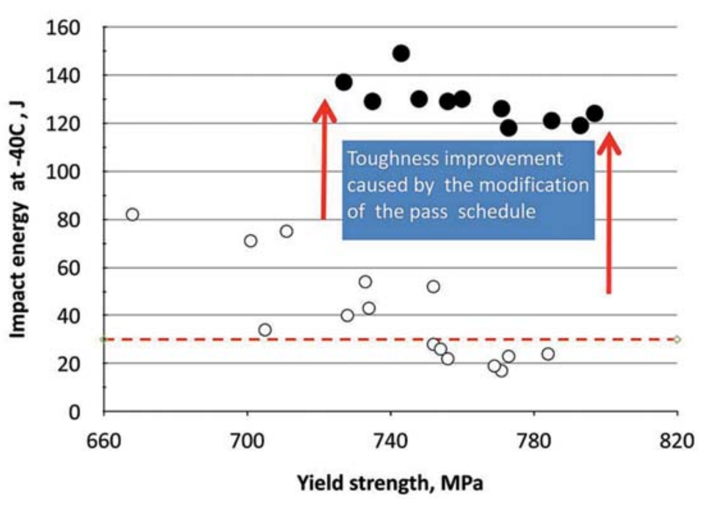

Figure 4. **Impact energy behaviour at –40 °C using conventional (white dots) and optimised (black dots) rolling pass schedules**

Sub-project "Prediction model for tailor-made cold rolling"

The processability of the new steel grades and dimensions can be predicted more accurately by using up-to-date results from the analysed process data. The production programme of high strength steels has been extended through use of a rolling prediction model, dispensing with the need for time-consuming rolling tests. Better delivery accuracy and new steel products have also been achieved during the project.

Results summary:

- New dimensional ranges in terms of steel thickness and width, as well as new steel products, Figure 5
- Faster response to customer inquiries
- More accurate pass schedule calculation for advanced high-strength steels (AHSS).

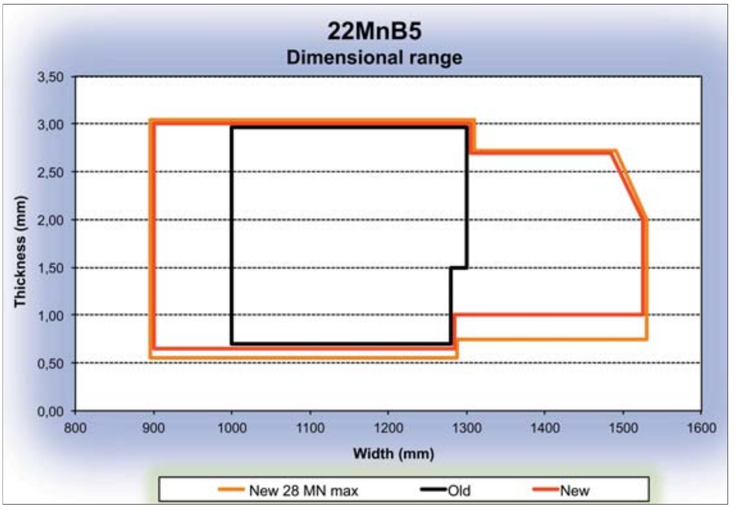

Figure 5. **The increase of dimensional ranges for cold-rolled boron steel 22MnB5 using the newly developed rolling prediction model and existing mill production data**

PROJECT NAME

WP5 Innovative Simulation Tools for Metallurgical Processes

NoProMo

CONTACT PERSON

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UNIVERSITY OF OULU

KATI RYTINKI
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JARI LARKIOLA
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PARTICIPANTS (ORGANISATIONS)

UNIVERSITY OF OULU
RUUKKI METALS OY
VTT

PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

1.415 MILLION

Development of Hot and Cold Rolling Processes by Novel Process Modelling Methods

Main targets & motivation

Achieving the necessary reheating furnace control accuracy requires a sound understanding of the interactions between combustion, fluid dynamics, external heat transfer processes and changes in slab internal energy due to solid-state phase transformations. In the previous Computational Fluid Dynamics (CFD) studies, the thermal and microstructural behaviour were mainly studied separately without the essential coupling between these phenomena. Dominating processes were merged in this project to achieve better temperature control during the reheating process.

Another important target was the development of microstructure models that are valuable tools in predicting the microstructural evolution, and predict precisely the real-time austenite grain size during heavy plate rolling.

The third important target was set as the development of a virtual cold rolling platform, which includes pre-calculated simulations and a monitoring system for determining accurate setup values and rolling schedules. The prediction model speeds up development work for the new steel products and dimensions. This will shorten the time from inquiry to trial, and onwards to customer delivery, and reduces any unwanted processing of coils and excess scrap.

Results With the aid of numerical and physical simulation, and production-scale reheating furnace experiments, we were able to show that the applied temperature–time path has a significant impact on the average grain size and grain size distribution.

To prevent abnormal grain growth during reheating, it is necessary to avoid too high a temperature and/or too long an annealing time, so that the pre-existing titanium nitride (TiN) precipitates effectively inhibit grain growth for the titanium-microalloyed steel studied in this work. These computational and experimental observations have also been verified through industrial plate mill scale production tests.

The key factor in austenite conditioning and grain refinement is a sound understanding and description of recrystallisation kinetics and grain size after full recrystallisation and grain coarsening. Furthermore, for the titanium-microalloyed steel that was studied, the two main factors that influence recrystallised grain size are strain and grain size before deformation.

To predict recrystallisation behaviour more accurately than is possible with temperature-compensated pseudo-time methods based on the additivity principle, we have developed a method for evaluating the Kolmogorov-Johnson-Mehl-Avrami equation applied to non-isothermal conditions using a temperature–time domain transformation based on a second-order polynomial.

With the aid of the simulation tool developed during the project, we have found that appropriate controlled rolling in a non-recrystallisation regime drastically improves the mechanical properties of ultra-high-strength steel plates. This enables the development of quenched and tempered structural steels for demanding applications.
The flatness and hot strip thickness profiles were decomposed into independent components by means of Chebyshev polynomial coefficients.

Virtual-sensors were used to estimate hard-to-measure variables and to detect automatically deviations in rolling values and friction conditions.

The project also embraced development of a feature extraction principle and hierarchical defect classification for automatic quality monitoring.
The processability of the new steel grades and dimensions are now predicted more accurate by using up-to-date results from the analysed process data, which has speeded up the development work for new steels and dimensions.

Expansion of the dimensional ranges has brought an extension of the production programme for the Hämeenlinna works through more advanced precalculation using the cold rolling prediction tool.

Better quality and yield in the form of less head- and tail-end scrap because of more accurate pass schedule calculation. Rolling values are better, being already within the limits for the first coil, so that quality factors such as thickness and flatness are achieved sooner during rolling.

Key publications

1. Larkiola, J., Nylander, J., Verho, M. & Judin, M. (2010), Virtual rolling quality system for cold rolling. Steel Research International, 81(9), pp. 170–173.
2. Martin, D. (2010), Application of Kolmogorov-Johnson-Mehl-Avrami equations to non-isothermal conditions. Computational Materials Science, 47(3), pp. 796–800.
3. Pyykkönen, J., Suikkanen, P., Somani, M. & Porter, D. (2012), Effect of temperature, strain and interpass time on microstructural evolution during plate rolling. Journées Annuelles de la SF2M 2012 / SF2M Annual Meeting 2012. Matériaux & Techniques Hors-série V100 2012, EDP Sciences. S1-17 - S1-19
4. Somani, M.C., Pyykkönen, J.M., Porter, D.A. & Karjalainen, L.P. (2011), Recent advances in physical simulation and modelling for innovative approaches to the processing of steels. In International conference on advances in analytical techniques and characterization of materials, 2011.

Number of publications: 6
Number of Master's Theses: 1

Networking and international co-operation

International co-operation

Jernkontoret, Sweden, Lowwear-WP2 Cold Rolling
Swerea/Mefos, Sweden, Rollgap Sensors

Participation in international conferences

Metal Forming 2010, 19–22.9.2010, Toyashi, Japan
Esaform 2011, 27–29.4.2011, Belfast, Northern Ireland
ATCOM 2011, 5–7.6.2011, Ranchi, India
SF2M Annual Meeting, 17–19.2012, Paris, France
Steel Rolling 2013, 10–12.6.2013, Venice, Italy

Applications & impact

The microstructure model was applied among others in the optimisation of the hot rolling schedule of S690QL grade quenched and tempered structural steel (Optim 700 QL as marketing name). This opened the way for the robust production of S690QL grade steel with good toughness and weldability.

During 2013, Ruukki expanded the thickness range of Optim 700QL steels to 60 mm. As a result, Ruukki is now better able to serve the heavy lifting equipment and mining industries, among others. The properties of Optim 700QL products improve end-product energy and material efficiency, as well as useful life, thereby promoting sustainability.

Intelligent process monitoring (PROMON) and rolling prediction (ROPRE) software were developed for the tandem cold mill. All exceptional customer inquiries are today calculated using ROPRE software, which ensures a fast response.

Other important improvements achieved in the NoProMo project:

- Significantly reduced need for cold rolling tests (13% → 4%).
- More accurate pass schedule calculation for advanced high-strength steels (AHSS).
- Reduced computing time for dimensional range calculations (15 h → 2 h).
- Faster process/product development.
- Extension of dimensional ranges and new steel products (e.g. cold-rolled boron steel 22MnB2 and ultra high-strength formable multiphase steel HCT780C).

WORK PACKAGE 6:
Development of Production Technology for Future Ultra-clean Steel

Dominating physical and chemical phenomena were studied and new process oriented models generated for the secondary metallurgical processes, as well as for ladle treatments, casting area and solidification stages. The research has given a solid scientific basis for the development of advanced ultra-clean steel grades.

PROJECT:

- Advanced Melt Metallurgy (AMMe)

Advanced Melt Metallurgy

Advanced steelmaking through digitalisation of physical phenomena

Unit processes in melt metallurgy of steelmaking share many similar characteristics. These processes can be used e.g. for refining the steel to remove impurities, alloying it with desired elements, and temperature control. Gases are usually injected either directly into the melt via bottom- or side-nozzles or at the steel surface via a top lance. Three common geometries were identified in the project for modelling purposes:

1. **Plane geometry** is employed for reactions between the steel surface and top-blown gas
2. **Bubble geometry** describes reactions between the steel and spherical gas bubbles
3. **Droplet geometry** can be used for reactions both between steel droplets and slag and between slag droplets and steel.

Table 1 illustrates how the three geometries can be used in modelling the dominating phenomena in AOD, BOF, CAS-OB and vacuum degassing processes.

Table 1. **Studied geometries in unit processes**

Process	Plane	Bubble	Droplet
AOD	X	X	X
BOF	X		
CAS-OB	X		X
Vacuum degassing		X	

These models are helpful not only in finding optimal practices, but also in increasing the understanding of the processes. For example, with the vacuum degassing model it was possible to determine how bubble and bath surfaces contribute to the dehydrogenation rate (see Figure 1).

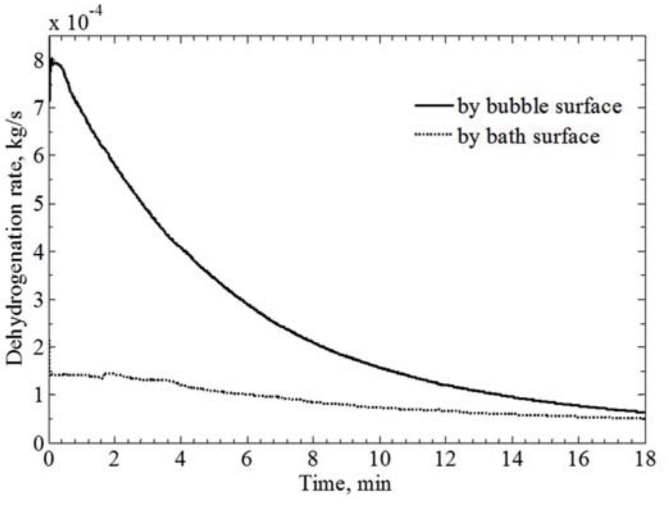


Figure 1. **Dehydrogenation rates by gas bubbles and bath surface in an industrial case**

The reaction models can be operated via user-interface, which not only makes them more user friendly, but also enables fast simulation of different practices.

However, in order to create such reaction models, it is necessary to have an in-depth understanding of the actual physical phenomena. Due to the nature of these processes, not much is seen from outside (see Figure 2) and direct measurement is often either very difficult or even impossible. For this reason, computational fluid dynamics (CFD) was used to study fluid flow behaviour during top- and bottom-blowing and emulsification of slag.

Figure 2. **Gas stirring in a CAS-OB station (Ruukki Metals Oy, Raahe)**

Many important modelling parameters, such as velocities of different phases, size of the slag-free area on top of the steel (see Figure 3) or slag droplet size distributions (see Figure 4) can be extracted from the results. Steel-slag interfacial tension and reactions between gas bubble and liquid steel were also studied.

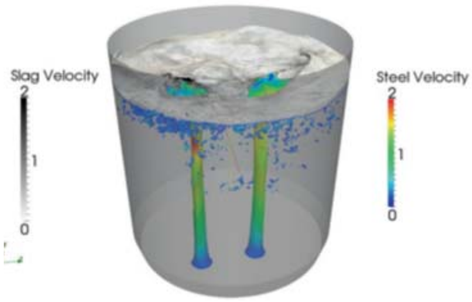


Figure 3. **Velocity of the slag phase at the surface of the melt in the CAS-OB process**

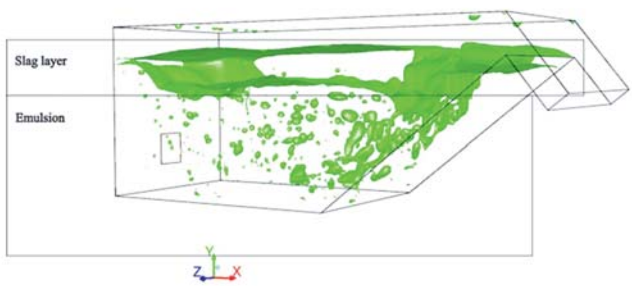
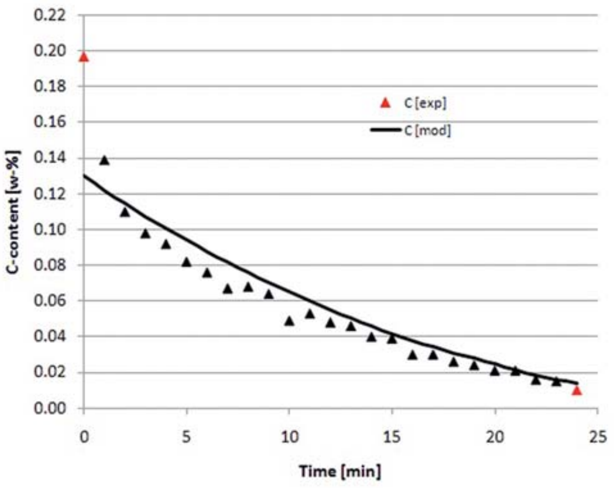


Figure 4. **Emulsification of slag droplets in the CAS-OB process**

A fundamental mathematical model for the AOD process, named "AOD Converter Process Simulator", has been developed and validated. So far, the model has been validated for decarburisation using side-blowing and the reduction stage. The accuracy of model is illustrated in Figure 5. Predicted carbon contents by model are compared to the measured carbon contents during decarburisation. The functionality of the reduction model is described by comparison of predicted and measured chromium (Cr), manganese (Mn) and silicon (Si) contents in steel before and after reduction.

The AOD Converter Process Simulator can be used for off-line simulation at Outokumpu Stainless, Tornio. Off-line simulation can be employed for developing new blowing practices and predicting decarburisation behaviour with varying steel composition.



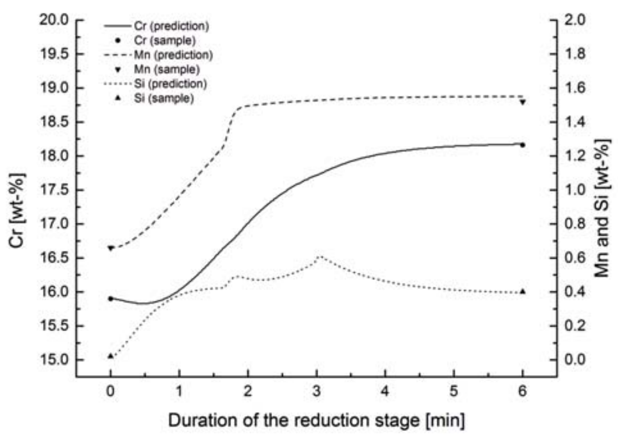


Figure 5. Predicted and measured carbon contents during decarburisation (above) and predicted and measured Cr, Mn and Si contents during the reduction stage (below)

fimecc

FINAL REPORT 5/2014

PROJECT NAME

WP 6 Development of Production Technology for Future Ultra-clean Steel

AMMe

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PROJECT DURATION

2009 – 2014

PROJECT VALUE (EUR)

6.459 MILLION

Advanced Melt Metallurgy

Main targets & motivation

The purpose of unit processes in primary and secondary steelmaking is to refine the steel so that the specified steel composition and temperature are achieved and the steel melt is ready for casting. The employed practices determine to a large extent the quality of the steel, environmental impact and overall economic profitability of steelmaking. Decarburisation, removal of dissolved gases, temperature control and inclusion control are of particular importance to the success of the outcome. In this regard, the Finnish steel industry already stands at high level. To improve existing practices still further, the following main targets were set for the AMMe project:

- Create a set of holistic process-oriented models describing certain phenomena similar to all unit processes in secondary metallurgy
- Develop new concepts for producing advanced steels and ferro-alloys with unit processes in secondary metallurgy
- Conduct industrial case studies related to holistic model development for a variety of unit processes in melt metallurgy, tcarried out by an industrial consortium.

Results

New reaction models were developed for *Argon-Oxygen Decarburisation* (AOD), *Basic Oxygen Furnace* (BOF), *Composition Adjustment by Sealed Argon Bubbling - Oxygen Blowing* (CAS-OB) and vacuum tank degassing processes. These models can be used for improving the productivity of the processes and for reducing their environmental impact. An electrolytic extraction method was developed for estimating the effect of inclusion population on mechanical properties of the final product.

Significant improvements were achieved by the industrial partners. Approximately 30% increase in lifetime of the bottom stirring and increased total lining lifetimes of BOF converters was achieved at Ruukki Metals Oy in Raahe. These improvements help to decrease both maintenance and refractory material costs. At Outokumpu Stainless Oy, the research work resulted in an increased average cast length and in a decreased amount of single cast sequences when producing ferritic stabilised steel grades.

Key publications

1. Fabritius, T., Riipi, J., Järvinen, M., Mattila, O., Heikkinen, E.-P., Kärnä, A., Kurikkala, J., Sulasalmi, P. & Härkki, J. (2010), Interfacial phenomena in metal-slag-gas system during AOD process, ISIJ International, Vol. 50, No. 6, pp. 797–803.
2. Järvinen, M.P., Pisilä, S., Kärnä, A., Ikäheimonen, T., Kupari, P. & Fabritius, T. (2011), Fundamental Mathematical Model for AOD Process. Part I: Derivation of the model. Steel Research International, Vol. 82, No. 6, pp. 638–649.
3. Pajarre, R., Koukkari, P. & Tanaka, T. (2013), Surface tension of a liquid metal-oxygen system using a multilayer free energy model. International Journal of Materials Research, Vol. 104, No. 8, pp. 736–747.
4. Visuri, V.-V., Järvinen, M., Sulasalmi, P., Heikkinen, E.-P., Savolainen, J. & T. Fabritius, T. (2013), A Mathematical Model for the Reduction Stage of the AOD process. Part I: Derivation of the Model. ISIJ International, Vol. 53, No. 4, pp. 603–612.
5. Yu, S. & Louhenkilpi, S. (2013), Numerical Simulation of Dehydrogenation of Liquid Steel in the Vacuum Tank Degasser. Metallurgical and Materials Transactions B, Vol. 44, No. 2, pp. 459–468.

Number of publications:	43
Number of Doctoral Theses:	1
Number of Master's Theses:	8

Networks and international co-operation

International co-operation

1. Aalto University: co-operation with steel plants Riva Caronno (Italy) and VASD (Austria).
2. Aalto University/University of Oulu: co-operation with Cybernetica AS (Norway).
3. Aalto University/University of Oulu: upcoming joint post-graduate course with KTH Royal Institute of Technology (Sweden) on Computational Fluid Dynamics.
4. University of Oulu: research exchange at RWTH Aachen University (Germany).
5. VTT: co-operation with Osaka University (Japan).

Participation in international conferences

1. SIMS2010 (Finland)
2. INFACON XII (Finland)
3. 38th International Conference of SSCHE (Slovak Republic)
4. STEELSIM2011 (Germany)
5. EOSC2011 (Sweden)
6. CleanSteel 8 (Hungary)
7. SCANMET IV (Sweden)
8. CSSCR2013 (Finland/Sweden)
9. ICPNS '13 (Finland)

Applications & impact

The following models and methods were developed:

- Holistic reaction models for *Argon Oxygen Decarburisation* (AOD) and *Composition Adjustment by Sealed Argon Bubbling – Oxygen Blowing* (CAS-OB) processes. These can be used for improving the process practices in order to improve energy efficiency and to maximise yield of alloying materials.
- CFD-based model for vacuum tank degassing, which can be used to determine the optimal deep vacuum time.
- Electrolytic extraction method; a new method for studying the effect of inclusion population on mechanical properties of the final product.

Main improvements achieved:

- Increased understanding of 1) fluid flow behaviour during top- and bottom-blowing, 2) steel-slag interfacial phenomena, particularly emulsification of slag and steel-slag interfacial tension. The knowledge obtained has been applied in the development of the process unit reaction models.
- Improved productivity and decreased refractory lining costs through improved lifetime of bottom stirring and lining in the *Basic Oxygen Furnace* (BOF) process.
- Improved productivity of stabilised ferritic stainless steel grades.

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