DIMECC

FINAL REPORT 1/2018

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FLEX – Flexible and Adaptive Operations in Metal Production

2017 – 2018

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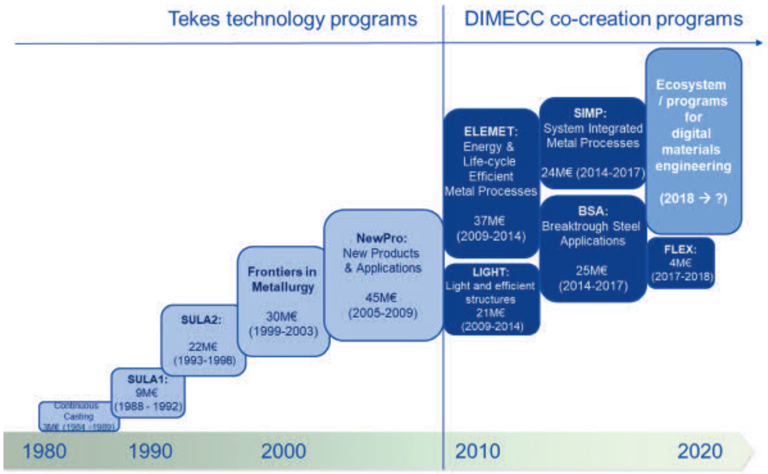
Co-creation Is an Elemental Part of Renewal in the Metals Industry

On July 3rd in 2017, we published our report, LAB – FAB – APP, to direct the future of European research and innovation (R&I) landscape in the form of a ninth framework program (FP9). The report was given by a high-level group (HLG) chaired by the former trade commissionaire Pascal Lamy and nominated by the R&I commissionaire Carlos Moedas. The primary target of our HLG was to maximize the impact of European R&I programs.

In LAB – FAB – APP, we give eleven recommendations to Europe. They all are based on the idea of investing in the European future that we want. It is about what we Europeans want for Europe, and implementing it. Extremely simple. We have the scientific evidence on how different scientific and research mechanisms impact our society, companies, and structures, and we know what we want from R&I funding as outcomes: jobs and growth.

One of our eleven recommendations is to increase the volume and share of mission-driven research. Companies, businesses, the European Commission, and taxpayers will be asked to define the missions that we fund in Europe, and to help in executing them. Why did we end up with such a recommendation? We have both statistical and qualitative evidence based on the empirical field work in forerunning countries, with novel R&I models and under unconventional leadership, that classical call-based research-oriented proposal writing and project execution may not produce the highest impact. In contrast, these all may be needed, but they may boost jobs and growth more when applied in novel combinations with private-sector leadership, non-hierarchical participation, and heterogeneously open ecosystems.

One of the most forerunning, novel, and unconventional R&I set-ups in Europe is DIMECC, our multi-organizationally owned innovation platform. We, meaning the more than 2 000 dedicated and creative people from companies and research institutes and Business Finland, have facilitated the digital transformation and co-creation activities of manufacturing industries, including the metals industry, in Finland since 2008. The time-to-market and innovation probability of the players on our platform have improved dramatically. We do not talk about incrementality, we talk about 20-fold pay back for R&I investments, as our 2017 customer survey show-cased, and speeding up R&I work by hundreds of percentage points. The almost 40-year continuum of metals industry co-creation and renewal programs is visualized in the figure below.



The almost 40-year continuum of metals industry co-creation and renewal programs

The future of metals industry co-creation activities and operations is now under construction. This has been the situation many times in history. With strengthened conceptualized and systemized co-creation services for all the different phases of the innovation funnel, DIMECC is ready to take a new step toward metals industry renewal execution. However, a lot of new co-creation and the service buzz around it will not work without the most evident competitive advantage of our innovation platform: the wide range of competencies and knowledge of our shareholders, which forms a unique set-up for all kinds of match-making in Europe. It is easy to build renewal on a proven track-record in impact and outcomes.

In this report, the latest metals industry results from our FLEX program are available. Enjoy reading!

Dr. **Harri Kulmala**
CEO
DIMECC Ltd.

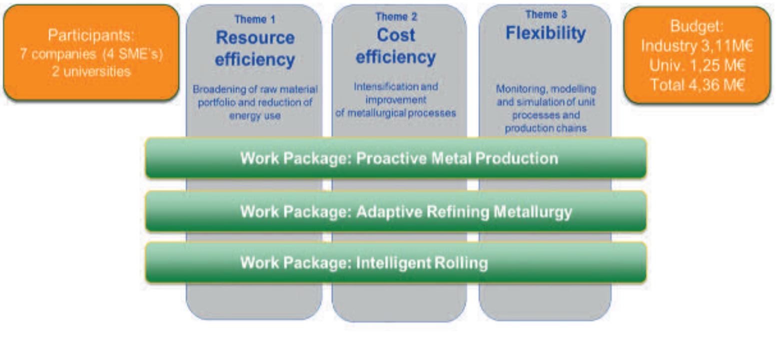
Cross Fertilization of Ideas and Knowledge

FLEX in DIMECC´s FLEX program stands for Flexible and Adaptive Operations in Metal Production. The program has been carried out by a consortium consisting of Outokumpu, Outotec, SSAB, Casim Consulting, Luxmet, Sapotech, and SFtec, together with Aalto University and the University of Oulu.

The ambition of the consortium has been to foster new innovations and business, and to strengthen the ecosystem of metal producers, universities, research institutes, and SMEs. The vision of the consortium is a paradigm shift from stiff and reactive production to a flexible and proactive operating mode, while moving the Finnish metal industry toward zero-waste plant and CO_2-lean metal production. The shift necessitates digitalized and interlinked information flows at various levels of the production chain.

The research themes of the FLEX program have been resource efficiency, cost efficiency, and flexibility in metals processing. The activities have been organized in three work packages to achieve the objectives outlined by the research themes. The work packages are:

- Proactive metal production, consisting of iron, ferrochrome, and other ferrometals production
- Cost efficiency, focusing mainly on the processes in the steel mill
- Intelligent rolling, optimizing the processes in both the hot- and cold-rolling mills



One of the main reasons for organizing the research activities in a program, as opposed to executing single research activities on their own, is the cross-fertilization of ideas and knowledge that takes place in a program. Representatives from several companies meet with academic researchers on a regular basis and get an opportunity to share their knowledge with each other at the same time as getting an opportunity to get an overall impression of all activities in the work package or program. When reading the one-pagers presenting the tools developed in the program, it is quite impressive to see the amount that has been developed in collaboration between industry, SMEs, and academia in a relatively short time.

Regardless of the short time-span of FLEX, we had the opportunity to arrange a research seminar at the SSAB Hämeenlinna cold-rolling plant. The seminar was attended by professors, both undergraduates and postgraduates, and industrial researchers. Again, the benefits of collaboration between industry, SMEs, and academia became evident.

DIMECC FLEX Research Seminar attendees at the SSAB cold-rolling plant in Hämeenlinna.

I want to thank all the participants in DIMECC FLEX for an excellent job, as well as for keeping up a very creative spirit. I sincerely hope that this creative and productive spirit will continue far beyond the horizon of FLEX.

Ingmar Baarman
DIMECC FLEX
Program Manager

Flexible Skills for Competitiveness in the Future

Metal production is facing major economic and environmental challenges globally. The main requirements for competitiveness in the future are the capability to response flexibly to changing demands and the ability to produce metal at high cost-efficiency with a reduced environmental load. These demands cannot be met with the existing operational paradigm, but require the implementation of a flexible, new approach. The aim of the program was to foster new innovations and business, and to strengthen the ecosystem of metal producers, universities, research institutes, and SMEs, interlinking data transfer and the exchange of talent specialists. Strong cooperation between academia and the Finnish metallurgical industry requires a very integrated and successful collaborative approach.

An important impact of the DIMECC FLEX program has been its support for resource efficiency, cost efficiency, and production flexibility through digitalization tools, but the duration of the FLEX program was not enough to fully utilize generated know-how. The short duration of the program caused major difficulties in realizing all the potential benefits in full-scale processes. However, the results indicate that the continuous research work that the Metals Producers Ecosystem has been actively doing can also benefit from such short-term investments provided that there is continuity in the form of consequent programs, in the short or longer term. Integrating and utilizing models in an industrial environment brings several constraints in the form of specific hardware and software utilized in the production process. The new models and measurement techniques need to be transferred to user interfaces that the operational staff can understand and manage. The industrial environment brings new challenges to our research and development, which significantly raises the level of complexity.

Despite the short duration of FLEX, two doctoral theses and 29 publications have been produced. However, much more will still be written and published after the program, as new results will be produced until the very end of the program. This not only supports industry, but also emphasizes the importance of metallurgy as a research field among the other less applied research areas in academia. All the theses and publications are based on profound interdisciplinary joint research. This is what we call a positive systemic spillover effect, and the impact is relevant not only to the metal production ecosystem players, but furthermore to economic and qualitative growth in Finland.

More than 36 tools were developed during the program. The ideas behind many of these tools originate from previous DIMECC programs, such as systems integrated metals processing (SIMP). The unique collaboration between the Finnish metal industry and academia supported by DIMECC platform is of fundamental importance to the future success of our industry. The importance of SMEs in the program must not be forgotten, as new tools have been brought to the industry and to academia for further exploration and exploitation. We must not lose the great opportunity to further develop the collaboration, which has shown its strength in getting real benefits and results for the metal industry.

One of the most important enablers for this successful collaboration between industry, SME:s and academia has been the public funding from Business Finland. This funding has been key to achieving the challenging targets of the FLEX-program. We want to direct our gratitude to Business Finland, and we look forward to continuing the co-operation with Business Finland in future programs.

CTO **Jarmo Lilja**
SSAB Europe Oy

Prof. **Timo Fabritius**
University of Oulu

Prof. **Ari Jokilaakso**
Aalto University

DIMECC FLEX Program in a Nutshell

Program Key Characteristics

Company partners (Pcs.): 7

Outokumpu Stainless Oy, Outotec (Finland) Oy, SSAB Europe Oy, Casim Consulting Oy, Luxmet Oy, Sapotech Oy, SFTec Oy

Research institute partners (Pcs.): 2

Aalto University, University of Oulu

Volumes:

Duration:	1.1.2017 – 30.09.2018
Budget:	4,4 M€
Company budget:	3,1 M€
Research institution budget:	1,3 M€
People involved:	Approx. 50 FTE

Results:

Number of publications:	29
Number of doctoral theses:	2
Number of master's theses:	5
Number of bachelor's theses:	3
Number of tools:	36

PROACTIVE METAL PRODUCTION

WORK PACKAGE 2

Antti Kemppainen, Olli Mattila, Timo Paananen/SSAB Europe Oy
Juho Kunelius, Esa Puukko/Outokumpu Stainless Oy
Henri Ervasti, Pasi Mäkelä, Petri Palovaara/Outotec (Finland) Oy
Mikko Jokinen/Luxmet Oy
Juha Roininen, Hannu Suopajärvi/Sapotech Oy
Anne Hietava, Mikko Iljana, Mamdouh Omran, Ville-Valtteri Visuri, Ari Vuokila, Tero Vuolio/University of Oulu
Juhani Heimo, Ari Jokilaakso/Aalto University

Summary of the project's motivation and achievements

Work on Work Package 2 has covered primary production of iron and ferroalloys, mainly ferrochromium. WP2 aimed for improved use of raw materials, a higher utilization rate of byproducts, and flexible use of unit operations. These features are needed to be competitive in today's global markets, where customer quality demands are more stringent, raw material quality is decreasing, and emission limits are stricter. The targets of WP2 were reached using new methods and technologies at different stages of the metal production process, such as raw material treatment, process measurements and analyses, and modelling.

Scientific goals for WP2 were:

- Deepen the understanding of parameters that have an effect on the byproduct agglomerate properties (OU)
- Clarify the phenomena related to the metallurgical properties of agglomerates in various process conditions (OU)
- Precisely identify the relevant phenomena and process variables in hot metal desulfurization that are mandatory for predicting the sulfur content of hot metal, using mathematical modeling and high temperature experiments (OU)
- Deepen the understanding of the thermal conductivity of ilmenite slag (Aalto)

Industrial goals for WP2 were:

- Characterize valuable byproducts and evaluate recycling possibilities in order to reduce waste (Outokumpu)
- Find suitable pre-treatment methods for difficult steelmaking byproducts (Outokumpu)

- Find optimal recipes and raw material properties for byproduct reuse in unit processes (Outokumpu)
- Utilize byproducts through new raw materials (Outokumpu, SSAB)
- Develop new online measurements and control and advisory systems to support a plant-wide expert system and to improve plant productivity, process performance, and sustainability (SSAB, Sapotech, Luxmet)
- Improve off-gas cleaning to support plant performance and sustainability (Outotec)
- Use new materials in smelting technology, such as silicon and FeSi, and further develop the existing process equipment (Outotec)
- Find methods to improve the cost and material efficiency of primary hot metal desulfurization (SSAB)

Key results and impacts

- A full-scale trial with cement-bonded briquettes was successfully conducted in a SAF in Outokumpu ferrochrome production.
- Sapotech's Reveal 360 was installed to monitor the refractories of hot blast furnace ladles at SSAB Raahe Steel Works.
- A 200kW pilot DC furnace was built at Outotec Research Center in Pori to conduct smelting tests on a smaller scale, improving safety and research efficiency.
- Laboratory-scale microwave treatments showed that zinc removal from dust and sludge was rapid and selective. The residue material can be recycled in steelmaking furnaces.
- A high prediction accuracy of hot metal desulfurization was obtained with a parametrized mathematical model.
- A variety of methods were found to increase material and cost efficiency, as well as to reduce the environmental load of hot metal desulfurization.
- A more stable, predictable, and efficient desulfurization process enabled a decrease in the sulfur target in primary desulfurization, leading to released secondary desulfurization and vacuum degasser capacity.

Company impact

"Improvements in desulfurization efficiency enable us to conduct our strategy towards the leading company for special steels."

***Petri Tuominen,** Head of hot metal production, SSAB Europe Oy*

Testing microwave treatments of dust and sludge (Tool 1)

Recently, there has been a growing interest in microwave energy as an alternative heating source. Microwave energy can be applied in the processing of primary and secondary raw materials. Microwave heating is fundamentally different from conventional heating because microwaves can penetrate deep into the sample. This allows sample heating to be initiated volumetrically, as opposed to conventional thermal processing, which heats the sample from the outside inwards via standard heat transfer mechanisms, meaning convection, conduction, and radiation. The microwave heating rate is high and this results in shorter heating times. Therefore, the disadvantages of conventional heating methods, such as large temperature gradient, long processing time, and high energy consumption, can be avoided with microwave heating.

Handling of sludge and dust is always a problem due to difficult material properties. Microwave treatment was tested on some steelmaking dust and sludge at the University of Oulu with the aim of zinc removal and the recovery of valuable metals from the waste. Ferrochrome converter (CRC) and electric arc furnace (EAF) dusts from Outokumpu (Tornio, Finland) and blast furnace sludge (BFS) from SSAB (Raahe, Finland) were characterized and treated with microwaves. The effect of different microwave parameters, such as microwave power, microwave exposure time, and microwave frequency, on the processing of waste was studied. A 1.5 kW power microwave furnace was used in the treatments. The laboratory-scale test results demonstrated that zinc removal was rapid and selective. The residue material can be recycled in steelmaking furnaces.

The microwave absorption ability tests indicated that the CRC and EAF dusts are good microwave-absorbing materials. The highest microwave-absorbing properties for the EAF dust can be attributed to the contents of carbon and iron oxides, which are classified as excellent microwave absorbers. The results indicated that zinc removal efficiency was influenced by the amounts of iron oxide and calcium oxide present in the mixtures.

Utilization of byproducts in ferrochrome production (Tool 2)

One large research topic for Outokumpu was to develop cement-bonded briquettes that are strong enough to be fed into a submerged arc furnace (SAF). The aim was to recycle dust and scale from ferrochromium and steel production. Preliminary laboratory-scale tests to study the effect of water-to-cement ratio on the mechanical strength of briquettes were first carried out at the University of Oulu. After verification of the briquette quality, a full-scale trial with 90 tons of cement-bonded briquettes was conducted in a submerged arc furnace in Outokumpu ferrochrome production. The campaign went well; it proved that it is possible to use briquettes in a SAF, and no effects on furnace power were noticed. The results are also usable in other kinds of recycling processes that use reduction furnaces. That is why the achieved experiences are useful even if another method for recycling is selected and dusts are not recycled by SAF in the future. A new test campaign with a larger number of briquettes is in the planning phase.

Company impact

"The results of the briquette test trial proved that it is possible to use oxide fines as raw material in a SAF. Now it is possible to develop new methods to recycle byproducts in our own processes and reduce the costs of recycling."

Esa Puukko, *Manager, Process Development, Outokumpu Stainless Oy*

Utilization of optical emission spectrum measurement in controlling EAF (Tool 3)

The scrap melting in an electric arc furnace can be evaluated by measuring the light emitted from the electrode hot-spot area. This information can be used for time charging of scrap buckets and optimizing refractory wear. By combining the control of scrap melting with current requirements for the speed of the process, it is possible to optimize the process to increase productivity or process efficiency, depending on the current requirements for the process. The tool was developed by Luxmet, and measurements were made at Outokumpu Stainless EAF1. The aim of the implementation was to reduce refractive power and electrode consumption. The tool integrates EAF optical emission spectrum measurement with intelligent control of electric arc furnace voltage ramps. It combines the novel measurement information with data from other sources to generate deeper understanding of the state of the electric arc furnace process.

Ladle measurement and imaging system (Tool 4)

Sapotech's Reveal 360 was installed to monitor the refractories of hot blast furnace ladles at SSAB Raahe Steel Works (*see Figure 1*). A lance with a measuring head goes inside the ladle, and makes several 360-degree rotations while imaging the refractory surface and measuring the inner dimensions. Data from ladle refractory scanning is transferred to the plant's manufacturing execution system for further use and decision-making. The status and history of ladle refractory condition is therefore always easy to track. The main aims are to increase safety by predicting and avoiding ladle leakages, to optimize the ladle refractory lifetime, and to create information on inner ladle volume as a function of liquid height.

Figure 1. **Sapotech's Reveal 360 installed at SSAB Raahe Steel Works.**

Company impact

"One significant cost in iron production comes from refractories. By commissioning novel measurement technology, the consumption of refractories can be decreased by optimizing the lifetime of hot metal ladles according to the actual wear – a measurement is always more accurate than the human eye."

Markku Vetoniemi, *Production Manager,*
Planning and support functions, SSAB Europe Oy

200 kW pilot DC furnace (Tool 5)

Direct current (DC) arc furnaces have been applied to a number of smelting processes, including chromite and ilmenite smelting. DC technology can also be used for the treatment of solid waste from metallurgical processes. The first smelting campaign with the 1 MW pilot DC furnace was carried out on chromite concentrate at Outotec Research Center in Pori in 2012. In this project, the pilot-scale DC furnace at Outotec Research Center in Pori was modified to conduct smelting tests at 200kW power with less raw material (*see Figure 2*). In a novel process development, the early operation on a smaller scale improves safety and research efficiency and reduces investment in both time and money.

Figure 2. **200 kW pilot DC furnace in operation.**

Company impact

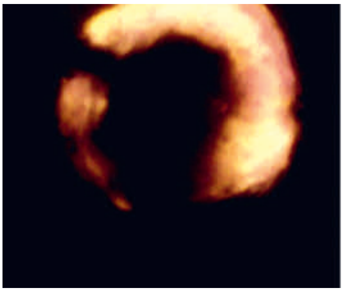
"It is crucial to have state-of-the-art testing facilities and expertise to develop DC arc smelting processes for our customers' needs. A multi-stage scaling-up approach is an excellent way to reduce risks in smelting process development."

***Pasi Mäkelä**, Development Manager,*
Ferroalloys Technology, Outotec (Finland) Oy

Tuyère-raceway simulation (Tool 6)

Combustion modeling was continued in WP2 at the University of Oulu using computational fluid dynamics (CFD). The combustion model was validated with experimental results from BHP Billiton-BlueScope Steel, and the model predicted combustion degree with good accuracy for three different coal types (medium- and high-volatile coals). The model was applied to study the effect of the lance position on PC combustion efficiency and the fouling of the tuyère wall. The particle size distribution used in the CFD model is approximated using measured data from SSAB Raahe. The results from the simulation indicate that the difference in the PC combustion degree with studied lance positions was small, and the lance could be moved to the closest point from the tuyère nose to minimize the fouling of the tuyère walls. The results have been used to aid decision-making in lance positioning. With improved combustion, auxiliary fuel injection can be increased to replace coke, which lowers the costs of iron production. A subroutine was added to the combustion model to report the surrounding atmosphere of each particle in each step. With this approach, the effect on particle combustion atmosphere can be studied for different particle sizes and trajectories, and the results can be applied in experimental studies. A doctoral thesis by Ari Vuokila was finalized on this research topic in this project.

Figure 3 shows tuyère camera images with one lance and two lance PCI practice. Tuyère cameras were installed at SSAB Raahe blast furnaces in the earlier project.



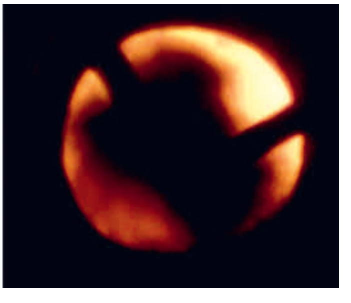


Figure 3. **PC injection with a single lance (left) and a dual lance (right).**

Improvements in hot metal desulfurization (Tool 7, Tool 8, Tool 9)

Sulfur is considered one of the main impurities in hot metal in blast furnace-based steel production. Sulfur originates mainly from coke, but also from other blast furnace input materials, such as scrap, limestone, and pulverized coal. Nowadays, the desulfurization of hot metal is commonly conducted using a powder injection technique.

Increased quantitative and qualitative requirements, and special steel qualities set high requirements for hot metal composition, too. One of the most important components is sulfur in hot metal. In order to develop stability, predictability, and efficiency in primary desulfurization, fundamental research was needed. The development area concerned both reagent quality and injection parameters. The aim of the hot metal desulfurization study was to identify the relevant phenomena and process variables that are mandatory for predicting the sulfur content of hot metal precisely at the end of injection. With the help of detailed system identification, a wide variety of methods was found to increase cost efficiency and material efficiency, as well as to decrease the environmental load of the process. The employed research methods consist of mathematical modeling and high-temperature experiments. The effect of reagent properties on the rate and efficiency of hot metal desulfurization was of great interest in mathematical modeling studies, whereas the properties of the top-slag were studied in high-temperature experiments. The high-temperature experiments were conducted in the Process Metallurgy Research Unit at the University of Oulu. The scope of the work was to reveal and quantify previously unidentified phenomena occurring in the process, and through that to offer a completely new viewpoint for the optimization of the hot metal production chain.

The mathematical modeling studies introduce two separate modeling approaches to desulfurization: parameterized and phenomena-based models. The accurate and computationally fast parameterized models can be applied in online process control, whereas fully phenomena-based models are suited for designing new process practices, such as testing new reagents or lance types. Both of the modeling approaches were exhaustively validated with industrial data.

In addition to quantifying the underlying process dynamics, mathematical modeling can help to reveal a demand for new measurements or introduce new control variables. In WP2, the importance of reagent particle size distribution was established for the prediction of the hot metal desulfurization process. With the help of mathematical modelling, it was established that particle size distribution affects several properties, most importantly the penetrability of the reagent particles in the hot metal and the mass transfer rates associated with individual particles. The achieved research results led to changes in the desulfurization reagent and practice in production. A more stable, predictable, and efficient desulfurization process enabled a decrease in the sulfur target in primary desulfurization. That change correspondingly enables the release of some capacity in unit operations that act as bottlenecks. An interesting aspect of the studied case is the applicability of computational intelligence to the parameterization of the partially phenomena-based models. In the future, the possibility of applying similar computational methods in the system identification task could be a fruitful research topic with economic potential. The next step in improving desulfurization is to optimize injection parameters utilizing combined CFD and the developed particle size model to predict desulfurization efficiency more accurately. One area of uncertainty is correlation between penetration and particle size, especially when particle size is very small (lower than 50 micrometers).

Electrical behavior of a submerged arc furnace's charge materials (Tool 10)

The electrical conductivity of a submerged arc furnace's charge is important because, among other things, it affects the productivity of the furnace. The electrical conductivity of the charge should ideally be low in the higher parts of the furnace and high near the electrode tip. This is to ensure that the electric current path travels through the metal bath via arcing, which provides the most effective heat transfer. Another option for the current path would be through the solid feed material via ohmic conduction, but since this zone is less reactive, the heat energy would be mostly wasted.

Anne Hietava finalized her doctoral thesis on the electrical behavior of a submerged arc furnace's charge materials. This work brings forth new information on the electrical behavior of coke and chromite pellets. The electrical conductivity was measured at room temperature for different simulated process conditions (different coke textures, different reduction degrees of chromite pellets, sulfur in the atmosphere, and replacing the coke used in chromite pellet production with charcoal). It was found that unlike gasification with a CO/CO_2 mixture, heat treatment at 950°C increased the degree of graphitization and changed the electrical behavior of coke. Furthermore, it was observed that increasing the chromite pellets' reduction degree reduced the electrical conductivity measured at room temperature. In the case of chromite pellets and sulfur in the atmosphere, it was found that sulfur affects the pellets' electrical behavior and structure during reduction, which in turn has an effect on the SAF performance when raw materials with varying sulfur content are used. Lastly, it was found that substituting coke with charcoal when producing chromite pellets affects the sintering behavior, cold compression strength, and electrical conductivity of the chromite pellets.

Technology development in production of Si metal (Tool 11)

The silicon smelting process differs from other common carbon-based reduction processes due to the formation of SiC and SiO gas, which significantly influences the reaction paths. Technology supplier Outotec has expanded the electric furnace supply for the silicon process. A diploma thesis was undertaken to investigate reduction behavior and the suitability of raw materials to the process through several smelting experiments at an induction furnace. The production of Si metal is a high-temperature process and more complex than conventional smelting processes. Quartz (silicon dioxide) is quite a stable oxide, and the reduction to Si metal is theoretically possible only if the temperature exceeds 1800°C.

The main observation in this work was that both the amount of reducing agent and the holding time have a significant effect on the formation of Si metal. The metal was formed when the fixed carbon content was less than a half compared to the stoichiometric ratio of the process. A longer holding time increased the amount of metal. In addition, the impurity content of the Si metal decreased with a longer holding time. Experimental research work showed that the silicon smelting process is challenging due to the extremely high temperatures needed for the reduction of quartz. The amount of metal that was formed in the smelting was low.

Thermal conductivity of titanium oxide slag at high temperature (Tool 12)

Knowledge of the thermal conductivity of ilmenite slag is essential for optimizing the ilmenite smelting process. The thermal conductivities of several TiO_2 slags were determined from room temperature to 1700 °C using laser flash analysis for a Master's thesis at Aalto University. This covers both solid and molten states of the slag. Both industrial and synthetic samples were analyzed.

Steel belt condition monitoring system

The concept has been tested at Tornio Ferrochrome plant and a large amount of data was collected during a six-month period. The data is now being processed at Outotec, and the machine vision will be optimized based on the collected data. The next step is to add more measuring devices to cover the whole width of the steel belt.

Technology development in off-gas cleaning in EAF

Wet gas cleaning systems are forbidden by some authorities due to high requirements for impurities in water. Therefore, Outotec is developing a dry off-gas cleaning system for smelting furnaces. The industrial-scale concept for the dry off-gas cleaning system has been finalized at WP2.

Further information

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CONTACT PERSONS:

Timo Paananen, Project chairman, SSAB Europe Oy
Mikko Iljana, Project secretary, University of Oulu

PARTICIPANTS:

Outokumpu Stainless Oy, SSAB Europe Oy, Outotec (Finland) Oy, Sapotech Oy, Luxmet Oy, University of Oulu, Aalto University

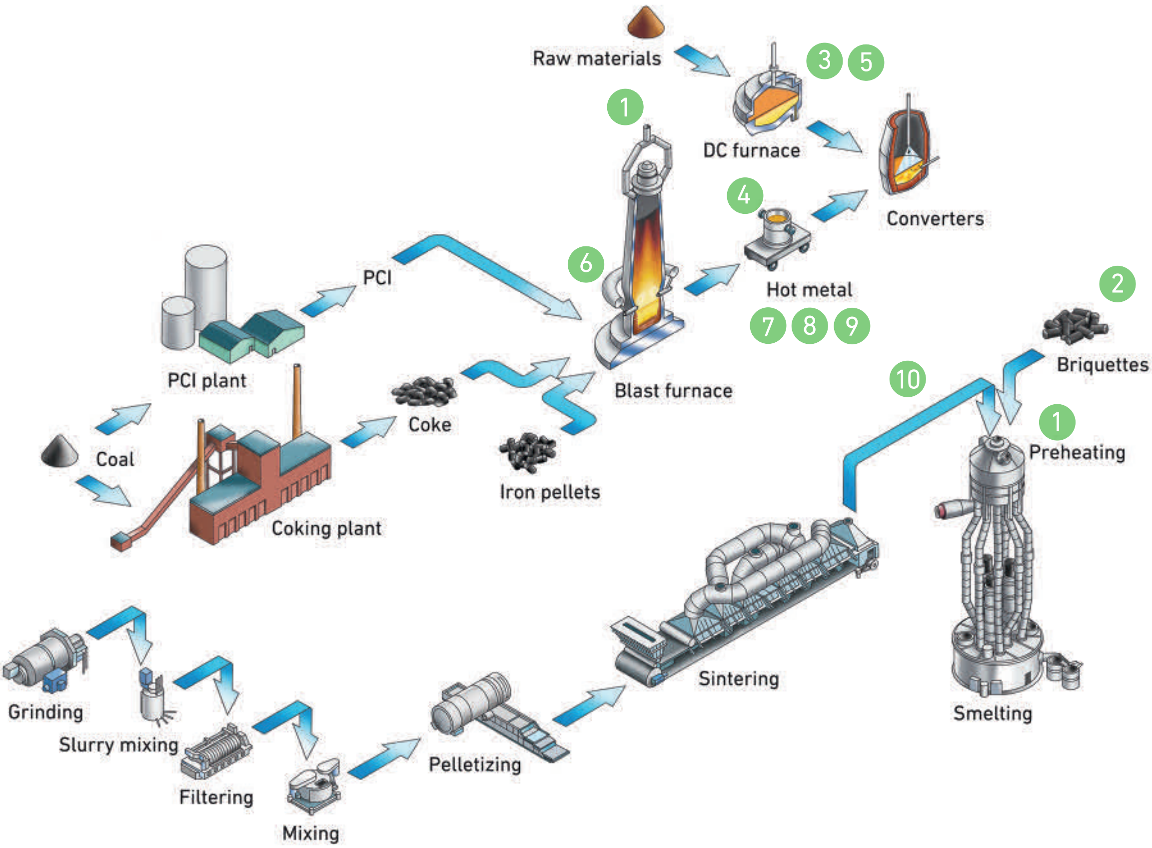
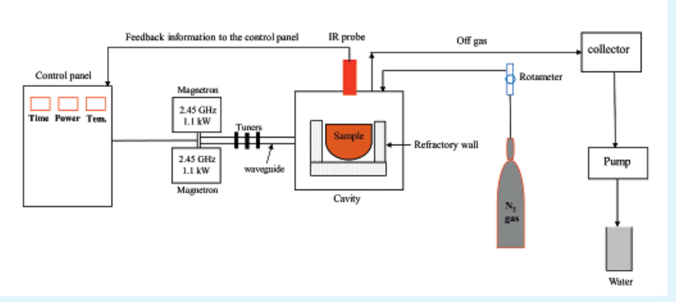


Figure 4. **Flow sheets of hot metal production (top) and ferrochrome production (bottom). The numbered bullets in the process schemes represent the tools developed in WP2.**

1 MICROWAVE-ASSISTED CHEMICAL REACTIONS

WORK PACKAGE 2



Description of the tool

Microwave energy is a non-ionizing form of electromagnetic radiation with frequencies in the range of 300MHz to 300GHz. Microwave heating is fundamentally different from conventional heating because microwaves can penetrate deep into the sample. This allows volumetric sample heating, as opposed to conventional thermal processing, which heats the sample from the outside inwards. Therefore, the disadvantages of conventional heating methods, such as a large temperature gradient, long processing time, and high energy consumption, can be avoided with microwave heating.

Application

Recently, there has been a growing interest in microwave energy as an alternative heating source. Microwave energy is a promising new technology that can be applied in the processing of primary and secondary raw materials. These include microwave-assisted carbothermic reduction of metal oxides, microwave-assisted drying and anhydration, microwave-assisted mineral leaching, microwave-assisted roasting and smelting of sulfide concentrate, and microwave-assisted waste management.

Technologies

The multivariate algorithms were implemented in Matlab but, in principle, any platform with linear algebra packages could be used.

Scope of application

Most of the studies of microwave applications have been carried out on a laboratory scale. The information obtained in the laboratory-scale microwave experiments are the effect of power and exposure time on the materials absorption of microwaves, materials structure, and the temperature increase rate. This information will be used later to design an industrial-scale microwave application.

Contact persons – Inventors

Mamdouh Omran, mamdouh.omran@oulu.fi, University of Oulu
Timo Fabritius, timo.fabritius@oulu.fi, University of Oulu
Guo Chen, Kunming University for Science and Technology

Additional Information/ Publications

M. Omran and T. Fabritius, “Improved removal of zinc from blast furnace sludge by particle size separation and microwave heating”, *Minerals Engineering*, Vol. 127, No. 10, pp. 265–276, 2018.

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2 SCALE BRIQUETTES

WORK PACKAGE 2

Description of the tool

One means to recycle dust and scale from ferrochrome and steel production is agglomeration and feeding in the form of briquettes to a SAF in ferrochrome production. Benefits are lower transportation and treatment costs, and a possibility to adjust the composition of the produced ferrochrome. The price of the ferrochrome has a notable impact on the cost of using of briquettes.

Application

The aim was to develop cement-bonded briquettes that are strong enough. First, test briquettes were manufactured in a laboratory, and after that a larger number in a briquetting plant for a production test in SAF. The campaign proved that it is possible to use briquettes in SAF, and the benefits can be achieved.

Technologies

Technologies utilized in designing and manufacturing the briquettes were particle size calculation for optimum packing (EMMA), briquetting, and strength measurement (Zwick).

Scope of application

Briquetting is a common technique to recycle dust in ironmaking. Briquetting could also be used in EAF raw material treatment.

Contact persons – Inventors

Antti Kemppainen, antti.kemppainen@ssab.com, SSAB Europe Oy (formerly University of Oulu)
Juho Kunelius, juho.kunelius@outokumpu.com, +358 40 712 2986, Outokumpu Stainless Oy
Niko Hyttinen, niko.hyttinen@outokumpu.com, Outokumpu Stainless Oy

Additional Information/ Publications

N. T. Farrokh, A. Kemppainen and T. Fabritius, “Production of cement bonded briquettes and strength measurements”, report, University of Oulu.

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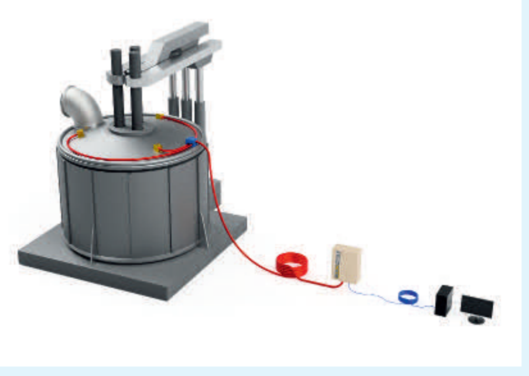
3 INTELLIGENT VOLTAGE TAP CONTROL FOR ELECTRIC ARC FURNACES

WORK PACKAGE 2



Description of the tool

Scrap melting in an electric arc furnace can be evaluated by measuring the light emitted from the electrode hot-spot area. This information can be used in time charging of scrap buckets and to optimize refractory wear. By combining the control of scrap melting with current requirements for the speed of the process, it is possible to optimize the process to increase productivity or process efficiency, depending on the current requirements for the process.

Application

The tool was developed for Outokumpu Stainless Oy electric arc furnace no. 1 (EAF1). The aim of the implementation is to reduce refractive power and electrode consumption.

Technologies

The tool integrates EAF optical emission spectrum measurement with intelligent control of electric arc furnace voltage ramps. It combines the novel measurement information with data from other sources to generate a deeper understanding of the state of the electric arc furnace process.

Scope of application

The system can be used to control electric arc furnaces in steelmaking. A similar control method could be scaled to other downstream processes.

Contact persons – Inventors

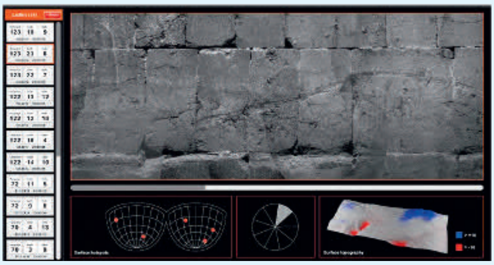
Mikko Jokinen, mikko.jokinen@luxmet.fi, Luxmet Oy
Matti Aula, matti.aula@luxmet.fi, Luxmet Oy
Tommi Veijola, tommi.veijola@luxmet.fi, Luxmet Oy

Additional Information/ Publications

T. Veijola, "Improving the control of electric arc furnace by combining optical emissions with process data", *Master's thesis,* 2018.

4 REVEAL 360 FOR INSPECTION OF BLAST-FURNACE LADLE REFRACTORIES

WORK PACKAGE 2



Description of the tool

Sapotech's Reveal 360 is a refractory monitoring solution that combines novel lance-based operating principle with the latest measurement technologies. The tool provides crucial information about the status of refractories for steel-plant operators and development staff to optimize the life-cycle of the refractories, hence increasing cost efficiency and safety.

Application

In this specific application, Reveal 360 is used to monitor the refractories of hot blast-furnace ladles. A lance with a measuring head goes inside the ladle, and makes several 360-degree rotations while imaging the refractory surface and measuring the inner dimensions. Data from ladle refractory scanning is transferred to the plant's manufacturing execution system for further use and decision-making. The status and history of ladle refractory condition is therefore always easy to track. The main aims are to: 1) increase safety by predicting and avoiding ladle leakages, 2) optimize the ladle refractory lifetime, and 3) create information on ladle inner volume as a function of liquid height.

Technologies

Reveal 360 combines high-resolution, laser-illuminated imaging with accurate laser distance measurements to provide full scanning of the ladle refractory condition and dimensions. Sapotech's Reveal IoT platform is used to collect, organize, and store the measurement information. Through the web-based user interface, anyone in the organization can access the system. The lance-based operating principle enables the monitoring of the surfaces even if there are skull formations or large hollow sections in the refractory walls.

Scope of application

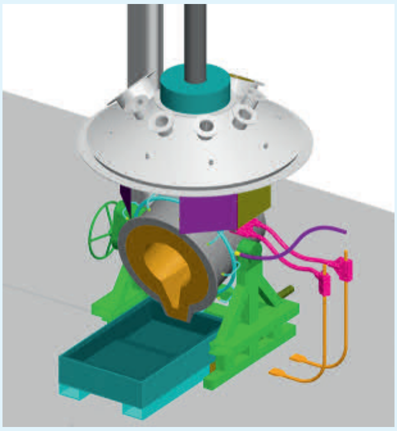
The installation of Reveal 360 can be either mobile or fixed, providing a flexible tool for any kind of surface monitoring needs. Mobile Reveal 360 has previously been applied in flash smelting furnace inner condition monitoring. In addition, Reveal 360 could be applied, for example, in RH degasser refractory monitoring and in an electric arc furnace cooling panel and refractory monitoring.

Contact persons – Inventors Hannu Suopajärvi, hannu.suopajarvi@sapotech.fi, +358 40 7627335, Sapotech Oy
Olli Mattila, olli.mattila@ssab.com, +358 50 3142945, SSAB Europe Oy

Additional Information/ Publications H. Suopajärvi, J. Roininen, L. Halonen and O. Mattila, "New ways to enhance refractory monitoring with latest IoT technology", *Proceeding of the 7th International Congress on Science and Technology of Steelmaking*, Associazione Italia di Metallurgia, Venice, Italy, 2018.

5 200 kW PILOT-SCALE DC FURNACE

WORK PACKAGE 2



Description of the tool

Direct current (DC) arc furnaces have been applied to a number of smelting processes, including chromite and ilmenite smelting. DC technology can also be used for the treatment of solid waste from metallurgical processes. The first smelting campaign with the 1 MW pilot DC furnace was carried out on chromite concentrate at Outotec Research Center in Pori in 2012. The current DC furnace is now modified to conduct smelting tests on the 200kW scale of operation, as well. In a novel process development, early operation on a smaller scale improves safety and research efficiency, and reduces investment in both time and money.

Application

The validation will be done using titanomagnetite. The tool is under cold commissioning.

Technologies

The pilot DC furnace is based on DC plasma arc technology.

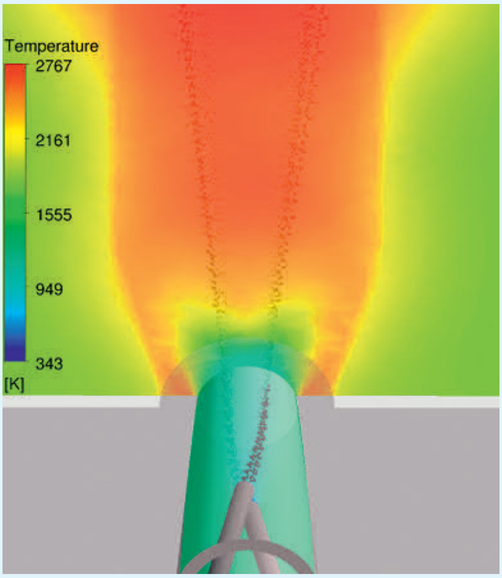
Scope of application

The pilot DC furnace can be applied to numerous materials for validating industrial-scale processes. The next step is the production of metallurgical grade silicon metal, which is conventionally produced in circular AC furnaces.

Contact persons – Inventors
Pasi Mäkelä, pasi.makela@outotec.com, +358 40 774 8031, Outotec (Finland) Oy
Petri Palovaara, petri.palovaara@outotec.com, +358 40 083 3360, Outotec (Finland) Oy

6 TUYÈRE-RACEWAY COMBUSTION MODEL

WORK PACKAGE 2



Description of the tool

Computational fluid dynamics (CFD) is used to create a tuyère-raceway combustion model for pulverized coal (PC) in a blast furnace. The tool can be applied to improve the double lance injection method for PC. The results are used to aid decision-making concerning lance positioning. With CFD modeling, experimental work can be reduced, which lowers the cost of process development and also lowers the risk of unwanted fouling of the tuyère walls. With improved combustion, auxiliary fuel injection can be increased to replace coke, which lowers the cost of iron production. Increased coke replacement also decreases CO_2 emissions. A subroutine was added to show the particle combustion atmosphere at each step, to gain information for experimental studies.

Application

The combustion model was validated using experimental results from BHP Billiton-BlueScope Steel, and the model predicted combustion degree with good accuracy for three different coal types (medium and high volatile coals). The model was applied to study the effect of lance position on PC combustion efficiency and the fouling of the tuyère wall.

Technologies

The CFD model was created with Ansys Fluent, but to solve the combustion chemistry, CHEMKIN solver was used.

Scope of application

The combustion model can also be applied to other metallurgical processes. For example, it could be used to model coal injection and combustion in an electric arc furnace.

Contact person – Inventor

Ari Vuokila, ari.vuokila@oulu.fi, +358 50 430 7989, University of Oulu
Olli Mattila, olli.mattila@ssab.com, +358 20 593 8709, SSAB Europe Oy

Additional Information/ Publications

A. Vuokila, “CFD modeling of auxiliary fuel injections in the blast furnace tuyere-raceway area”, *Doctoral thesis*, University of Oulu, 2017.
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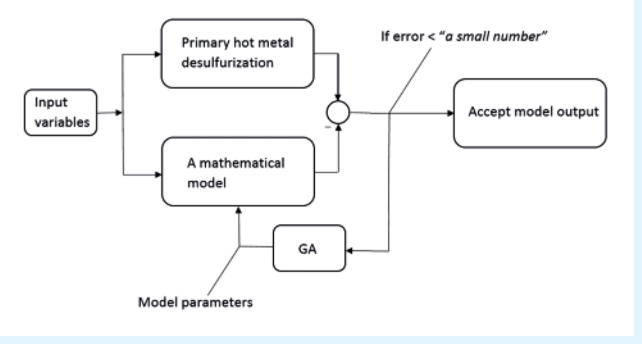
AN ADAPTIVE PARAMETERIZED PREDICTION MODEL FOR PRIMARY HOT METAL DESULFURIZATION

7

WORK PACKAGE 2



Description of the tool

The aim of this work was to develop a prediction model for hot metal desulfurization that is suitable for process control and model-based optimization purposes. To be suitable for this purpose, the model has to have adequate prediction performance and short computational time. The implementation of the model as a part of the process control system possibly allows improved cost and material efficiency, as well as a more predictable primary hot metal desulfurization process. However, the analysis of the modeling results can also be applied in fast and detailed value-in-use calculations.

Application

The structure of the model is identified based on mass transfer controlled kinetics. To tackle the problems related to the uncertainties in the system identification of hot metal desulfurization, the analytical solution of the surface area approximation is parameterized with a multivariate regression vector that is solved with a numerical parameter identification procedure (genetic algorithm). The modeling results are evaluated using a cross-validation procedure. Both the fitting and validation data-sets consist of actual industrial data. At the current stage, the model is validated for offline use. The modeling results indicate that the model is capable of explaining a majority of the variance in the end-content of sulfur in hot metal at the end of reagent injection.

Technologies

The numerical parameter identification (genetic algorithm) and cross-validation procedures are implemented using Matlab®.

Scope of application

The applicability of the parameterized prediction model approach is recommended to be studied in the case of other metallurgical processes or process stages.

Contact persons – Inventors

Tero Vuolio, tero.vuolio@oulu.fi, +358 40 574 7248, University of Oulu
Ville-Valtteri Visuri, ville-valtteri.visuri@oulu.fi, +358 50 350 7611, University of Oulu

Additional Information/ Publications

T. Vuolio, V.-V. Visuri, S. Tuomikoski, T. Paananen and T. Fabritius, "Data-Driven Mathematical Modeling of the Effect of Particle Size Distribution on the Transitory Reaction Kinetics of Hot Metal Desulfurization", *Metallurgical and Materials Transactions B*, Vol. 49, No 5, pp. 2692–2708, 2018.

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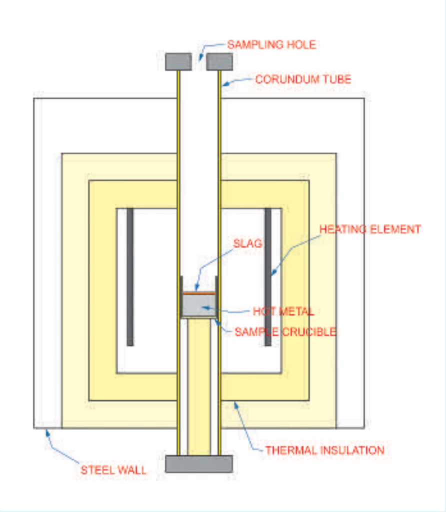
8 A METHOD TO EVALUATE RESULFURIZATION OF HOT METAL

WORK PACKAGE 2



Description of the tool

The scope of this study is to study whether or not the resulfurization of hot metal is a technically relevant phenomenon. The rate of resulfurization needs to be evaluated in order to acquire a detailed mixer mass-balance with respect to sulfur. A detailed mass balance for the sulfur in the production route of hot metal can yield remarkable cost and material savings, and thus can be applied in the optimization of the manufacture chain. As the resulfurization of hot metal has not been extensively studied, the results of this work are also of scientific interest.

Application

The rate of resulfurization is studied via permanent phase contact (slag-metal contact) in a high-temperature furnace. The synthetic slag phase is a four-component system. The alkaline flux content of the slag phase is the main independent variable in the test series. The experimental conditions are designed based on dimensional homogeneity, to compare the results with an industrial-scale process. As support for the experimental data, the results are analyzed concurrently with thermodynamic and kinetic calculations.

Technologies

The high-temperature experiments are carried out in a crucible by applying an induction furnace in an argon atmosphere. The calculations for the study are carried out using Matlab®.

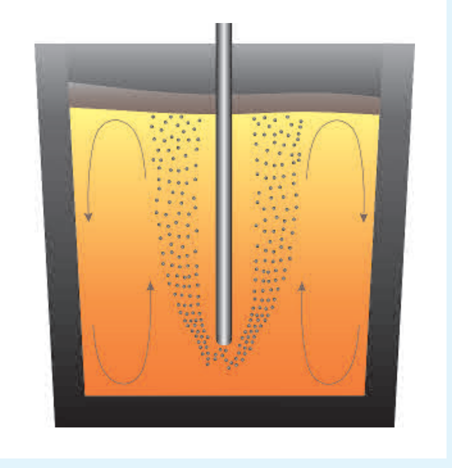
Scope of application

The industrial validation of the approach could be a fruitful research topic. The modeling approaches and the results of this study can be implemented as a part of a comprehensive system model for the hot metal production chain.

Contact persons – Inventors
Tero Vuolio, tero.vuolio@oulu.fi, +358 40 574 7248, University of Oulu
Ville-Valtteri Visuri, ville-valtteri.visuri@oulu.fi, +358 50 350 7611, University of Oulu
Riku Mattila, riku.mattila@oulu.fi, +358 40 730 1094, University of Oulu

9 MATHEMATICAL MODEL FOR HOT METAL DESULFURIZATION

WORK PACKAGE 2



Description of the tool

The model predicts the evolution of metal bath composition and temperature based on a mathematical formulation of the chemical kinetics of hot metal desulfurization with lance injection practice. The model accounts for the effect of different reagent compositions, particle size distributions, and injection practices (e.g. the type of lance tip) on the rate-controlling mechanisms.

Application

The model can be applied to comparing reagent injection practices and desulfurization reagents and is well suited for designing new operating practices.

Technologies

Mathematical descriptions of the kinetic and thermodynamic characteristics of transitory metal-reagent and permanent metal-slag reactions.

Scope of application

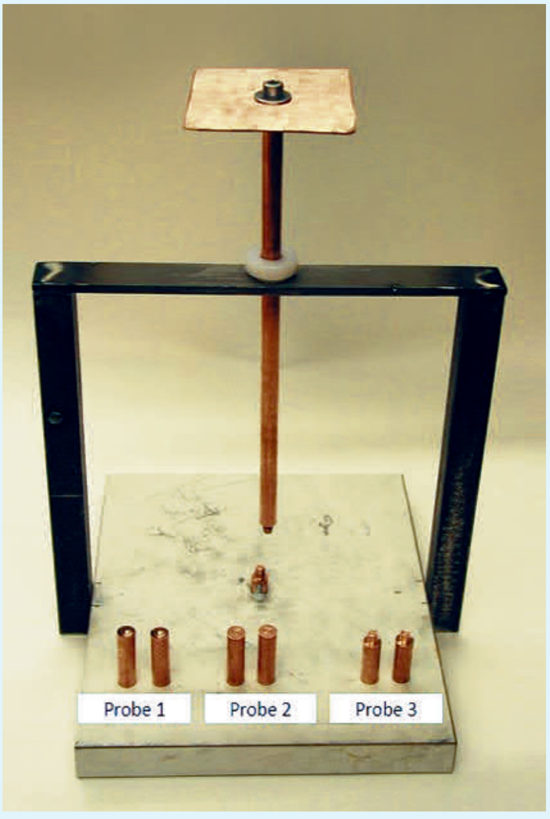
The model is designed for the simulation of hot metal desulfurization. In further work, the model will be extended to cover the evolution of the sulfur content from a blast furnace to mixers.

Contact persons – Inventors

Ville-Valtteri Visuri, ville-valtteri.visuri@oulu.fi, +358 50 350 7611, University of Oulu
Tero Vuolio, tero.vuolio@oulu.fi, +358 40 574 7248, University of Oulu
Petri Sulasalmi, petri.sulasalmi@oulu.fi, +358 50 350 7027, University of Oulu

10 ELECTRICAL BEHAVIOR OF A SUBMERGED ARC FURNACE'S CHARGE

WORK PACKAGE 2



Description of the tool

The electrical behavior of the charge in a submerged arc furnace is important because it affects the productivity of the furnace. A measurement device was developed at the University of Oulu to measure the electrical conductivity at room temperature.

Application

The measurement device was used to study what effect the coke texture has on the electrical behavior, what effect the chromite pellet's reduction degree has on the electrical behavior, what effect the sulfur in the atmosphere has on the chromite pellet's electrical conductivity, and what effect charcoal substitution in the chromite pellets has on the electrical behavior.

Scope of application

The measurement device has a low threshold for use in various settings. However, preliminary tests are needed to see if some treatments affect the electrical behavior.

Contact person – Inventor

Anne Hietava (née Heikkilä), anne.heikkila@oulu.fi, +358 50 350 2463, University of Oulu

Additional Information/ Publications

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11 METALLURGICAL GRADE SILICON METAL PRODUCTION

WORK PACKAGE 2

Description of the tool

The production of Si metal is a more complex high-temperature process than conventional smelting processes. Moreover, quartz (silicon dioxide) is quite a stable oxide and the reduction is theoretically possible only when the temperature exceeds 1800°C. The highest temperatures in the furnace might be around 2000°C. The experiments were conducted in a graphite crucible, which was heated in an induction furnace.

Application

Laboratory-scale smelting tests were carried out due to cost effectiveness. During a set of experiments, the raw material particle size and raw material ratios were changed.

Technologies

The smelting tests were carried out in an induction furnace. B-type thermocouples are normally used on a laboratory scale, but these thermocouples have limitations at extreme temperatures. Therefore, a pyrometer was also applied to the temperature measurements.

Scope of application

A similar laboratory-scale test setup can be used in other smelting tests in which extremely high temperatures are required (>1800°C).

Contact persons – Inventors

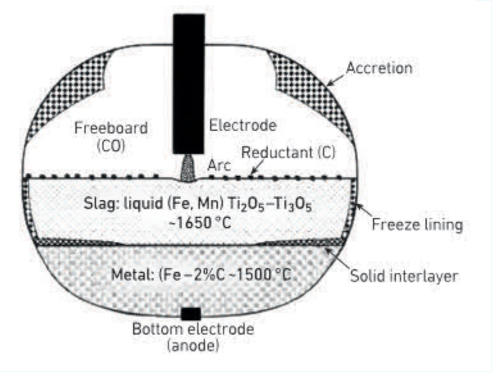
Pasi Mäkelä, pasi.makela@outotec.com, +358 40 774 8031, Outotec (Finland) Oy
Petri Palovaara, petri.palovaara@outotec.com, +358 40 083 3360, Outotec (Finland) Oy
Henri Ervasti, henri.ervasti@outotec.com, +358 50 361 6930, Outotec (Finland) Oy

Additional Information/ Publications

H. Ervasti, "Si-metallin valmistuksen pyrometallurgiset haasteet ja ilmiöt laboratorio-mittakaavassa", *Master's thesis*, University of Oulu, 2018.

12 THERMAL CONDUCTIVITY OF ILMENITE SLAG

WORK PACKAGE 2



Description of the tool

Knowledge of the thermal conductivity of ilmenite slag is essential for optimizing the ilmenite smelting process. Especially important for ilmenite smelting in an electric arc furnace is the formation of the freeze-lining of solidified slag on the walls of the furnace. This lining protects the refractory surface from dissolution into the highly aggressive slag. The necessity of the freeze-lining is three-fold. Firstly, the TiO_2-rich slag has very low impurity tolerances, imposing quality requirements on minimizing refractory dissolution. Secondly, a stable freeze-lining prolongs refractory life, which results in reduced costs for the smelting operation. Thirdly, the dissolution of refractories can lead to a breakthrough event, resulting in catastrophic failure.

Application

The thermal conductivities of several TiO_2 slags were determined from room temperature to 1700 °C using laser flash analysis. This covers both solid and molten states of the slag. Different samples, both industrial and synthetic in nature, were analyzed.

Technologies

The Laser Flash Analysis and Hot Disk methods were used to determine the thermal conductivity of the samples.

Scope of application

Knowledge of the thermal conductivity of high TiO_2 slag is applicable to the production of the aforementioned slag.

Contact persons – Inventors

Juhani Heimo, juhani.heimo@aalto.fi, Aalto University
Ari Jokilaakso, ari.jokilaakso@aalto.fi, Aalto University
Marko Kekkonen, marko.kekkonen@aalto.fi, Aalto University
Michael Gasik, Michael.gasik@aalto.fi, Aalto University
The research was conducted with cooperation from NTNU (Merete Tangstad) and SINTEF (Anne Støre) in Trondheim, and Outotec (Finland) Oy (Timo Haimi, Petri Palovaara and Pasi Mäkelä).

Additional Information/ Publications

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ADAPTIVE REFINING METALLURGY (ARM)

WORK PACKAGE 3

Seppo Louhenkilpi, Ari Jokilaakso/Aalto University
Jukka Laine, Risto Vesanen/Casim Consulting Oy
Pentti Kupari, Juho Moilanen, Marko Petäjäjärvi/Outokumpu Stainless Oy
Agne Bogdanoff, Seppo Ollila, Ismo Rentola, Tuomas Antola/SSAB Europe Oy
Tuomas Alatarvas, Timo Fabritius, Toni Liedes, Mika Pylvänäinen,
Satu Tamminen, Ville-Valtteri Visuri, Anna-Mari Wartiainen/University of Oulu

Summary of the project's motivation and achievements

Adaptive refining metallurgy (ARM) focuses on the integration of different measurement systems for control of melt-shop processes and implementation of more flexible production practices and strategies. The project activities aim to improve quality and yield, decrease energy consumption, and increase the cost-effectiveness of production. One of the main requirements for competitive refining metallurgy in the future is the capability for a flexible response to changing demands and customer expectations. New process models and simulators enable the testing of new practices with less time and cost. Steel cleanliness and control of inclusions are important factors determining product quality and are of particular importance for the new third-generation high-alloyed automotive grades.

The scientific goals for the ARM were

- Find novel methods for the control of unit processes with the fusion of multiple measurement methods (University of Oulu, SSAB, Outokumpu)
- Validate chosen theoretical approaches and new modeling methods for practical problems (University of Oulu, Aalto University, SSAB, Outokumpu, Casim)
- Produce scientific output in the form of Master's and Doctoral theses, as well as scientific articles (University of Oulu, Aalto University)

Industrial goals for the ARM were

- Implement physico-chemical simulators as support tools (SSAB, Outokumpu, Casim)
- Integrate different measurement systems for the control of melt-shop processes (SSAB, Outokumpu, University of Oulu)
- Implement more flexible production practices and strategies (SSAB, Outokumpu)

- Improve the yield, decrease the energy consumption, and increase the cost-effectiveness of production (SSAB, Outokumpu)
- Stabilize the production process with better process control (SSAB, Outokumpu)
- Optimize complex systems and production sites with respect to raw material and energy use, costs, and emissions (SSAB, Outokumpu, University of Oulu)
- Acquire the ability to produce next-generation steel grades (SSAB, Outokumpu)
- Improve methods for online steel cleanliness and quality determination (SSAB, Aalto University, University of Oulu)

Key results and impacts

- An advanced in-house analysis tool for OES-PDA was developed. The concept is sufficiently fast for online purposes. The concept is a good instrument for long-term statistical analysis of quality development for each steel type and for studying the effects of changes in the processes on steel quality.
- New information on the evolution of inclusion population in high-aluminum steels.
- A tool for statistical analysis of inclusion clusters from SEM specimens was developed, which makes analysis work faster in the SSAB laboratory and product development.
- At Outokumpu Tornio, the skulling of ladles could be reduced by 21% and 50%, while an additional benefit is that lower sulfur contents can be obtained when synthetic slag former is used.
- With vibration measurements in the vacuum tank, degassing can be monitored in a more efficient and robust manner than before. The quality variations in the produced steel and the consumption of the stirring gas can be reduced.
- By measuring and analyzing the vibration at BOF, valuable information can be obtained and used in enhancing the control of the phosphorus refining process.
- With the help of Tempsimu and IDS, the casting speed for higher carbon martensitic steel grades was increased by 19.1%.
- The oscillation study helps to understand the effect of oscillation on slab quality.
- A new GPU-based dynamic heat transfer model for steel slabs has been constructed and implemented.
- The replacement of fluorspar with fluorine-based synthetic flux may help to reduce the required amount of flux in the AOD process.

Online analysis of steel cleanliness and inclusions (Tools 4, 5 and 9)

Online control of steel cleanliness is a current topic in all steel plants, as problems in steel cleanliness may lead to severe quality problems, downgrading of products, poor castability, and internal rejections. Because traditional microanalysis methods are too slow for online control, the use of Optical Emission Spectrometry with Pulse Discrimination Analysis (OES-PDA) has been proposed. Nevertheless, OES-PDA necessitates an advanced mathematical analysis tool, which calculates the cleanliness indexes and the state of inclusions from the OES-PDA raw data. In ARM, an advanced in-house analysis tool for OES-PDA was developed (*Tool 5*). The new tool is based on statistical and logistical concepts coupled with metallurgical and thermodynamic knowledge. The concept is sufficiently fast for online purposes. The model was developed together with Aalto University and SSAB Europe Oy in Raahe. International cooperation has been carried out with the steel plant of Voestalpine AG in Linz, Austria.

A large number of industrial samples was taken and analyzed to validate the model. As shown in *Figure 1*, the total oxygen calculated from the OES-PDA measurement corresponds well with the total oxygen measured with a Leco analyzer. It is also very important to remove incorrect peaks from the OES-PDA raw data. Incorrect peaks can originate for many different reasons at the entry of the top slag into the sample during sampling. We are still improving that part of the model slightly. The outcome of this new concept is that industry can control steel cleanliness and the state of inclusions much better than before. Necessary revising operations can be undertaken if the values are not as desired, and many kinds of quality and practical problems can be solved. Furthermore, the concept is a good instrument for long-term statistical analysis of quality development for each steel type, and for studying the effects of changes in processes on steel quality.

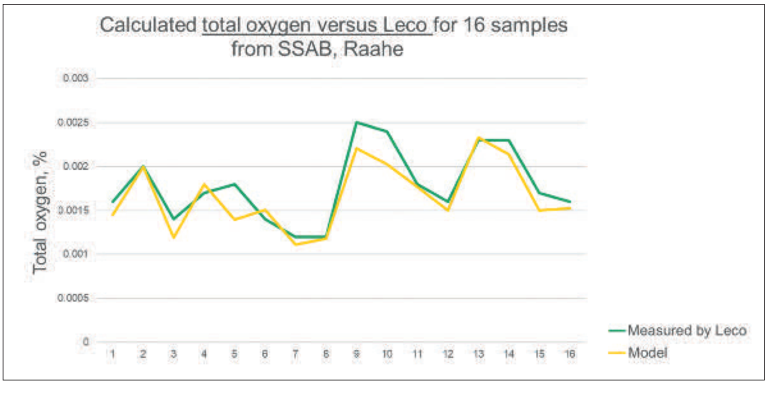


Figure 1. Calculated and measured total oxygen content.

At SSAB Europe Oy, steel cleanliness, and control of inclusions, are important factors determining product quality, especially in the production of new, third-generation high-alloyed automotive grades and other premium steel grades. In ARM, the inclusion characteristics were determined in samples taken throughout the process chain from two heats of high-aluminum steels; the aluminum content in the steels was up to 1.0 wt-% (*Tool 4*). The amount and composition of non-metallic inclusions in the steelmaking temperatures were calculated using the FactSage thermodynamics software.

Despite the lack of calcium treatment, the prevailing inclusion type in the mold samples of both heats was liquid calcium aluminate, indicating adequate modification of aluminum oxides into liquid oxides. The amount of stable inclusions in the mold samples was calculated with FactSage and is illustrated in *Figure 2*. According to the thermodynamic calculations, the dissolved oxygen content in the steel is larger than in conventional aluminum-killed steels. In addition, the dissolved magnesium content during continuous casting, according to the FactSage calculations, was higher than 10 ppm in both heats. This leads to a higher amount of precipitated inclusions during continuous casting, compared to conventional aluminum-killed steels.

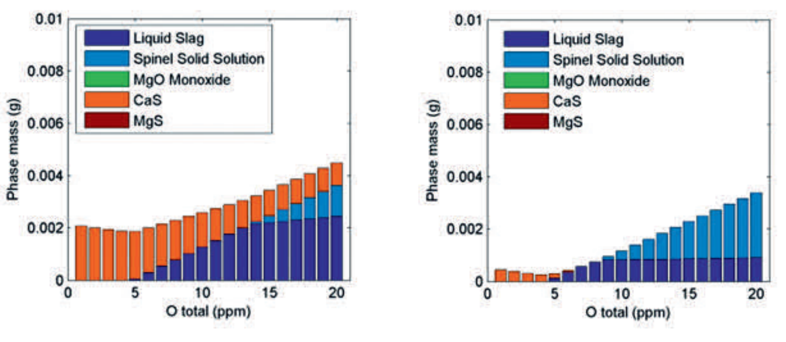


Figure 2. Calculated amount of stable inclusions in two high-aluminum steels at 1550 °C.

The criteria for characterizing the purity of steel and enabling the comparison of different specimens are important for the development of next-generation steel grades at SSAB Europe Oy. In ARM, a tool for the statistical analysis of inclusion clusters from SEM specimens was developed (*Tool 9*). Here, the clustering is based on the elliptical approximation of the inclusion shapes and the distances between them. The tool has flexible parameterization for the cluster definition, which enables usage for different SEM specimen types. The properties of the inclusion clusters, such as the size, shape, position within the specimen, and chemical composition, are calculated automatically. This information can be utilized to find the explanatory or predictive connections between these properties, and the mechanical quality factors (e.g. the results of the impact toughness test, tensile strength test, or flangeability test) of the steel by using Gradient Boosting Machine (GBM) models. The tool improves steel purity control by enabling the automation of finding predictive connections between the properties of the inclusion clusters and the steel properties. The connection between cluster properties and the process parameters would be equally interesting, as this information can be used to find process settings that produce steel with higher purity.

The GBM models were applied to study the explanatory connections between the properties of the inclusion clusters and the impact toughness test results. SEM analyses of 234 specimens and 15 heats were included in the study. The free statistical program R was used for inclusion clustering, finding the explanatory or predictive connections, and visualization. It was shown that inclusion cluster properties provide valuable information that can be utilized in mechanical property prediction and product quality determination.

Company impact

"The FESEM - INCA feature inclusion analysis is used for analyzing non-metallic inclusions in steel samples. It generates a great amount of data, of which only a small fraction is utilized in basic table tools. The data consists of the amount, location, and composition of individual inclusions. Some mechanical properties of steels, such as bendability, are influenced by inclusion clusters located, for example, near the surfaces of the steel plates or strips. The inclusion cluster tool gives us a lot of additional information about the location, composition, and sizes of inclusion clusters."

Teppo Pikkarainen, *Senior product development engineer, SSAB Europe Oy*

New removal practices for impurities: LF slag practice modification using synthetic slag

To obtain better control of steel sulfur content and to reduce possible skull formation in steelmaking ladles, the use of slag formers in the production of stainless steel was studied in ARM. A new synthetic slag former was trialed at the Outokumpu Stainless Oy, Tornio melt shop. The right amount and timing for addition of synthetic slag former was also studied. As a result, the skulling of ladles could be reduced by 21% and

50%, while an additional benefit is that lower sulfur content can be obtained when synthetic slag former is used. Synthetic slag has been introduced into the production practice at the Outokumpu Stainless Oy, Tornio melt shop, and is currently in active use.

Measurements and sensor fusion (Tools 1, 2 and 7)

Controlling the intensity and duration of gas stirring is important for ensuring a high degree of productivity and quality control. In the case of vacuum tank degassing, a major hindrance is poor reachability. To achieve more accurate control of stirring, a clear insight to gas stirring performance should be obtained. Earlier studies have shown that the mechanical vibration of the ladle or its supporting structures correlates well with the intensity of the stirring. Within the scope of this work, an online measurement system capable of monitoring stirring intensity in real time was developed and implemented in an industrial environment at SSAB Europe Oy, Raahe (*Tool 1*). The system is an improved version of the one piloted in the SIMP program. The monitoring system output serves as a new information channel for process operators. Hence, particular attention was paid to low latency and noise in the indicator output. As a result, the gas stirring process can be monitored in a more efficient and robust manner than before. Hence, the quality variations of the produced steel and the consumption of the stirring gas can be reduced.

The conducted research on the vacuum tank degassing process also revealed a promising source of novel information. A comprehensive analysis of a high frequency (8–12.5 kHz) vibration showed a regular decreasing trend in vibration level during the degassing process. The root cause of this phenomenon is still unknown and further research is needed. It is possible that the found phenomenon will provide a novel way to monitor the degassing process. As mentioned earlier, the degassing process is not easy to monitor directly. Thus, indirect methods ("soft sensors") are preferred. A model for predicting desulfurization kinetics during the vacuum tank degassing treatment was also developed. With the developed tool, the process operator can control the intensity and duration of the gas stirring to achieve sufficient desulfurization. This reduces the cost of poor-quality steel due to finishing the gas stirring too early. Wastage of the stirring gas is reduced, because unnecessary over-stirring time is minimized. The developed model is not yet ready for continuous operational use, but will be improved in further work with an improved description for the equilibrium sulfur content.

The basic oxygen furnace (BOF) process emits an information-rich flow of mechanical vibrations to the surrounding structures. By measuring and analyzing the vibrations, valuable information can be obtained and used in enhancing the control of the phosphorus refining process (*Tool 2*). Earlier studies have shown that a good location to measure vibration is the BOF trunnion pin. However, the trunnion pin may rotate through 360 degrees, which makes it impractical to use cables as information transferring media. In this work, a measurement system suitable for a rotating trunnion pin was developed. The system consists of a 3-axis vibration sensor, a logging and processing unit, and a powerpack for energy supply. All the hardware is encapsulated in a housing that connects to the trunnion pin by means of strong magnets. As a result, a measurement system capable of measuring wide frequency vibration from the rotating pin was developed. An operator of the BOF process has better insight into dephosphorization and can adjust the BOF process parameters accordingly to achieve a high-quality steel. The system is not yet ready for everyday operational use in an industrial environment, but it will be further developed in the future.

Mold oscillation and the impact of oscillation parameters on the surface quality of slabs were studied at SSAB Raahe. The purpose of the study was to measure the functioning of the oscillation equipment and to find out how the oscillation can be seen on the slab surfaces. In the future, the new steel grades require better knowledge of the mold area because deep oscillation marks increase the risk of surface defects, and especially transverse cracks. The study helps in understanding the effect of oscillation on slab quality (*Tool 7*).

Company impact

"Oscillation data collected during the project can be utilized in quality development. Better information on the position of the liquid pool in the strand avoids unnecessary alarms. Data can be used for predictive control of quality."

Maija Kärkkäinen, *Quality manager, Steel production, SSAB Europe Oy*

Utilization of the Tempsimu simulation tool to increase casting speed

The Outokumpu Stainless Oy, Tornio melting shop got a challenging task in 2017 to start producing martensitic steel grades. Several different grades were successfully introduced into production during 2017. In particular, higher carbon martensitic grades needed accurate continuous casting simulations using the Tempsimu and IDS programs, because those grades have a very wide gap between liquidus and solidus temperatures.

Solidifying behavior defines the maximum casting speed and the casting speed is one of the main parameters affecting the productivity of a steel grade. With the help of Tempsimu and IDS, the casting speed of higher carbon martensitic steel grades was increased by 19.1%. Development work still continues, because current speeds are not yet the maximum speeds according to the simulations done with Tempsimu.

Company impact

"Martensitic steel is challenging to cast because of the wide range between liquidus and solidus temperatures. With the help of Tempsimu simulations, we could increase the average casting speed of martensitic steel grades by 12%. The improvement directly affects the productivity of these steel grades, since the casting machine is the bottleneck at the melting shop."

Juho Moilanen, *Development engineer - Steel melting shop, Outokumpu Stainless Oy*

Simulation of continuous casting (Tools 6 and 8)

An online continuous casting simulator, CastManager, has been implemented in the process automation system to visualize strand solidification and to predict the quality indexes for slabs. Validation of the online model has been done by comparing the results of solidification simulators CastManager and Dynacs3D with temperature data measured by pyrometer and infrared camera (*Tool 8*). Another important factor for model validation was the feedback of slab quality. In addition to the visual inspection of slabs, the infrared camera was tested to detect the surface defects immediately after the casting machine.

Based on the simulation results, the cooling of the casting machine was changed. The simulations showed that secondary cooling at the casting machine is too intensive for crack-sensitive steel grades. After the cooling change, plate rejections due to slab defects decreased significantly.

One aim in FLEX was to create a web-based application of the systems (CastManager, FurnaceManager) to improve the information transfer to and from end-users. The systems provide a huge number of accurate model-based calculation results from the process, and the key factor is that the process operators and the development engineers should access the information in real time. For international marketing, the tools need to be, in some cases, translated into the local language. This is especially the case for China. The IDS software enables end-users to change the software user interface language from English to Chinese.

A new GPU-based dynamic heat-transfer model for steel slabs has been constructed and implemented (*Tool 6*). The computational model is implemented as highly parallel with the use of the NVIDIA CUDA architecture, which enables the launch of the model on graphics processing units (GPUs), allowing for its acceleration. The model takes advantage of the GPU's ability to process thousands of threads simultaneously and can calculate up to 100 slab temperature distributions at the same time. It provides the rapid computation capabilities required for online use in continuous casting, and tracking of each slab after it is transferred from the caster to the reheating furnace and then to rolling. It is also a more power- and cost-efficient solution than previously developed CPU models.

The acceleration for a single slab was evaluated with the use of the relative computational time, which is the dimensionless ratio between the computational time that the model needs to compute the simulation and the wall-clock time of the real slab-heating process being simulated. The relative computational time of the GPU-based computational model is between 0.0015 for a coarse mesh and 0.0072 for a fine mesh. The corresponding multiple of GPU acceleration, which is the ratio between the computational times of the GPU-based model and the CPU-based model for the identical simulation, is between 5 and 13.

The GPU model is connected to the reheating furnace system FurnaceManager and it calculates up to 30 slab temperatures and total heat energies in real time. A modified version of the model, which can be used in continuous casting for calculating strand temperatures, will be connected to the continuous casting simulator CastManager.

Company impact

"The DIMECC FLEX program has had a great impact on the growth of the company and the international marketing of the products. We now have very close and active cooperation with the Finnish steel industry. Our products are now more tested, validated, and finalized, which is important for international marketing. Many discussions and smaller agreements with international customers have already been carried out."

Jukka Laine, *Managing director, Casim Consulting Oy*

Study of novel flux usage (Tool 3)

High refractory wear is characteristic of the argon-oxygen decarburization process. A significant share of the refractory wear is associated with the use of fluxes in the reduction stage. In ARM, the use of a synthetic fluorine-based flux to replace fluorspar was studied using experimental and computational methods (*Tool 3*). High-temperature crucible experiments were used to study the effect of the type and amount flux on the wear of doloma refractories. Furthermore, the liquid fraction and dynamic viscosity of the slag were calculated using FactSage thermodynamics software. The results of the experiments suggest that roughly 20% less flux is required if fluorspar is substituted with the synthetic flux.

Company impact

"Deeper research on slag-refractory interaction increases knowledge of the possibilities when choosing suitable slag additives for stainless steelmaking processes. With the help of this knowledge, the slag fluxing practice can flexibly be changed according to production and raw material market conditions."

***Teijo Södervall,** VP – Steel melting shop, Outokumpu Stainless Oy*

Further information

KEY PUBLICATIONS:

X. Liu, S. Tamminen, X. Su, P. Siirtola, J. Röning, J. Riekki, J. Kiljander and J. P. Soininen, "Enhancing Veracity of IoT Generated Big Data in Decision Making", *Proceedings of the 1st International Workshop on Context-Awareness for Multi-Device Pervasive and Mobile Computing (PerCrowd 2018) in conjunction with 2018 IEEE International Conference on Pervasive Computing and Communications (PerCom 2018)*, 2018.

A. Kärnä, M. Järvinen, P. Sulasalmi, V.-V. Visuri and T. Fabritius, "An Improved Model for the Heat-up Stage of the CAS-OB Process: Development and Validation", *Steel Research International*, forthcoming.

V.-V. Visuri, R. Mattila, P. Kupari and T. Fabritius, "A comparative study on refractory wear associated with fluxes for AOD slags", *Proceedings of the 7th International Congress on Science and Technology of Steelmaking*, Associazione Italia di Metallurgia, Venice, Italy, 2018.

C. Westerlund, "Efficient parallel implementation of a transient heat transfer model", Master's thesis, Aalto University, 2018.

CONTACT PERSONS:

Agne Bogdanoff, Project chairman, SSAB Europe Oy
Ville-Valtteri Visuri, Project secretary, University of Oulu

PARTICIPANTS:

Aalto University
Casim Consulting Oy
Outokumpu Stainless Oy
SSAB Europe Oy
University of Oulu

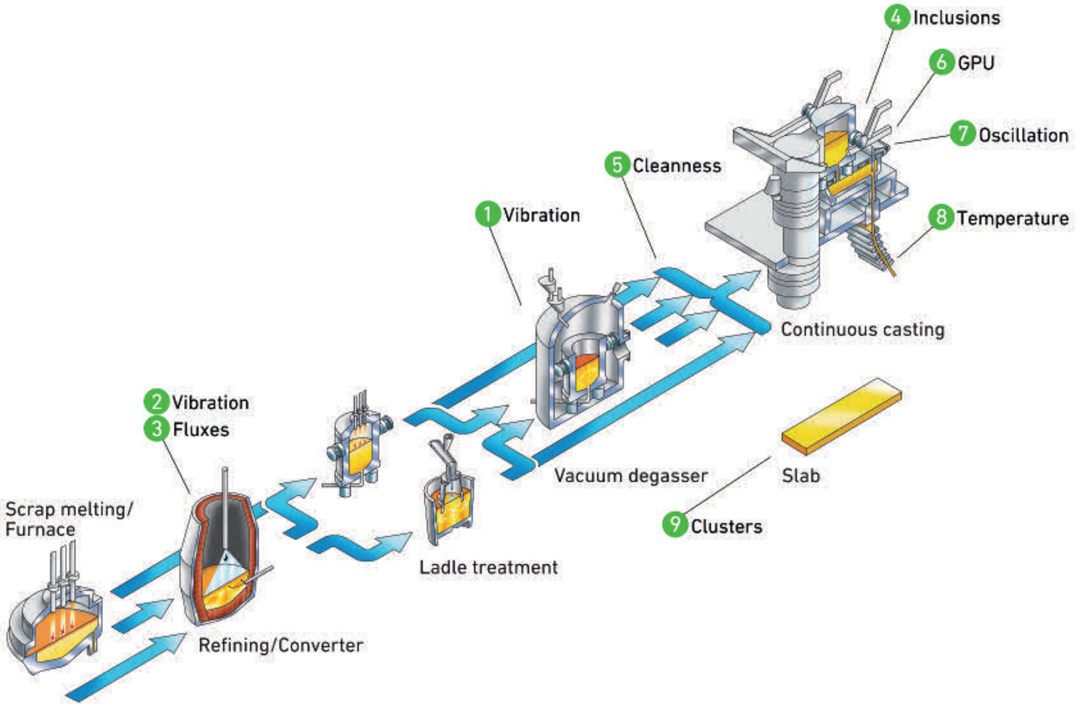


Figure 3. **Secondary steelmaking flow sheet.**

DIMECC

1 VIBRATION-BASED PREDICTION OF THE VACUUM TANK DEGASSING PROCESS

WORK PACKAGE 3

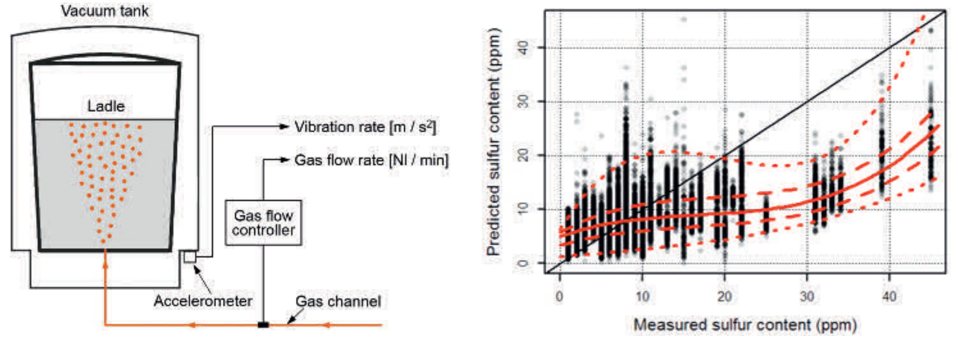


Figure 1. **Left: measurement system; right: predicted and measured final sulfur content values after vacuum tank degassing.**

Description of the tool

The objective of this work is to develop a model to predict the desulfurization kinetics during vacuum tank degassing treatment. With the developed tool, the process operator can control the intensity and duration of gas stirring to achieve sufficient desulfurization. This reduces the cost of poor-quality steel due to finishing gas stirring too early. Wastage of stirring gas is reduced, because unnecessary over-stirring time is minimized.

Application

The prediction model was developed and cross-validated with the process data recorded from the vacuum tank degasser in the secondary metallurgy area of SSAB Europe Oy, Raahe. The process data consists of the content of steel alloys measured before degassing treatment, and the root mean square (rms) calculated from the vertical velocity signal measured from the ladle support beam. Based on the cross-validation results, the prediction error is too high and should be reduced before the model is mature for use in daily plant operations.

Technologies

Vibration measurement data obtained from the vacuum tank degasser was treated using digital signal processing methods (e.g. filtering and numerical integration) using Matlab. Prediction modeling and cross-validation were conducted using R.

Scope of application

Once the prediction error has been reduced to an acceptable level, the prediction model is going to be applied at the vacuum tank degasser at SSAB Europe Oy in Raahe.

Contact persons

Mika Pylvänäinen, University of Oulu, mika.pylvanainen@oulu.fi
Ville-Valtteri Visuri, University of Oulu, ville-valtteri.visuri@oulu.fi
Jouni Laurila, University of Oulu, jouni.laurila@oulu.fi
Juhani Nissilä, University of Oulu, juhani.nissila@oulu.fi
Toni Liedes, University of Oulu, toni.liedes@oulu.fi
Seppo Ollila, SSAB Europe, seppo.ollila@ssab.com

2 VIBRATION-BASED PREDICTION OF BASIC OXYGEN FURNACE

WORK PACKAGE 3

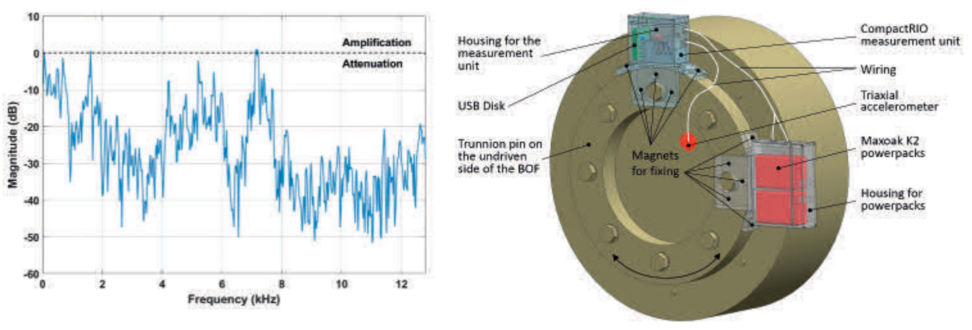


Figure 1. **Left: transfer function estimate, in which the input is the vibration at the trunnion pin of the BOF and output is the vibration at the fixed side; right: vibration measurement instrumentation on the trunnion pin on the undriven side of the BOF.**

Description of the tool

The objective of this work is to develop a mechanical vibration-based methodology to enhance control of the phosphorus refining process and slag formation in the basic oxygen furnace (BOF). With the developed tool, the operator of the BOF process has better insight into dephosphorization during the BOF process.

Application

The preliminary vibration measurements have been conducted on the BOF at SSAB Europe Oy, Raahe. The parallel vibration measurements were conducted on the undriven side of the BOF. Triaxial accelerometers were installed on the trunnion pin (turning part) and on the fixed side (non-turning part) of the bearing. A transfer function estimate reveals that the vibration signal attenuates at almost all frequencies in its transmission from the trunnion pin to the fixed side. In order to avoid information loss in the mechanical vibration generated in the BOF process, vibration measurements have to be conducted on the trunnion pin, which may rotate by 360° in normal operating conditions. Consequently, the measurement instrumentation, including electrical powering, has to be fixed on the turning trunnion pin.

Technologies

The data from the preliminary vibration measurements was analyzed using Matlab and its built-in transfer function estimation procedures. The housing to hold the measurement unit and power packs was 3D-printed from ABS plastic in Fab Lab at the University of Oulu, and it is attached to the trunnion pin with magnets.

Scope of application

The measurement instrumentation is nearly finished and ready for a measurement campaign.

Contact persons Mika Pylvänäinen, mika.pylvanainen@oulu.fi; Ville-Valtteri Visuri, ville-valtteri.visuri@oulu.fi; Jouni Laurila, jouni.laurila@oulu.fi; Juhani Nissilä, juhani.nissila@oulu.fi; Atte Rankinen, atte.rankinen@oulu.fi; Pasi Ruotsalainen, pasi.ruotsalainen@oulu.fi; Toni Liedes, toni.liedes@oulu.fi: University of Oulu

Seppo Ollila, seppo.ollila@ssab.com, SSAB Europe

3 EXPERIMENTAL COMPARISON OF FLUXES FOR AOD SLAG

WORK PACKAGE 3

Figure 1. **Refractory wear with 10 wt-% addition of fluorspar or synthetic flux.**

Description of the tool

Experimental and computational evaluation of refractory wear.

Application

A comparative study of refractory wear associated with fluxes for AOD slag. More specifically, the substitution of fluorspar with a synthetic fluorine-based flux was studied. The results suggest that the amount of flux can be reduced by roughly 20% if fluorspar is substituted with the synthetic flux.

Technologies

High-temperature crucible experiments with a chamber furnace, differential thermal analysis of the melting point, optical microscopy, and computational thermodynamics.

Scope of application

The same experimental principle is applicable as such for studying the refractory wear induced by metallurgical slag, provided that the refractory wear is relatively aggressive. If the refractory wear is very slow, the weight of the residual mass does not provide much information, and hence it is recommendable to use scanning electron microscopy to measure refractory wear from the crucibles.

Contact persons Ville-Valtteri Visuri, University of Oulu, ville-valtteri.visuri@oulu.fi
Riku Mattila, University of Oulu, riku.mattila@oulu.fi
Pentti Kupari, Outokumpu Stainless Oy, pentti.kupari@outokumpu.com

Publications V.-V. Visuri, R. Mattila, P. Kupari and T. Fabritius, "A comparative study on refractory wear associated with fluxes for AOD slags", *Proceedings of the 7th International Congress on Science and Technology of Steelmaking*, Associazione Italiana di Metallurgia, Venice, Italy, 2018.

4 INCLUSIONS IN HIGH-ALUMINUM STEEL – FACTSAGE CALCULATIONS

WORK PACKAGE 3

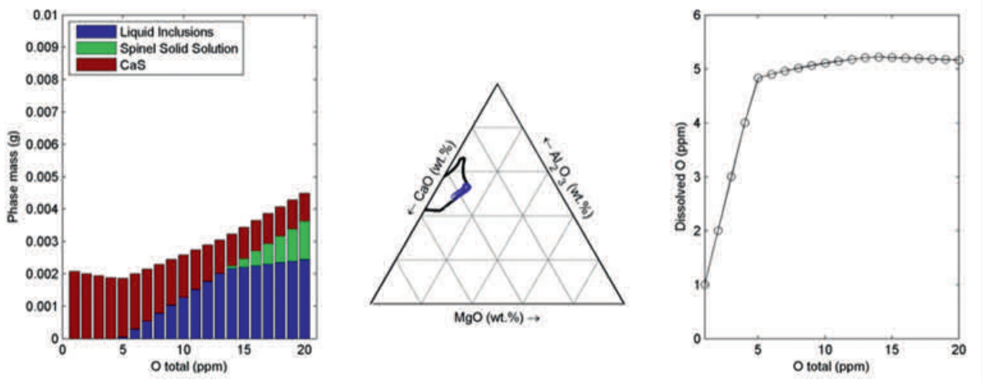


Figure 1. **Stable inclusions in high-aluminum steel at 1550°C, calculated by FactSage. Left: Amount of stable inclusions, as a function of total oxygen. Middle: Composition of liquid inclusions in Al2O3-CaO-MgO ternary diagram. Right: dissolved oxygen in liquid steel, as a function of total oxygen.**

Description of the tool

Thermodynamic calculations were performed in order to determine stable non-metallic inclusions in liquid steel with an aluminum content of 1.0 wt-% at 1550°C. The chemical composition of a mold sample, taken during continuous casting, was used as input data for the calculations. The high aluminum content affects the composition of the oxide inclusions in the steel. The target composition for the oxide inclusions is calcium aluminates appearing liquid at steelmaking temperatures, reducing the clogging tendency during continuous casting. The target composition area of liquid oxides is plotted in the middle figure.

Application

The calculations were performed offline. The calculated results were compared to inclusion analyses obtained from a polished steel sample using a scanning electron microscope. The analyzed and calculated inclusions are fairly well comparable.

Technologies

FactSage was used for the thermodynamic calculations, and MATLAB for the data treatment and plotting.

Scope of application

Thermodynamic calculations are widely used in the field of process engineering. FactSage calculations are well suited for assessing stable non-metallic inclusions in liquid steel, owing to the high temperatures and reaction rates. Thermodynamic calculations are a valuable tool in determining stable compounds in liquid steel, given that the composition of the steel is accurately known.

Contact person Tuomas Alatarvas, University of Oulu, tuomas.alatarvas@oulu.fi

5 PREDICTION OF STEEL CLEANLINESS

WORK PACKAGE 3

Figure 1. Online prediction.

Description of the tool

A new in-house analysis tool for Optical Emission Spectrometry with Pulse Discrimination Analysis (OES-PDA) has been developed. The OES-PDA analyzer with advanced mathematical tools is a relatively fast method for determination of steel cleanliness, meaning the amounts, types, and size distributions of inclusions in steel samples. This method is widely used in industry for research purposes offline but not generally for online purposes. However, older tools coupled with OES-PDA do not predict the inclusion types accurately and robustly enough. The new tool is based on statistical and logistical concepts coupled with metallurgical and thermodynamic knowledge, and it is fast enough for online purposes. The cleanliness can now be predicted reliably using the OES-PDA analyzer coupled with our new in-house tool.

Benefits:

- The outcome of this new concept is that the industry can control steel cleanliness and the state of inclusions much better than before
- Necessary revising operations can be done if the values are not as desired
- Many kinds of quality and practical problems can be solved
- Saving the results in a databank system: longer-term statistical analyses of quality development for each steel type and the effect on quality of changes in the processes can be carried out.

Application

Industrial samples have been taken and analyzed for the purpose of validating the model. The calculated total oxygen contents exhibit a very good agreement with the total oxygen contents measured with LECO equipment. The feasibility of the concept was proven and the development work will be continued.

Technologies

An OES-PDA analyzer coupled with the new in-house computer tool.

Scope of application

The concept can be applied by all steel plants to analyze steel cleanliness and the state of inclusions.

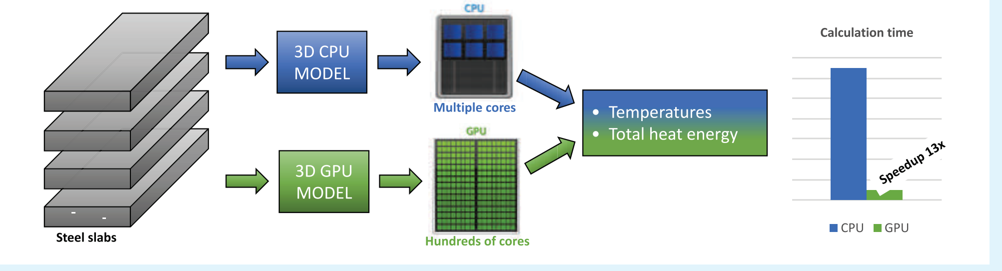
Contact person Seppo Louhenkilpi, Aalto University, seppo.louhenkilpi@aalto.fi

Publications

S. Louhenkilpi, T. Antola, T. Fabritius and A. Jokilaakso, "OES-PDA method for fast on-line analysis of the state of inclusions and cleanliness in liquid steel", *Proceedings of the 10th International Conference on Clean Steel*, Hungarian Mining and Metallurgy Society, Budapest, Hungary.

6 GPU-ACCELERATED COMPUTING OF A TRANSIENT HEAT TRANSFER MODEL

WORK PACKAGE 3



Description of the tool

Accurate calculation of steel slab temperature distribution needs a 3D model and a fine mesh. Therefore, calculating temperatures of dozens of slabs in real time is too time-consuming using CPU-based models. A highly parallelized and fast GPU-based dynamic heat transfer model has been developed and implemented for steel slabs, which takes advantage of the GPU's ability to process thousands of threads simultaneously. The model can calculate up to 100 slab temperature distributions and total heat energies at the same time. It provides the rapid computation capabilities required for online use in continuous casting, and tracking of each slab after it is transferred from the caster to the reheating furnace and then to rolling. It is also a more power- and cost-efficient solution than previously developed CPU models.

Application

The acceleration for a single slab was evaluated using of the relative computational time, which is the dimensionless ratio between the computational time that the model needs to compute the simulation and the wall-clock time of the real slab-heating process being simulated. The relative computational time of the GPU-based computational model is between 0.0015 for a coarse mesh and 0.0072 for a fine mesh. The corresponding multiple of the GPU acceleration, which is the ratio between the computational times of the GPU-based model and the CPU-based model for an identical simulation, is between 5 and 13.

Technologies

The fully implicit and three-dimensional formulation of the heat transfer model is based on the Crank–Nicolson finite difference method. Algebraic equations of the model are solved using the modified Gauss–Seidel–Newton–Raphson method. The computational model is implemented as highly parallel with the use of the NVIDIA CUDA architecture, which enables the launch of the model on graphics processing units (GPUs), allowing for its acceleration.

Scope of application

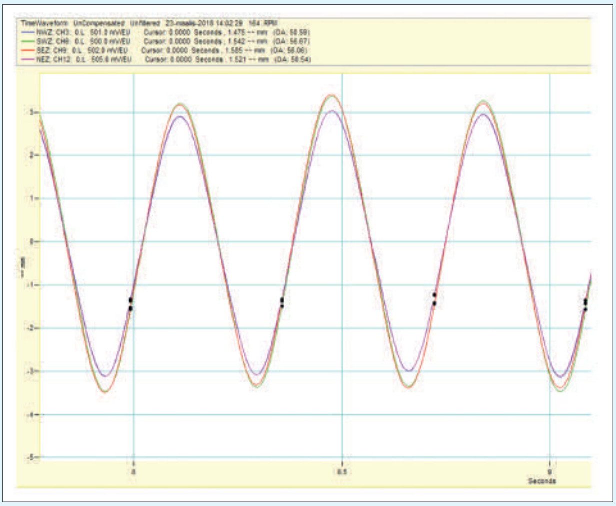
The GPU model is connected to the reheating furnace system FurnaceManager, and it calculates up to 30 slab temperatures and total heat energies in real time. A modified version of the model, which can be used in continuous casting to calculate strand temperatures, will be connected to the continuous casting simulator CastManager.

Contact persons Jukka Laine, Risto Vesanen, Casim Consulting Oy, Agne Bogdanoff, SSAB Europe Oy, Esa Puukko, Outokumpu Stainless Oy, Ari Jokilaakso, Aalto University

Publications C. Westerlund, "Efficient parallel implementation of a transient heat transfer model", Master's thesis, Aalto University, 2018.

7 OSCILLATION STUDY OF CONTINUOUS CASTING

WORK PACKAGE 3



Description of the tool

The aim of this study is to manage and exploit oscillation more effectively in the future. The oscillation has a direct effect on slab quality and mold phenomena. More accurate knowledge and control of the oscillation would provide the next step in continuous casting process control. Especially for automotive and premium grades, more optimized oscillation will provide several benefits.

Application

The study examined how the oscillation equipment works, what the present condition of equipment is, how the logic works in the background, and what the future oscillation possibilities are. After the study, we will have better understanding of oscillation and its possibilities. In the future, oscillation will play a greater role in continuous casting process management and testing.

Technologies

The study has been based on data from the vibration measurement of mold movement and laser-based slab surface profile measurements. The vibration measurement data has been utilized to model the actual movement of the mold. Surface profile measurements have been used to try to detect oscillation and other mold phenomena directly from the slab surface..

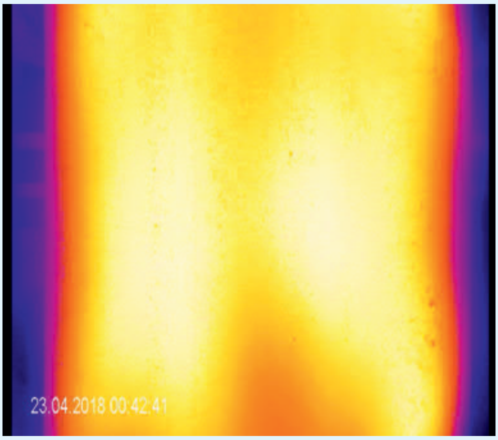
Contact persons Mika Amonsen, SSAB Europe Oy, mika.amonsen@ssab.com
Ismo Rentola, SSAB Europe Oy, ismo.rentola@ssab.com
Leena Määttä, SSAB Europe Oy, leena.maatta@ssab.com

Publications M. Amonsen, “Oscillation study of continuous casting to improve quality of steel”, Master’s thesis, University of Oulu, 2018.

DIMECC

8 MEASUREMENT OF CONTINUOUS CAST STRAND SURFACE TEMPERATURE USING A THERMAL CAMERA APPLICATION

WORK PACKAGE 3



Description of the tool

The aim is to form an overview of how strand surface temperatures develop during casting and to see if there are differences between temperatures at the edges. Temperature differences could reveal problems with the secondary cooling nozzles that have an impact on the slab surface quality and the lifetime of the machine rolls. A second important aim is to have validation data for the Tempsimu and Cast-Manager simulators, which also calculate strand surface temperatures. Simulator parameters can be adjusted using the measurement data to match the temperatures at the measurement point. Validation of the simulation results would improve the safety and quality of continuous casting, because simulators are being used, for example, in calculating the solidification point of the strand.

Application

Temperature measurement is online in the Outokumpu Stainless Oy, Tornio melt shop. The graphical user interface and functions are under development. This development work will continue in an RFCS project called SUPPORT-CAST.

Technologies

The latest infra-red technology, in conjunction with Sapotech's knowledge of slab surface inspection systems and IoT platforms, was used to develop a solution for acquiring and processing surface temperature data from the hot slabs.

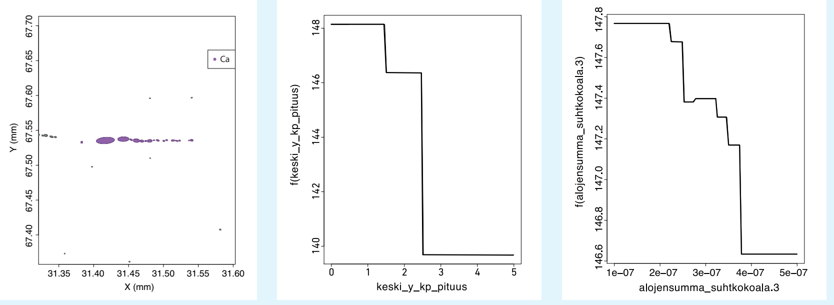
Scope of application

This tool could easily be adapted to other continuous casting machines and rolling processes, where temperature has a role. The full benefits of temperature measurement remain to be seen, since the measurement campaign was launched in April 2018.

Contact persons Juho Moilanen, Outokumpu Stainless Oy, juho.moilanen@outokumpu.com
Marko Petäjäjärvi, Outokumpu Stainless Oy, marko.petajajarvi@outokumpu.com
Hannu Suopajärvi, Sapotech Oy, hannu.suopajarvi@sapotech.fi

9 MODELING OF MECHANICAL PROPERTIES BASED ON INCLUSION CLUSTER ANALYSIS

WORK PACKAGE 3



Description of the tool

In this study, we utilize the tool that we developed to examine inclusion clusters in SEM specimens. The clustering is based on the elliptical approximation of the inclusion shapes and the distances between them. The tool has flexible parameterization for cluster definition, which enables its use for different SEM specimen types. The properties of the inclusion clusters, such as the size, shape, position within the specimen, and chemical composition, are calculated automatically. This information can be utilized to find explanatory or predictive connections between these properties and the mechanical quality factors (e.g. the results of the impact toughness test, tensile strength test, or flangeability test) of the steel using GBM models. The tool improves steel purity control by enabling the automation of finding predictive connections between the properties of the inclusion clusters and the steel properties. The connection between cluster properties and process parameters would be equally interesting, as this information can be used to find process settings that produce steel of higher purity.

Application

GBM models were applied to study the explanatory connections between the properties of the inclusion clusters and the impact toughness test results. SEM analysis of 234 specimens and 15 heats were included in the study. The statistical program R was used for inclusion clustering, finding explanatory or predictive connections, and visualization. The results suggest that inclusion cluster properties provide valuable information that can be utilized in mechanical property prediction and product quality determination.

Technologies

The statistical program R was used for inclusion clustering, finding explanatory or predictive connections, and visualization.

Scope of application

The tool can be used for studying predictive connections between the properties of the inclusion clusters in SEM specimens and the steel properties at any steel plant.

Contact persons Anna-Mari Wartiainen, University of Oulu, anna-mari.wartiainen@oulu.fi
Satu Tamminen, University of Oulu, satu.tamminen@oulu.fi
Teppo Pikkarainen, SSAB Europe Oy, teppo.pikkarainen@ssab.com
Leena Määttä, SSAB Europe Oy, leena.maatta@ssab.com

Publications A.-M. Wartiainen, S. Tamminen, T. Pikkarainen, T. Alatarvas and J. Röning, “Automated inclusion clusters analysis for steel products”, journal paper manuscript.

INTELLIGENT ROLLING

WORK PACKAGE 4

Jarkko Vimpari, Jari Nylander, Juha Jokisaari, Petri Jussila, Eero Putaansuu/SSAB Europe Oy
Esa Puukko, Olli Haapala, Tapani Ylimäinen, Timo Manninen/Outokumpu Stainless Oy
Jari Larkiola, Timo Fabritius, David Porter, Aarne Pohjonen, Joonas Ilmola, Oskari Seppälä, Satu Tamminen, Henna Tiensuu, Aleksi Laukka, Sami Koskenniska, Olli Leinonen, Antti Kaijalainen, Riku-Pekka Nikula, Konsta Karioja, Esko Juuso/University of Oulu
Martti Verho/Marvesoft
Jukka Laine/Casim Consulting Oy
Saku Kaukonen, Juha Roinen, Hannu Suopajärvi/Sapotech Oy
Peter Råback/CSC – IT Centre for Science

Summary of the project's motivation and achievements

Should the world remain stable or should we also think about metal processing from a totally different point of view? For decades, the metal industry has been riding on the crest of a wave of technology and has eagerly implemented new techniques to help the manufacturing processes become faster, more efficient, and environmentally friendly, and to produce better quality. This same trend has continued in the DIMECC FLEX program, partly financed by Business Finland. In Work Package 4, we concentrated on improving the efficiency of hot and cold rolling by using modeling and new measurement technology as key tools.

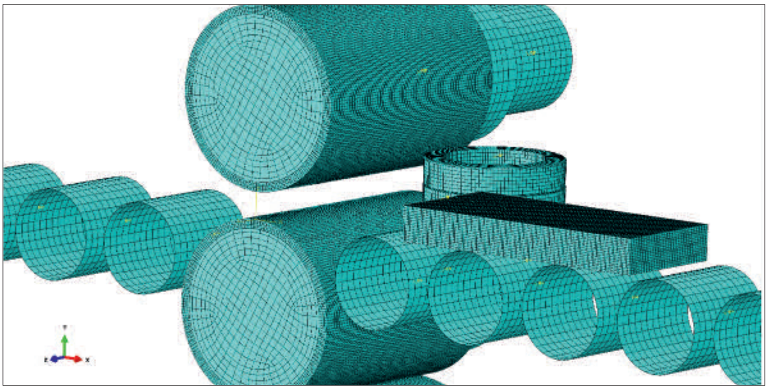


Figure 1. **Symmetrical finite element mesh of a roughing mill.**

Digitalization is changing the operational basis of companies totally and forever. The same work that used to take a huge amount of manual work is nowadays done simply by pressing one button. In the future, even this button pressing could become unnecessary as models and automation systems can make the right decisions leading to the best available solution. Anticipation of this, in particular, has been a core idea of the whole Work Package 4 in the FLEX program. Communication between humans and machines becomes more accurate and it happens in real time, resulting in value chain formation coming faster and faster.

Traditionally, the rolling processes have been controlled by reacting to problems that occur, but now the main idea was to change the playground to be more proactive and to be able to foretell the final result by monitoring the processes reacting to changed situation already before the problems occur. Autonomous models helping human decision-making surely have the capabilities to answer the call of ever-increasing quality demands and complexity in steel manufacturing processes.

The ultimate goal was to raise the efficiency of Finnish rolling mills to the level of the strongest rivals. In order to meet this goal, we should minimize production disturbances, stabilize the rolling process itself, improve quality, and minimize scattering. The powerful tool chosen was modeling in all forms. This includes mathematical, statistical, physical, and finite element (FEM) models. The main industrial partners were Outokumpu and SSAB, with a couple of SMEs. The main role of the major industrial players was to produce enough data for modeling and to implement models in everyday life. The main research partner was the University of Oulu, where most of the models were created. The new models created in this program are quite unique and there are no such models available on the markets.

The major industrial goal of this project was to improve productivity in the rolling mills of Outokumpu and SSAB. On the scientific side, this means a lot of new knowledge and many articles in high-level papers and conferences, written by the University of Oulu in close collaboration with the above-mentioned industrial partners. SMEs like Sapotech, Marvesoft, and Casim Consulting were also involved either as partners or subcontractors. The main idea was to turn the traditional way of reacting to process disturbances into a more predictive way. High production efficiency requires minimizing process disturbances and production breaks, and modeling was seen to be a potential way of doing this. The major industrial goals were: optimized reheating parameters of the slabs (Outokumpu, University of Oulu, Casim Consulting), an innovative approach to improve the production stability of high-strength steels in rolling processes using modeling and automated analysis (SSAB, University of Oulu, Marvesoft), integrating FEM modeling into the optimal set-up of rolling processes (SSAB, Outokumpu, University of Oulu), and the control of scale formation in a walking beam furnace (Outokumpu, University of Oulu). In addition, several other topics were covered in this project.

Company impact

> "The achievements of DIMECC FLEX help us realize energy savings and minimize the amount of unnecessary scrap during the production of advanced high-strength steels. This supports our ambition to become one of the most sustainable steel companies in the world, whereas our customers will benefit from the improved consistency of materials."
>
> ***Petri Jussila,*** *Product Development Engineer, SSAB Europe*

The different roles of the large companies, research institutes, and SMEs have been quite clear. The researchers at the university model the existing processes and apply the result to rolling metallurgy. The created new knowledge helps the industry to make its own processes more efficient. The SMEs produce new data using new measurement technologies. The major companies had a clear role in comprehensive research of manufacturing processes, combining the right measured data in models, and above all exploitation and application of results in the correct way. Without the actual data and measurements, the academic research would have remained inadequate. This kind of symbiosis has enabled taking fast development leaps and has been beneficial for all involved parties. We should maintain this kind of collaboration in the future. The companies can utilize the results in the number of production disturbances or higher mill availability, and the university has gained several new scientific papers and PhD subjects. High level know-how provided by the university and the application of it in a real industrial environment are crucial matters in the success of this kind of program.

Hot rolling itself is quite a condensed concept. Therefore, it is better to discuss rolling as a larger entity. In this work, the reheating of slabs, roughing and finishing mills, and strip cooling are included. For cold rolling, a similar decision to include all major process steps was made. As the program proceeded, we were forced to reduce this ambitious goal because the budget and schedule were cut. Naturally, this affects the results and the utilization of them.

It is surely not enough to focus only on rolling and the modeling of it, but we should see the research field as a part of an even larger entity. The models created in this program help the industry to make even more challenging products, the time to develop them decreases, and research contributions are more easily focused on matters that are currently acute. In this sense, the DIMECC FLEX program has a tight bond with another Business Finland funded program, StEFA (Steel Ecosystem for Focused Applications), which has concentrated more on this product-related side of the steel industry.

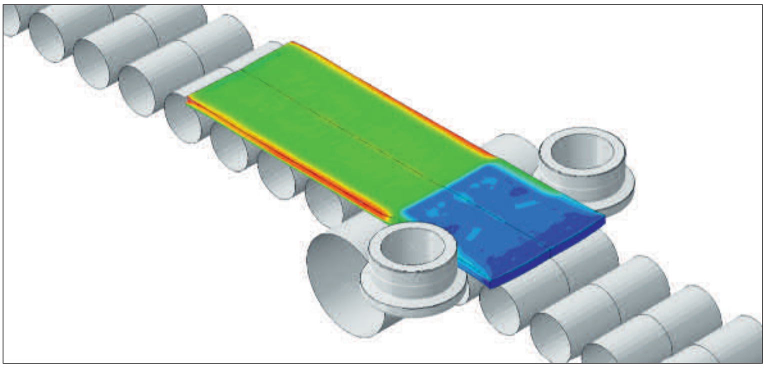


Figure 2. **Pass schedule simulation for vertical roll profile optimization.**

Key results and impacts

A lot of work has been done and plenty of results are available. Here are some example highlights of the key results of this program:

- The main factors affecting the ski-end effect in the transfer bar and hot-rolled strip are now far better understood. This makes it easier to affect those problems in the hot rolling mill.
- Combining the phase transformation models in CCT diagrams has helped a lot in producing high-strength steel grades, which have suffered from difficult hot and cold rolling. Using the results of combined models for AHSS, it has been possible to reduce the number of expensive and massive production tests in both the SSAB Raahe and Hämeenlinna plants. This has been one of the first times optimizing both hot and cold rolling at the same time, and also the continuous hot dip galvanizing process all the way to the final customer. These positive experiments will also be beneficial for other parties.
- The model of strength of steel at high temperatures helps estimations of rolling forces and deformation resistance in hot rolling conditions.
- A dynamic FEM-based model of vertical rolls has been created and it helps to optimize the process.
- A dynamic FEM-based model of slab reheating can be used in process control.
- More intelligent monitoring methods have been piloted to find hard-to-measure phenomena during cold rolling, which are related to the incoming material properties of AHSS. This enables quality improvement, rolling stability, and faster optimization of process parameters for new steels, and speeds up the launch of a new product to market. This improves the competitiveness of the Finnish steel industry. This is one step closer to a fully automatic system for decision support.
- The measured energy efficiency of different steel grades and dimensions is shown online. The best and worst cases are displayed and

followed. The program suggests changes to pass schedule values to lower consumption using cold rolling theory.

- An innovative measurement technology has been piloted in quality monitoring of a hot rolled strip.

Online implementation of the slab heating model is expected to minimize our slab temperature deviation by 40%, thus significantly improving stability of further hot rolling processes. Implementation of a physically based laminar cooling setting will decrease our hot coiling temperature deviation by 30%.

Company impact

Development of FurnaceManager

FurnaceManager enables accurate slab temperature information that is a crucial starting point of reliable hot rolling process. Decreased deviation will also improve quality and decrease energy consumption.

Pekka Vainio, *Manager – Hot rolling, Outokumpu Tornio Operations BA Europe*

A complete rough rolling FE model will be used to design optimal edge roll shapes for different slab thicknesses. By means of the new design, slab width could be targeted closer to minimum tolerance. Due to high volumes, a yield improvement of 0.1–0.2% has significant economic value.

Company impact

Roughing Mill optimization by Fem-Modelling

FEM-simulation is an excellent tool to avoid expensive and time-consuming tests when optimizing design of vertical rolls. Simulation result will be a basis of new edge roll shape that minimizes material losses.

Esa Puukko, *Manager – R&D, Outokumpu Tornio Operations BA Europe*

Quality prediction models (slivers, centerline) installed in the existing QMT platform will improve our predictability to meet customer requirements.

New measurement technology for transfer bar inspection will improve our descaling control. Therefore, the rate of defects related to rolled-in-scale and roughness will be decreased by 50%.

An offline simulation tool for batch annealing will enable optimal settings from an energy and product properties point of view. By using an optimal setting, at least 10% energy savings will be expected.

The exit speed of AHSS coils is increased by over 50 m/min because of optimized mill set-up values. The estimated annual saving is more than 0.5 MEUR. The best operational practice is now easier to achieve by using information from the summary classification of similar AHSS coils.

Cold rolling is one of the most energy-intensive processes of plastic deformation. Power demands on the tandem cold mill can be reduced by optimizing set-up values (e.g. tension distribution and lower total reduction) and the usage of main pumps during rolling phases and breaks. A real-time monitoring system for used energy helps to improve operating efficiency. The specific total energy (kwh/t/mm) of a tandem cold rolling mill is reduced by approximately 2% by optimizing entry thickness and load distribution.

Further information

KEY PUBLICATIONS:

Ilmola, J., Pohjonen, A., Seppälä, O., Leinonen, O., Larkiola, J., Coupled Multiscale and Multiphysical Analysis of a Hot Steel Strip Tandem Rolling and Microstructure Formation During Water Cooling (Accepted for a publication Metal Forming 2018, Procedia Manufacturing, Elsevier).

Seppälä O., Pohjonen A., Kaijalainen A., Larkiola J., Porter D., Simulation of bainite and martensite formation using a novel cellular automata method (Accepted for a publication Metal Forming 2018, Procedia Manufacturing, Elsevier).

Ilmola, J., Seppälä, O., Leinonen, O., Pohjonen, A., Larkiola, J., Jokisaari, J., Putaansuu, E., Multiphysical FE-analysis of a Strip Head Curving Phenomenon in a Tandem Mill, AIP Conference Proceedings 1960, 090007 (2018); https://doi.org/10.1063/1.5034933.

Tamminen S., Ferreira E., Tiensuu H., Helaakoski H., Kyllönen V., Jokisaari J., Puukko E. and Röning J., "An online quality monitoring tool for information acquisition and sharing", International Journal of Industrial and Systems Engineering, 2018.

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Nikula, R.-P., Karioja, K., Steel grade specific stress predictions to support roller leveller maintenance. First World Congress on Condition Monitoring, London, 13–16 June, 2017.

CONTACT PERSONS:

Jarkko Vimpari, SSAB
Esa Puukko, Outokumpu
Jari Larkiola, University of Oulu

PARTICIPANTS:

Outokumpu Stainless Oy
SSAB Europe Oy
Marvesoft
Casim Consulting Oy,
University of Oulu

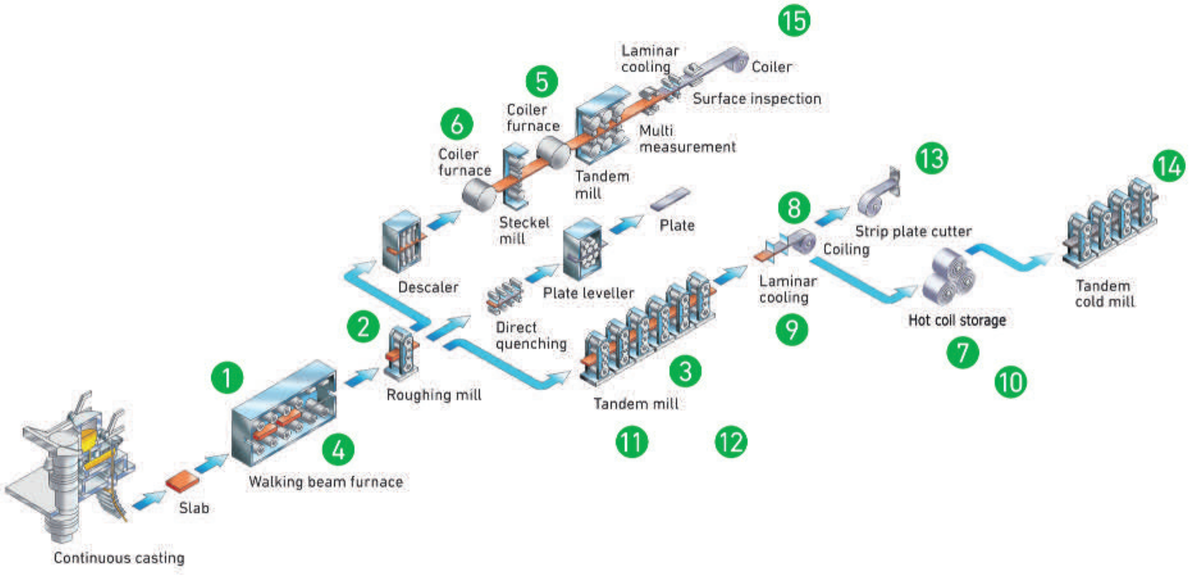
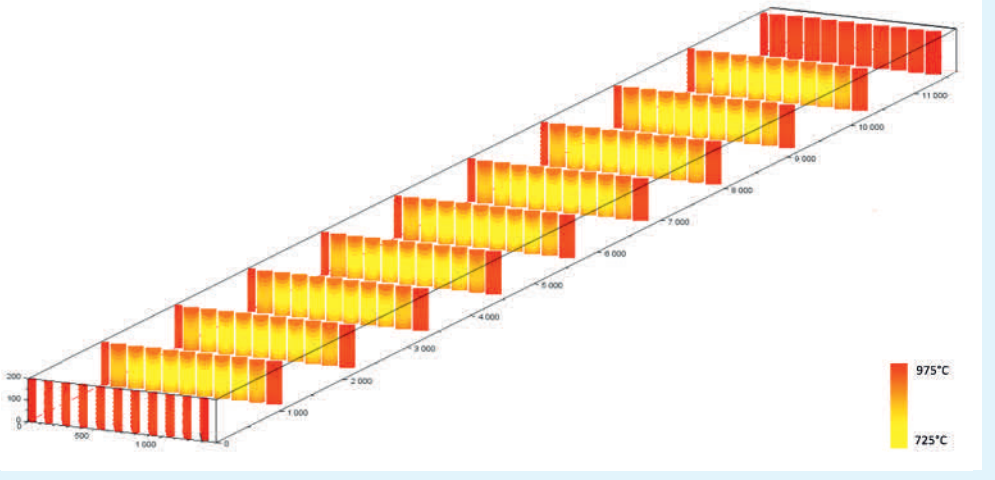


Figure 3. **The Rolling Mill.**

1 DEVELOPMENT OF FURNACEMANAGER

WORK PACKAGE 4



Tools for optimizing Hot & Cold Rolling

Description of the tool

FurnaceManager is a tool to calculate how slab temperature distribution evolves in the walking beam furnace. Temperature is calculated using a three-dimensional heat transfer model that is based on a thermodynamic database and the material properties of IDS.

Accurate slab temperature information is crucial for the hot rolling process. Traditional pass schedule calculation models are based on average or core temperature, but a full temperature distribution model allows new and more accurate methods to control the rolling process.

Application

An online connection to the Outokumpu Stainless Tornio hot rolling mill is under construction and the tool will be used for online slab heating control at operator level and for pass schedule calculation.

Technologies

The introduction of GPU technology has reduced the calculation time by 60%, compared to traditional CPU computing. The target calculation performance level set for online usage was achieved.

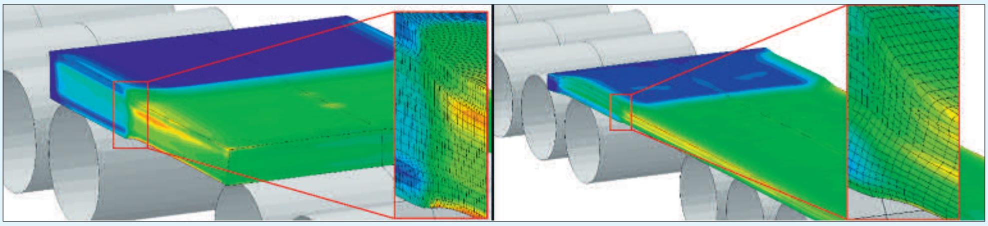
Scope of application

FurnaceManager can be coupled with CastManager and the upcoming SlabManager to follow a slab's full temperature history from casting to hot rolling. Having the full thermal history from the whole process chain creates new possibilities to develop advanced quality indicators such as the scale formation module.

Contact persons – Inventors Jukka Laine, Casim Consulting Oy, Olli Haapala Outokumpu Stainless

2 ROUGHING MILL OPTIMIZATION BY FEM-MODELING

WORK PACKAGE 4



Description of the tool

In the roughing process, a slab is horizontally and vertically rolled. Vertical rolling is used for odd passes to control strip spreading and achieve a specified transfer bar width. A high-quality surface of finished stainless-steel products is demanded. In the vertical rolling process, the corner of the slab may be placed on the transfer bar causing edge scratches by the combination of horizontal and vertical passes, as well as the profile of the vertical mill roll. The FE model is used to simulate combined horizontal and vertical rolling passes and thus optimize pass schedules and vertical roll profile.

Application

The model has recently been completed, and in the preliminary simulations with a set-up pass schedule and vertical roll profile, the corner of the slab was placed on the transfer bar. Optimization simulations will be carried out in further studies.

Technologies

A complete rough rolling FE model has been created using the non-linear functions of Abaqus Explicit software. The automation logic of the roughing mill inside the FE model is implemented using a self-coded Fortran 77 VUAMP-subroutine. The automation logic requires pass schedule parameters as an input, and the whole simulation is automated. Material properties are defined using the Inter Dendritic Solidification (IDS) analysis package (developed in SIMP). Experimental tests to determinate material deformation resistance have been carried out at the University of Oulu. Experimental results are fitted to the Hensel-Spittel fitting model to extrapolate and interpolate non-experimentally defined parameters.

Scope of application

The created model for rough rolling optimization can be coupled to the FE model of the Steckel mill created in the SIMP program. In addition, doctoral student Oskari Seppälä is developing a model to estimate static recrystallization in hot rolling. This physical model can be implemented in the rough rolling process in the future.

Contact persons – Inventors Joonas Ilmola, Oskari Seppälä, Jari Larkiola, University of Oulu
Olli Haapala, Esa Puukko, Outokumpu Stainless Oy

DIMECC

3 FEM MODEL FOR THE ROUGHING MILL AND FINISHING MILL IN HOT STRIP ROLLING

WORK PACKAGE 4

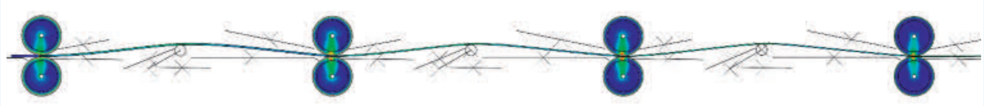


Figure 1. **Four hot strip rolling stands with strip tension controlling loopers (Mises stress distribution).**

Description of the tool

In hot steel rolling processes, a slab is generally rolled to a transfer bar in a roughing process and to a strip in a hot strip rolling process. Over several rolling passes, the front-end may bend upward or downward due to asymmetrical rolling conditions, causing entry problems in the next rolling pass. Many different factors may affect the front-end bending phenomenon and are very challenging to measure. Thus, a customized multiphysical finite element model is designed and built to simulate front-end bending in a hot strip rolling process. To simulate the functioning of the hot strip mill precisely, the automated controlling logic of the mill must be considered. A complete model of the hot strip rolling process is required to achieve reliable boundary conditions between sequential rolling stands.

Application

Roughing and finishing mill models are utilized to study front-end bending and the effect of strip tensioning on longitudinal flatness and material flow stabilization between sequential rolling stands. A built-in automation system inside the FE model was validated using IBA process data. Offline hot strip rolling simulations with setup pass schedules correlated with the rolling process.

Technologies

A complete hot strip rolling FE model has been created using the non-linear functions of Abaqus Explicit software. The automation system inside the FE model has been implemented using a self-coded Fortran 77 VUAMP subroutine. Material properties are defined using the Inter Dendritic Solidification (IDS) analysis package (developed in SIMP) and experimental material testing at the University of Oulu.

Scope of application

The hot strip rolling model has been extended to consider accelerated water cooling on a run-out table. In addition, a microstructure formation model developed by Dr. Aarne Pohjonen has been implemented in the water cooling model. We have successfully coupled multiphysical and multiscale models from several researchers in a single model to simulate hot strip rolling and accelerated water cooling with microstructure formation. In further studies, the final microstructure can be estimated using a microscale model that utilizes a novel cellular automata method developed by doctoral student Oskari Seppälä.

Contact persons – Inventors Joonas Ilmola, Oskari Seppälä, Aarne Pohjonen, Jari Larkiola, University of Oulu, Juha Jokisaari, Eero Putaansuu, Jarkkko Vimpari, SSAB Europe

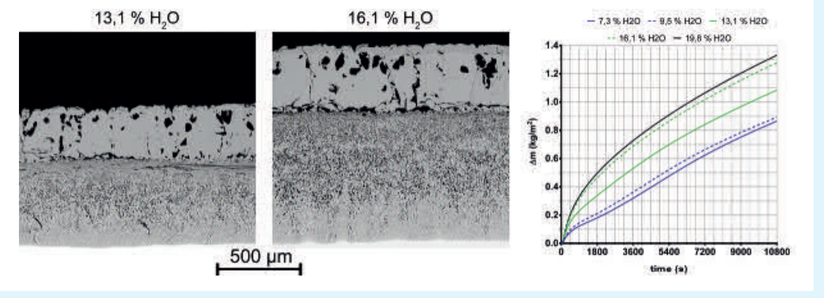
Publications

Ilmola, J., Seppälä, O., Leinonen, O., Pohjonen, A., Larkiola, J., Jokisaari, J., Putaansuu, E., Multiphysical FE-analysis of a Strip Head Curving Phenomenon in a Tandem Mill (ESAFORM 2018).

Ilmola, J., Pohjonen, A., Seppälä, O., Leinonen, O., Larkiola, J., Coupled Multiscale and Multiphysical Analysis of a Hot Steel Strip Tandem Rolling and Microstructure Formation During Water Cooling (Metal Forming 2018).

4 SCALE GROWTH MODELING

WORK PACKAGE 4



Description of the tool

This research was based on the transition from using propane (C3H8) to using methane (CH4) as the burning agent in the steel slab reheating furnace at Outokumpu Tornio works. Compared to burning propane, burning methane produces an atmosphere with a higher water content and thus, theoretically, should lead to a higher oxide growth rate on the steel slabs' surface as they are reheated prior to hot rolling. The main aim for this task was to find out whether thermogravimetric results show a significant difference between varying H_2O contents in the furnace atmosphere on the oxide scale growth of AISI 304 austenitic stainless steel. Chosen H_2O (g) contents were 7.3, 9.5, 13.1, 16.1, and 19.8%. Other gaseous contents were 9.8% CO_2, 4% O_2 and N_2 bal. The 13.1% H_2O (g) atmosphere corresponds to a theoretical full burn of propane with 20% excess air (79% N_2, 21% O_2), whereas the 16.1% H_2O (g) corresponds to the same when burning methane. Other aims included scale layer thickness, morphology, and adhesion properties between the 13.1% and 16.1% H_2O atmospheres. The test hold time was 180 minutes at isothermal 1260 °C.

Scope of application

Thermogravimetric results showed a similar growth pattern for all atmospheres with the end scaling amounts being in the same order as the H_2O content in the atmosphere. However, the end scaling amount did not scale linearly, and the differences between 7.3% and 9.5%, as well as between 16.1% and 19.8% H_2O atmospheres' area normalized end scaling amounts, were small, whereas the difference between 9.5% and 13.1%, and 13.1% and 16.1% was high at almost 20%. Outer oxide (Fe_2O_3) thickness is the same in all atmospheres, which complies with the outer oxide growth being only a function of time and temperature. Inner oxide layer thickness varied between different simulated furnace atmospheres and was 450 µm for 13.1% H_2O atmosphere samples and 740 µm for 16.1% H_2O samples. The inner oxide layer pore (void) count increased significantly from 5.9% of the total inner oxide area to 15.4% of the total area when going from 13.1 to 16.1% H_2O in the atmosphere. In both 13.1% H_2O and 16.1% atmospheres, the scale layer–steel interface was continuous. Based on the results, and the benefit gained from increased porosity, using water jet descaling to remove the scale layer formed in the atmosphere, simulating methane burn, is easier than removing one formed in a propane burn atmosphere.

Contact persons – Inventors
Aleksi Laukka, University of Oulu, aleksi.laukka@oulu.fi
Timo Fabritius, University of Oulu, timo.fabritius@oulu.fi
Esa Puukko, Outokumpu Stainless Ltd., esa.puukko@oulu.fi

Participants
University of Oulu, Process metallurgy research group
Outokumpu Stainless Ltd., Tornio Research Centre

5 MODELING THE CENTERLINE DEVIATION OF THE STEEL STRIP

WORK PACKAGE 4

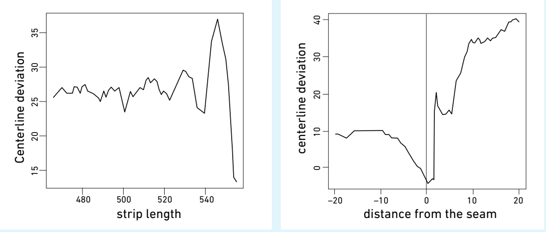


Figure 1. **Two different ways to model centerline deviation. The figure on the left shows the tail of the steel strip and the figure on the right shows the seam area of two strips.**

Description of the tool

This tool is based on the models for steel strip centerline deviation. Strip centerline deviation is a critical problem on the Outokumpu RAP line in Tornio. In the worst case, a strip position can stop all production and brake the devices. The purpose is to find out risky strips based on the hot rolling history of the products, and to find the root causes behind the centerline deviation. With better process control, the company can improve the quality of products and the cost effectiveness of the company.

Application

Due to the complexity of deviation measuring, a lot of attention has been given to which response describes best the deviation. The most critical thing is to find out which strips should not be welded together. The final model will predict the risk for a seam when two strips are welded together. Figure 1 shows the alternatives for the response variable. The first alternative is to model the tail area of the strip and the second is to model the seam area of two strips. During the first year, the seam areas between two strips were located and the hot rolling data was allocated accordingly.

Next steps

We are going to classify the shapes of the deviation to different groups and use that as a response for the models. With our models, it is possible to find out what kind of hot rolling history is dangerous and what strips match each other well. The final model will be implemented on the Outokumpu RAP line in Tornio.

Technologies

The free statistical program R was used for pre-processing and analyzing the data, classification, modeling, and visualization. R enables easy implementation on devices used by product design engineers. Powerful machine learning methods are capable of modeling highly nonlinear process dependencies and enable the effective use of process data. The tool was developed in co-operation with Outokumpu.

Scope of application

The tool can be used in any other processes involving strip-like products. The developed model enables users to understand better the quality of products, how the process works, and how the model predicts and performs.

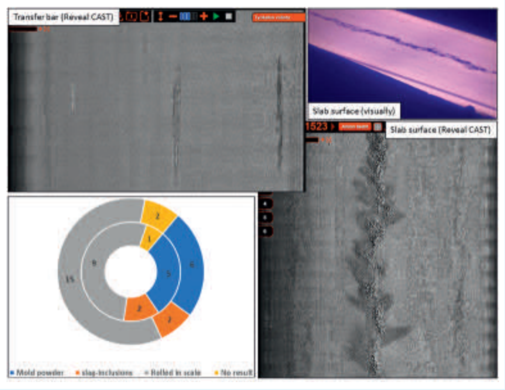
Contact persons – Inventors
Henna Tiensuu, Satu Tamminen, University of Oulu/BISG
Olli Haapala, Outokumpu Stainless Oy

Additional Information/ Publications

Tamminen S., Ferreira E., Tiensuu H., Helaakoski H., Kyllönen V., Jokisaari J., Puukko E. and Röning J., "An online quality monitoring tool for information acquisition and sharing", International Journal of Industrial and Systems Engineering, 2018.
Tamminen S, Tiensuu H, Ferreira E, Helaakoski H, Kyllönen V, Jokisaari J, Puukko E, " From Measurements to Knowledge – Online Quality Monitoring and Smart Manufacturing", ICDM, 2018.
Tamminen S., Liu X., Tiensuu H., Ferreira E., Puukko E., Röning J., "AI enhanced alarm presentation for quality monitoring", SmartData, 2018.

6 UTILIZATION OF SAPOTECH REVEAL CAST CAMERA INSPECTION FOR HOT ROLLING QUALITY MONITORING

WORK PACKAGE 4



Description of the tool

Sapotech Reveal CAST is a system designed for hot metal surface monitoring, providing high-definition images of a cast and rolled product surface. The combined system, consisting of imaging units and laser illumination, is capable of providing image data for online surface quality monitoring purposes, as well as for long-term surface quality analysis and development activities. Automatic surface defect detection using advanced image analysis algorithms creates a great potential for cost savings by enabling quick corrective actions when unexpected defects are observed during hot rolling operations.

Application

Reveal CAST technology has been utilized in the process environment for monitoring and detection of defects formed on the transfer bar surface during the hot rolling process of stainless steels. Various characteristics of the transfer bar top and bottom side can be evaluated and compared to processing parameters to gain deeper understanding of the effect of these parameters on strip surface quality. Upcoming integration with a slab imaging system will enable more precise tracking of defect origins.

Technologies

A web-based user interface provides easy access to image data, which is stored on a cloud server. Depending on the needs of the end-user, additional integrated technologies can be added (e.g. integration of multi-camera systems, product dimension measurements).

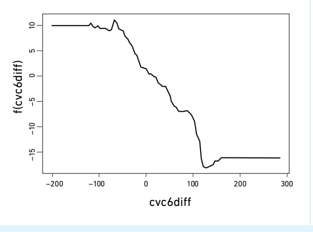
Scope of application

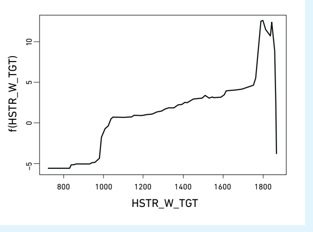
- Utilization of Reveal CAST technology to monitor and visualize the hot rolling process, which is impossible to do with the human eye, to recognize surface imperfections and to provide instant quality feedback for daily operations, as well as for long-term surface quality development
- Implementation of Reveal CAST technology to estimate the feasibility of the imaging steel strip with relatively high velocity and simultaneously provide image data of sufficient image quality
- Investigation of image data to verify which surface defects can be visually observed from the image. The second step includes the utilization of algorithms for automatic defect recognition.

Contact persons – Inventors Tapani Ylimäinen, Outokumpu Stainless; Saku Kaukonen, Sapotech Oy
Juha Roininen, Sapotech Oy

7 PREDICTING THE FLATNESS OF STEEL STRIPS

WORK PACKAGE 4





Description of the tool

The flatness of a steel strip is a quality property that is important information for process settings. To be able to determine safe process values, flatness should be described with a simple value that covers the magnitude, variation, and direction of the possible defect. Currently, only the average flatness is used in process settings planning, without knowledge of the direction. Thus, in the worst case, the wrong settings may cause damage to the machinery. There is a need for an improved description of the flatness and a prediction model that can be used to find the root causes of reduced quality in process settings.

Application

During the first year, the research revealed that the link between average, standard deviation or total deviation (aggregate of average and deviation) of the flatness measurements and the process settings is quite weak. However, the effect of last passes increased in every model. In particular, the CVC position and the change in it after the previous strip had an effect on flatness. The conclusion was that, in order to be able to link process parameters with the defect, a better response variable will be needed. A data set with 30 measurement points from each product was collected and analyzed. As a result, we developed a rule-based analysis tool to find flatness defects with the corresponding process settings.

Technologies

The free statistical program R was used for prediction models and rule-based analysis. Powerful machine learning methods are capable of modeling highly nonlinear process dependencies and enable the effective use of process data. The tool was developed in co-operation with SSAB.

Scope of application

These methods can be utilized to find links between data streams or time series in industrial processes, without limiting application areas.

Contact persons – Inventors

Satu Tamminen, University of Oulu/BISG
Juha Jokisaari, SSAB

Additional Information/ Publications

Tamminen S., Ferreira E., Tiensuu H., Helaakoski H., Kyllönen V., Jokisaari J., Puukko E. and Röning J., "An online quality monitoring tool for information acquisition and sharing", International Journal of Industrial and Systems Engineering, 2018.
Tamminen S, Tiensuu H, Ferreira E, Helaakoski H, Kyllönen V, Jokisaari J, Puukko E, "From Measurements to Knowledge – Online Quality Monitoring and Smart Manufacturing", ICDM, 2018.
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Liu X, Tamminen S, Su X, Siirtola P, Röning J, Riekki J, Kiljander J, & Soininen JP, "Enhancing Veracity of IoT Generated Big Data in Decision Making". Percrowd in PerCom, 2018.

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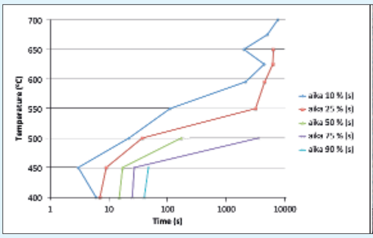
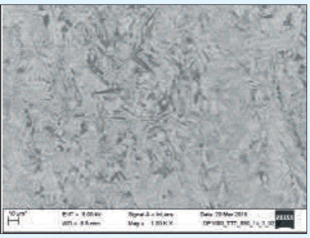
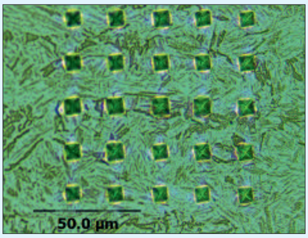
8 PHASE TRANSFORMATION MODEL FOR HIGH-STRENGTH STEEL COIL

WORK PACKAGE 4







Description of the tool

In order to simulate phase transformations occurring after coiling of the steel strip at 600°C, the phase transformation was fitted to experimental isothermal TTT data. The different phases were identified using combined image analysis and hardness measurements. The model was fully coupled with Abaqus finite element software, which enables simulations of different boundary conditions relevant to actual coil storage and transportation conditions. The purpose of the model is to analyze and predict possible variations in mechanical properties, which can occur due to non-uniform cooling of the steel strip after it has been coiled.

Application

The model was fitted to experimental data, and test simulations corresponding to some realistic coil-cooling conditions were performed.

Technologies

The phase transformation model was programmed using the Fortran 90 programming language, and Matlab was used for image analysis in order to identify the fractions of different phases (ferrite, bainite and martensite). Extensive microscopy and hardness measurements were performed in order to increase the reliability of the experimental data and analysis.

Scope of application

Fully coupled heat conduction and phase transformation models can be applied in different thermo-mechanical process simulations.

Contact persons – Inventors

Aarne Pohjonen, Aarne.Pohjonen@oulu.fi
Sami Koskenniska, Sami.Koskenniska@oulu.fi
Joonas Ilmola, Joonas.Ilmola@oulu.fi
Olli Leinonen, Olli.Leinonen@oulu.fi

Additional Information/ Publications

Pohjonen, A., Somani, M., Porter, D. *Modelling of austenite transformation along arbitrary cooling paths*, Computational Materials Science, Vol. 150, pp. 241–251, 2018.
Pohjonen, A., Kaijalainen, A., Mourujärvi, J., Larkiola, J. *Computer simulations of austenite decomposition of hot formed steels during cooling*, Procedia Manufacturing, accepted for publication.

9 CELLULAR AUTOMATA PHASE TRANSFORMATION MODEL FOR BAINITE AND MARTENSITE

WORK PACKAGE 4

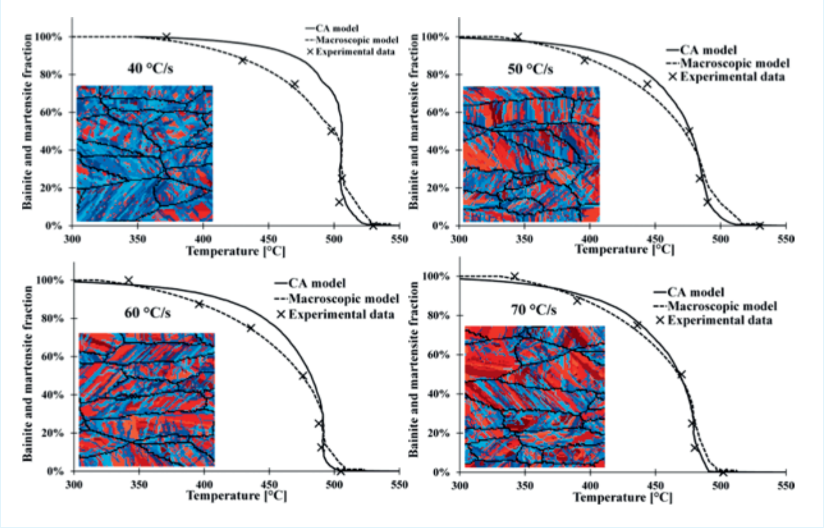


Figure1. **Bainite and martensite formation curves compared to a macroscopic model and experimental data, as well as images of resulting microstructures for each cooling rate.**

Description of the tool

A novel cellular automaton is used to simulate the evolution of microstructure of steel during cooling. The tool is used to predict the resulting microstructure of steel after rolling and cooling.

Application

The CA simulation was compared to a macroscopic simulation method, as well as test samples obtained from a rough rolled strip that were compressed and cooled at constant cooling rates. We found good correspondence between these different methods.

Technologies

Coding: Python 2.7; Measurement technology: Gleeble 3800, SEM.

Scope of application

With detailed information about the microstructure, various mechanical properties, such as yield strength and fatigue properties, can be estimated with greater accuracy than before.

Contact persons – Inventors

Oskari Seppälä, Aarne Pohjonen, Antti Kaijalainen, Jari Larkiola, David Porter, University of Oulu

Additional Information/ Publications

Seppälä O., Pohjonen A., Kaijalainen A., Larkiola J., Porter D., Simulation of bainite and martensite formation using a novel cellular automata method, to be published in Metal Forming 2018 conference proceedings.

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10 HEAT EXCHANGE BETWEEN HOT AND COLD COILS IN STORAGE

WORK PACKAGE 4

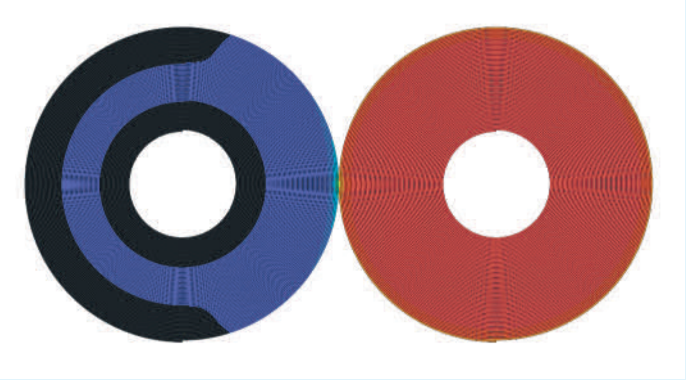


Figure1. **Heat transfer between hot and cold steel coils.**

Description of the tool

The FE model of coil heat exchange was developed to predict coil temperature evolution in storage between hot and cold coils. High temperatures and rapid temperature changes can cause phase changes and thereby defects to the mechanical properties of a material near the contact point of coils.

Application

The model predicts the heat exchange between coils and between layers in a coil. The temperature evolution of coils can be used to predict the phase changes and resulting mechanical properties over the whole length of a strip. For now the tool is in offline use, but the calculation is fast enough compared to cooling phenomena to be used online as well.

Technologies

The accuracy of FE calculation is based on an accurate determination of the effective heat transfer coefficient at the contact interface and the emissivity factor of the coil surface. The coefficients were measured using the laboratory mill at the University of Oulu.

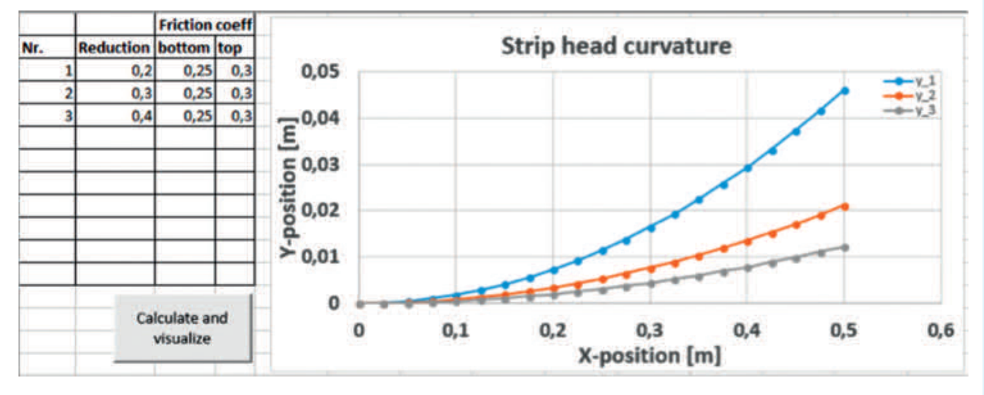
Scope of application

The tool and calculation can be implemented in all cases where any number of coils are touching or near each other and a temperature difference is present. The temperature difference can be between coils and/or between the coils and the ambient temperature. In cases of multiple coils, symmetry can be used to reduce the size of the model.

Contact persons – Inventors Olli Leinonen, Jari Larkiola, University of Oulu

11 MODEL FOR STRIP HEAD CURVATURE

WORK PACKAGE 4



Description of the tool

This tool is designed to be user-friendly and informative. That is why it has been created using Excel. It is used to estimate strip head curvature after a pass with various variables.

Application

A simple equation was created and fitted into curvatures obtained from our FEM model.

$$y = -Dr + D\sqrt{r^2 - x^2}, \qquad r(R, \Delta\mu) = r_1 R^{r_2} r_3 \Delta\mu^{-1},$$

where *x* and y are coordinates, *r* is the radius of curvature, *R* is the reduction, $\Delta\mu$ is the friction coefficient difference, r_1 are fitting variables, and *D* determines the direction of curvature. The current version of the equation works only in a situation with no previous front-end bending, meaning a first pass.

Technologies

GUI coding: VBA (Excel coding language); fitting: Matlab.

Scope of application

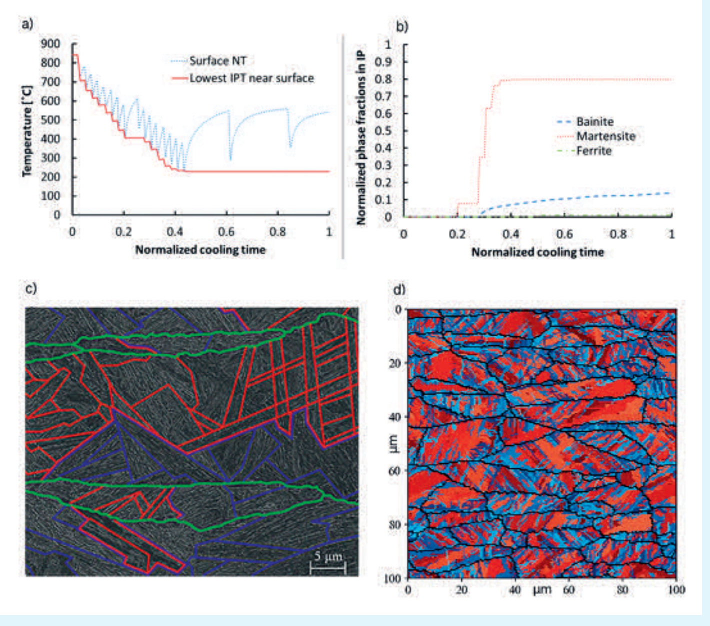
In the future, this tool will be updated to include multiple passes. Then it can be used to design pass schedules so that the strip head tilts slightly upward after each pass. This makes the process more stable, which makes it easier to control, and it decreases the number of scrapped strips.

Contact persons – Inventors Joonas Ilmola, Oskari Seppälä, Aarne Pohjonen, Jari Larkiola, University of Oulu, Juha Jokisaari, Eero Putaansuu, Jarkko Vimpari, SSAB Europe

Additional Information/ Publications Ilmola J., Seppälä O., Leinonen O., Pohjonen A., Larkiola J., Jokisaari J., Putaansuu E., Multiphysical FE-analysis of a Front-end Bending Phenomenon in a Hot Strip Mill, ESAFORM 2018 conference proceedings.

12 COMBINED HOT ROLLING, COOLING, AND MICROSTRUCTURE MODELS

WORK PACKAGE 4



Description of the tool

The developed model can be used to simulate the microstructure evolution in steel during water cooling, taking into account the hot deformation conditions. The full coupling of thermal and phase transformation models (a and b) provides a physical basis for simulating the microstructure affecting the mechanical properties. The experimentally observed microstructure (c) was compared to the simulation (d), with bainite in blue, and martensite in red (note the different length scales in the figures). In future work, the heat transfer between cooling water and the steel strip needs to be accurately determined in order to apply the model in an industrial setting.

Contact persons – Inventors Aarne Pohjonen, Joonas Ilmola, Oskari Seppälä, University of Oulu

Additional Information/ Publications

Ilmola, J., Pohjonen, A., Seppälä, O., Leinonen, O., Larkiola, J., Jokisaari, J., Putaansuu, E., Lehtikangas, P. *Coupled multiscale and multiphysical analysis of hot steel strip mill and microstructure formation during water cooling*, Procedia Manufacturing, accepted for publication.
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Pohjonen, A., Kaijalainen, A., Mourujärvi, J., Larkiola, J. *Computer simulations of austenite decomposition of hot formed steels during cooling*, Procedia Manufacturing, accepted for publication.
Pohjonen, A., Somani, M., Porter, D. *Modelling of austenite transformation along arbitrary cooling paths*, Computational Materials Science, Vol. 150, pp. 241–251, 2018.

13 MECHANICAL STRESS PREDICTION TOOL

WORK PACKAGE 4

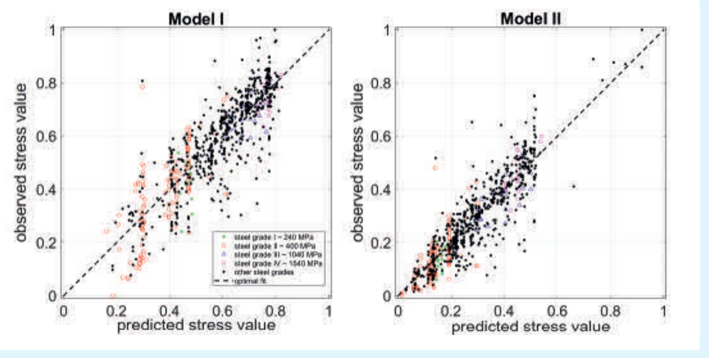

Figure1. **Performance of two models on training data consisting of 752 steel strips.**

Description of the tool

Models for relative stress prediction on a roller leveler. The tool provides advanced evaluation of the relative stress level to improve failure prevention by maintenance planning.

Application

The tool was validated using measurement and process data from a roller leveler that is in continuous operation at a steel mill. The primary application of the tool is maintenance planning, and it could be used to support production planning. Currently, the model is an offline engineering tool, and it could be developed for online applications.

Technologies

Vibration measurements, process data, Matlab-based signal processing, feature extraction, and regression modeling.

Scope of application

This technology is widely applicable in steel mill machinery stress monitoring. Similar signal processing techniques have been applied in steel cutter stress-level evaluation.

Contact persons – Inventors

Riku-Pekka Nikula, University of Oulu / Control Engineering
Konsta Karioja, University of Oulu / Mechatronics and Machine Diagnostics
Esko Juuso, University of Oulu / Control Engineering

Additional Information/ Publications

Karioja, K. Nikula, R.-P., Liedes, T., Vibration Measurements and Signal Processing in Stress Monitoring of a Steel Leveller, Maintenance, Condition Monitoring and Diagnostics & Maintenance Performance Measurement and Management, MCMD 2015 and MPMM 2015 (2015).
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14 MONITORING AND OPTIMIZATION TOOL TO IMPROVE COLD ROLLING OF AHSS STEELS (IPROMON)

WORK PACKAGE 4

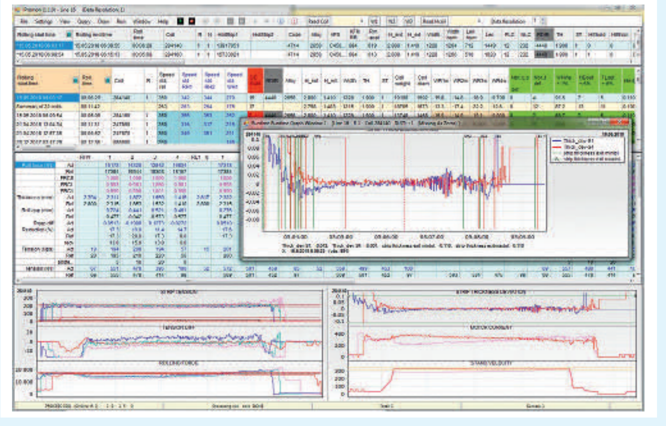


Figure1. **Main view of the iPROMON program.**

Description of the tool

Continuous measurements and monitoring make it possible to see variations in the process. Virtual sensors are used to estimate hard-to-measure variables and automatically to detect deviations in rolling values. Using defects, it is possible to find the relationship between operating conditions and product properties. The best operational practice to achieve good quality is sought and analyzed using information from the summary classification of similar coils. This leads to the one important goal of iPROMON and it is a recipe for successful rolling. The program is designed to be used in process development, and it is directed at persons who are in charge of pass schedule calculation and cold rolling stability. With detailed analysis of data and virtual sensors, it has been possible to expand the dimensional range of the cold mill. It is a vital tool to develop faster new products and dimensions.

Application

At the moment, it is adapted for a 4-stand cold mill and skin pass mill in Hämeenlinna. The program reads data from the factory-wide process data warehouse (PDW), and it is in everyday use in process development in Hämeenlinna.

Technologies

Coding: MS Visual Studio 2017, .NET, Steema TeeChart, Python, MySQL, MSSQL.

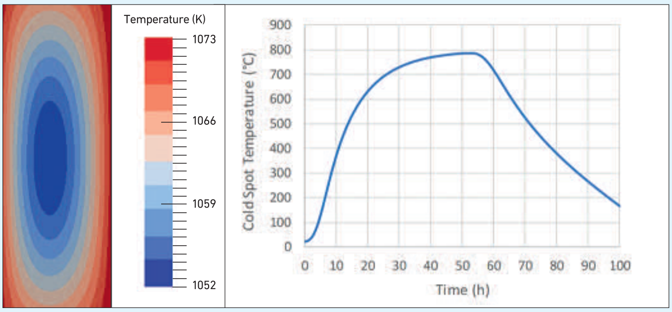
Scope of application

The program can be adapted to any 1–5 stand 4 HI rolling mill. The definition of variables, parameters, and database system must be done again.

Contact persons – Inventors Jari Nylander, SSAB Europe Oy
Martti Verho, Marvesoft

15 BATCH FURNACE ANNEALING SIMULATOR

WORK PACKAGE 4



Description of the tool

Batch annealing is an important process step in the production of martensitic stainless steel. In this process step, hot-rolled coils are stacked in a bell-shaped furnace and annealed for hours in a hydrogen atmosphere. During this treatment, the hard and brittle martensitic microstructure is transformed into soft and ductile spheroidite. The batch annealing simulator is an offline tool for predicting temperature distribution and microstructural changes occurring in the coil in the batch annealing furnace. The simulator enables the optimization of batch annealing practices for coils with different properties, such as chemical composition, strip thickness, and coil width. Improved process control is expected to yield 10% savings in energy and the same reduction in the related CO_2 emissions.

Application

The simulator is implemented using Elmer open source finite element software. The coil is modeled as an axisymmetric body with non-linear orthotropic heat conductivity. Factors such as the thickness of the strip, the thickness of the oxide layer, and the thickness of the gap between subsequent layers are considered. The heat transfer model takes into account convective heat transfer in the furnace and radiation between the coil and the furnace cover. The heat transfer model is coupled with a mathematical model describing the evolution of the mean radius of chromium carbides. The heat transfer model is validated using temperature measurements conducted in the batch annealing furnace with thermocouples. The microstructure evolution model is validated using laboratory measurements.

Technologies

The simulator is implemented using Elmer open source finite element software. Material properties were predicted with ThermoCalc 2018a. The coarsening of carbides was determined in the laboratory with SEM and optical microscopy.

Scope of application

With minor changes, the simulator can be applied to other batch annealing processes, such as batch annealing of cold-rolled coils in the SSAB Hämeenlinna cold rolling mill.

Contact persons – Inventors
Timo Manninen, Outokumpu Stainless Oy
Peter Råback, CSC – IT Centre for Science

DIMECC Oy
Korkeakoulunkatu 7, 33720 Tampere, Finland
DIMECC Factory, Helsinki
DIMECC Factory, Oulu
DIMECC Factory, Tampere
DIMECC Factory, Turku

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