AMET

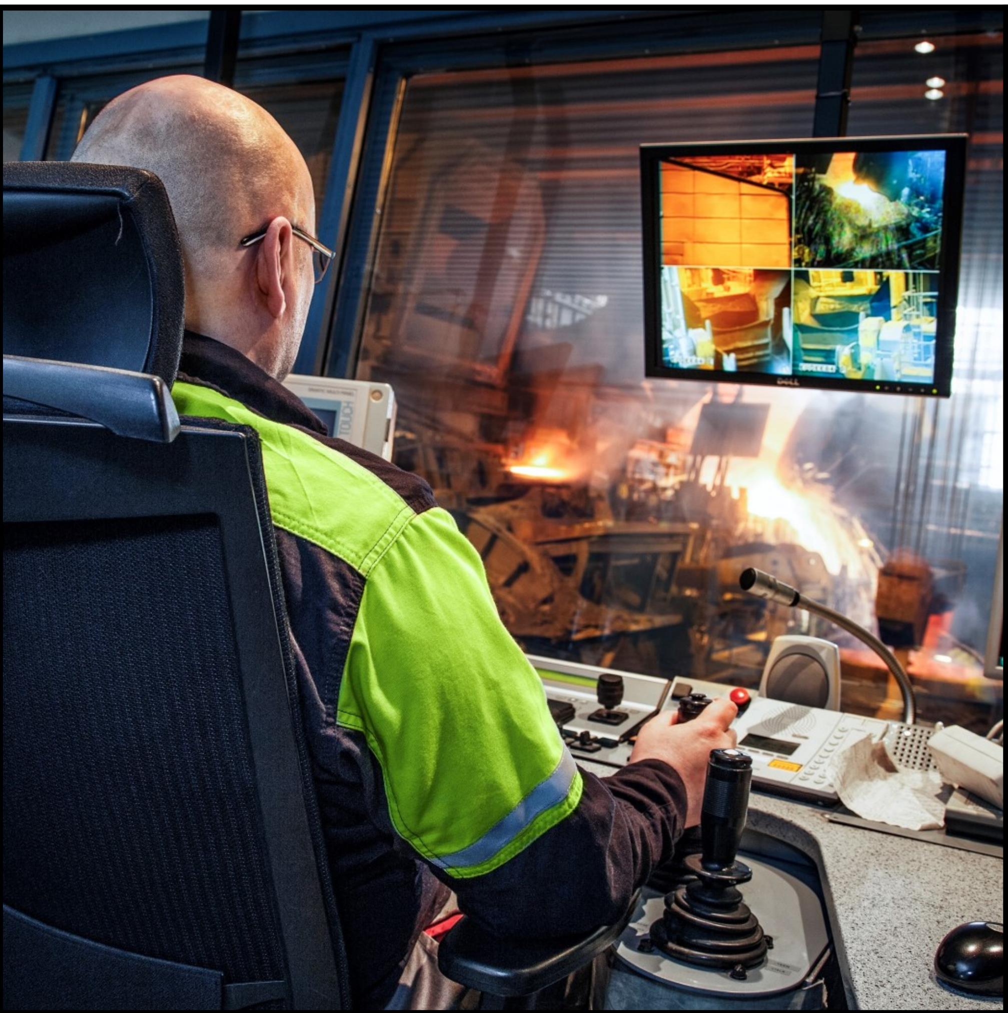
ALUSTATALOUS METALLINJALOSTUKSESSA

PLATFORM ECONOMY IN METALS PROCESSING

FINAL REPORT

LOPPURAPORTTI

2021



ALUSTATALOUS METALLINJALOSTUKSESSA

PLATFORM ECONOMY IN METALS PROCESSING

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PREFACE

We have combined high education, profound research, and high technology successfully in Finland. We have especially focused on innovations and new applications in metallurgical technologies and ICT in Finland for decades. One result and a significant contributor to the effort of combining these two sectors for true solutions in heavy industry are the globally operating spin-off companies providing practical solutions to energy and material efficiency issues. This development has been even faster over the last decade.

The metallurgical industry is inherently driven towards a low environmental load with efficient energy and material use, as well as strongly implemented advanced monitoring and measuring methods or systems for online data collection and process control. Strong and successful cooperation between research institutes and the Finnish metallurgical industry with rising SMEs not only encourages but also requires a very integrated collaborative approach. Nevertheless, there remains a need for an authentic testing environment for monitoring and control systems on the industrial scale. This is what we sought to achieve in the AMET consortium, with universities, measurement method developer SMEs, and the Finnish metallurgical industry offering their process chains for implementation demonstrations. More than a dozen practical new solutions have been tested and implemented in operation, providing more accurate measurements that improve process efficiency, as well as results that can contribute to the effort to reduce emissions in the industry.

An important impact of the AMET project has been its support for fundamental and academic research covering the selected unit processes in the steelmaking process chain. This essential research work has focused on the modelling of the main phenomena that determine the behaviour of studied processes (blast furnace, electric arc furnace, refractory management, continuous casting and rolling). These models and artificial intelligence (AI) applications combined with further developed online measuring methods formulate AMET's scientific background. The close connection between universities, SMEs, and steel producers has enabled the AMET consortium members to profile their activities and maximise their skills, not only at national level but also globally. During the project, several studies were conducted simultaneously in projects funded by the European Union.

Even if AMET has promoted fundamental and academic research, its main objective has also been to apply the research results in new AI-based monitoring and controlling services and to utilise the platform approach in industrial pilots and full-scale tests. AMET's industrial implementation orientation has brought several additional challenges to the research, which would never have been confronted in the laboratory environment or in computational work. The demands concerning the stability of the models and the measurement techniques are entirely different in an industrial environment. Many of the developed new models, measurement techniques, and expert systems have been successfully tested in the industrial partners' process environments. In total, more than a dozen solutions will be commercialised because of AMET's results. These tools are available for the metallurgical industry, measurement method developers, and the entire R&D network for utilisation in process control, monitoring, and the further future development of measurement methods.

During the project, it was also shown how the approach of connectivity between different platforms was used to analyse, collect, and transmit data between the connected entities within the platform and external systems of large steel plants. As a project AMET has thus proven truly to be the latest approach in Finland to create innovations and execute their operational implementations even more efficiently.

The strong and in-depth scientific knowledge generated for process monitoring and controlling purposes in AMET has enabled the involved academic research groups to participate in the preparation and implementation of four Horizon 2020 and Research Fund for Coal and Steel (RFCS) projects. In some of these projects, SME companies are also included, aiming to offer methods for implementing systems, broadening the market, and finalising the systems' TRL level to 9. This is a significantly positive systemic scale effect which supports, broadens, and strengthens the background of medium- and long-term research, as well as joint development and innovation actions in the Finnish metal producers' ecosystem, and thus also as part of the international network.

One of the most important enablers of this successful collaboration between the industry, SMEs, and academia has been the public funding from Business Finland. This funding has been crucial in achieving the challenging targets of the AMET project. We wish to express our gratitude to Business Finland, and we are looking forward to continuation and an even higher number of SME companies offering and testing their solutions for the benefit of the metallurgical industry, because we also see great benefits in the cooperation in future programmes.

Juha Roininen

Coordinator for SME sector

Innovation responsible
Chief Metallurgist and CoB

Sapotech Oy & Luxmet Oy

Professor Timo Fabritius

Principal Investigator of AMET

Head of Process Metallurgy Research Unit

University of Oulu

AMET IN BRIEF
PROJECT SUMMARY

AMET in numbers

Duration	**1.7.2019 – 31.12.2021***
Budget total:	**€5.16 M**
SME budget:	**€2.38 M**
Steelmaker budget:	**€0.98 M**
Universities budget:	**€1.80 M**
Publications:	**12 peer-reviewed journal articles, 9 conference papers**
Degrees:	**1 doctoral thesis, 13 master's theses, 1 bachelor's thesis**

* The planned end date was 30.6.2021, but major partners applied for an extension of 6–9 months because of the effects of the pandemic

Consortium

Steelmakers

SSAB Europe Oy
Ovako Imatra Oy Ab**

Universities

University of Oulu
Åbo Akademi University

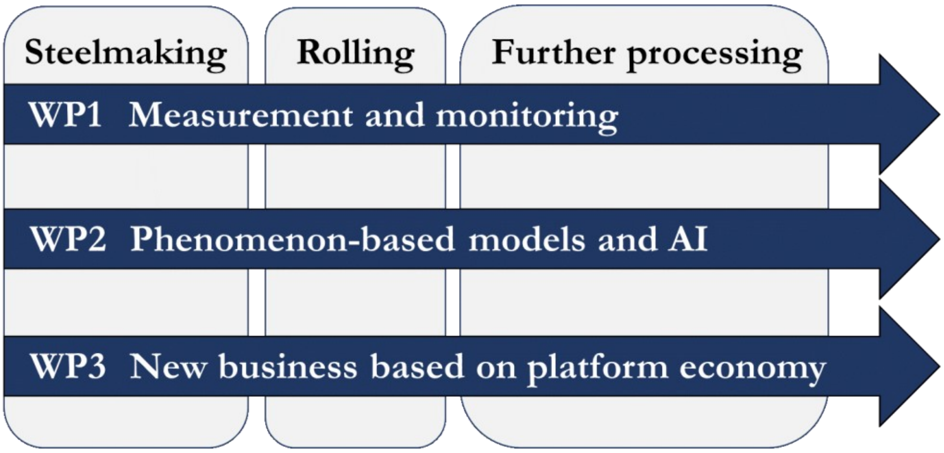
SMEs

Sapotech Oy
Luxmet Oy
Sensmet Oy
Kaltio Technologies Oy**
Quva Oy**

** Collaborating partner without a budget in AMET

Programme structure and management

The project was divided into three work packages, covering the entire value chain from iron and steelmaking to rolling and further processing. The work packages and their interconnections with the production value chain are depicted below.



The project steering group, consisting of representatives of each partner met regularly to manage the project in terms of overall progress and costs, and to decide on any operative matters.

Role	Name	Organisation
Chair	Juha Roininen	Sapotech Oy
Secretary	Professor Jari Larkiola	University of Oulu
Other members	Janne Viemerö	Business Finland
	Professor Timo Fabritius	University of Oulu
	Tuomas Alatarvas	University of Oulu
	Joonas Ilmola	University of Oulu
	Mika Pylvänäinen	University of Oulu
	Ville-Valtteri Visuri	University of Oulu
	Professor Henrik Saxén	Åbo Akademi University
	Agne Bogdanoff	SSAB Europe Oy
	Ismo Rentola	SSAB Europe Oy
	Jyrki Polet	Kaltio Technologies Oy
	Mikko Jokinen	Luxmet Oy
	Hannu Suopajärvi	Sapotech Oy
	Toni Laurila	Sensmet Oy

Impact

As a result of the research work conducted within the project, 12 peer-reviewed journal papers and 9 conference papers were published. Open access publishing was preferred to gain visibility and to disseminate the results to a larger audience. The project members participated in virtual and hybrid conferences for the presentation of the research work and international networking. Here, the completed tasks are presented as compact one-pagers. Many of them present novel applications of measurement technology or phenomenon-based modelling. An important aspect is to visualise the obtained results for the operators and R&D personnel, as seen in the work of Sapotech, Luxmet, and Sensmet. The platform-based solutions developed in the framework of the AMET project constitute a step towards the digitalisation of the Finnish steel industry and contribute to the aim of establishing thought leadership in this area.

Today, the emerging topics in steelmaking include the utilisation of big data, artificial intelligence, machine learning, and online methods, all of which are well within the AMET project's framework. Novel and advanced methods are essential in future steelmaking. To operate both sustainable and profitable steelmaking, high flexibility and efficiency must be achieved in unit processes. The topical themes were widely considered at the University of Oulu and Sapotech when applying for funding in collaboration with the contacts made during the AMET project. During the autumn 2021 call, one Horizon Europe and four RFCS project proposals with similar themes were prepared in collaboration with European steelmakers, universities, and research institutes.

The strategic renewal of the workforce requires high-level university education based on scientific excellence. During the AMET project, lectures on the digitalisation and modelling of metallurgical unit processes have been revised and expanded to provide the students with an up-to-date understanding of the main developments in these areas. Based on the research work conducted within the project, a doctoral degree, 13 master's theses and a bachelor's thesis were completed at the University of Oulu and Åbo Akademi University, the two institutional partners participating in the AMET project. These fresh graduates, equipped with the capability of using modern modelling tools and measurements, will for their part help the industry and SMEs to further strengthen their competences.

Platform-based solutions enable cost-effective market entry with a short time to market. The new platform type of business models can also foster innovation and mutual growth through cooperation possibilities, as stated by Drs Suopajärvi and Aula. The results provide a basis for SMEs to scale their business through a better understanding of what can be sold and delivered. Furthermore, the SMEs are encouraged to strive for growth through novel platform ecosystem business models.

> *"For Sapotech, AMET has been a huge opportunity to develop its technologies and solutions further in a spirit of co-creation with research institutes, other SMEs, and steel industry experts. Sapotech developed and tested many new solutions, but also fine-tuned existing ones to better fit the needs of the steel and metal industries. It is expected that these new developments will be added to the Sapotech product and service portfolio in the very near future. For Sapotech, AMET has not just been a matter of development of new cutting-edge solutions. It has been a forum to share and discuss ideas of platform-based industry with the leading experts for increased efficiency through shared platforms."*
>
> **Dr Hannu Suopajärvi**, Sales Director, Sapotech Oy

> *"For Luxmet, taking part in AMET has been a significant step forward in product development, as well as acquiring expertise and connections to implement new devices for the Luxmet platform. We have been able to incorporate new sensor technologies such as 3D cameras into our platform and to connect it to factory data systems and other control platforms. The developed solutions will see implementation in Luxmet products in the very near future. The joint research with the University of Oulu concerning the EAF modelling has paved the way for the model predictive control of EAF. Furthermore, the active testing of the technique in other fields of metallurgy has allowed us to widen our view of potential customers. The sharing of ideas and results in scientific and technical conferences has allowed us to connect our research with the worldwide steel community."*
>
> **Dr Matti Aula**, Head of Research, Luxmet Oy

Beneficial and feasible collaboration as in AMET is therefore also expected in future projects, while numerous applicable and novel solutions have already been implemented during this project.

Tuomas Alatarvas

Postdoctoral researcher

Process Metallurgy Research Unit

University of Oulu

Ville-Valtteri Visuri

Senior Research Fellow, Docent

Process Metallurgy Research Unit

University of Oulu

INTERNATIONAL ASPECTS
COLLABORATION AND NETWORKING

During the project, four AMET webinars were organised for the dissemination of project results and discussion of the ongoing research tasks. The webinars included ones with the themes Measurement, held in January 2021, and Modelling, held in May 2021. In addition, a webinar for the SMEs to present their products and capabilities was organised in September 2021. The SME webinar language was English, and invitations were sent to reach a larger audience. The webinar gained interest abroad, and of the total of approximately 50 attendees, around 10 were international contacts, including personnel from Swedish steel plants for instance.

The consortium partners participated in nine international conferences to present their research and the current topics in the fields of iron- and steelmaking, including measurements, modelling and digitalisation. These conferences are listed below.

- The 61st International Conference of Scandinavian Simulation Society (**SIMS2020**)
- The 9th International Conference on Modeling and Simulation of Metallurgical Processes in Steelmaking (**STEELSIM2021**)
- The 4th European Academic Symposium on EAF Steelmaking (**EASES**)
- The 12th European Electric Steelmaking Conference (**EEC2021**)
- The 10th European Conference on Continuous Casting (**ECCC 2020**)
- MATERIALSMEET 2021 Conference (**MATERIALSMEET2021**)
- The 5th European Steel Technology and Application Days (**ESTAD2021**)
- The 11th International Conference on Processing & Manufacturing of Advanced Materials (**THERMEC2021**)
- The 18th International Conference on Metal Forming (**METALFORMING2020**)

Despite the pandemic of the last couple of years, the need of academic events for scientists and researchers persists. During this exceptional period, virtual conferences have secured their position as public forums. Consequently, most of the conferences listed above were held online. A notable exception was the 10th European Conference on Continuous Casting (ECCC), which was held as a hybrid event in Bari in Italy. At the ECCC conference, Sapotech presented a conference paper on surface quality monitoring, prepared in collaboration with Swedish and Spanish steelmakers. As well as presenting their research, researchers from the AMET project also had the possibility to chair sessions at STEELSIM2021 and EASES.

During the AMET project, an exchange student (A. Ringel) completed his master's thesis for RWTH Aachen University on "Online modelling of an electric arc furnace". The work on the modelling of electric arc furnaces has since continued intensively, and multiple journal articles have been published in collaboration with RWTH Aachen University (T. Echterhof, T. Hay). Discussions of the utilisation of the EAF model have emerged with Georgsmarienhütte GmbH. In addition, Docent V.-V.

Visuri was the editor of a special issue of journal Metals, "Modeling and Simulation of Metallurgical Processes in Ironmaking and Steelmaking", alongside Dr. Thomas Echterhof (RWTH Aachen University) and Professor Ko-Ichiro Ohno (Kyushu University). In relation to the modelling and process monitoring activities in the AMET project, Visuri has also served as an opponent, pre-examiner, and evaluation committee member for four doctoral theses submitted at RWTH Aachen University (T. Hay), KTH Royal Institute of Technology (P. Ternstedt and Y. Liu) and Swinburne University of Technology (R. Kadam).

Within the AMET project, SSAB has studied the effect of the immersion depth of a submerged entry nozzle on the surface quality of cast products. The computational fluid dynamics (CFD) calculations were carried out in collaboration with SWERIM. In addition, CFD simulation of fluid flow in a bloom casting ladle shroud was conducted as a joint master's thesis supervision with KU Leuven.

Despite the travel restrictions caused by the pandemic, the SMEs participating in the AMET projects have been successful in their international outreach.

Figure 1. Saku Kaukonen presents recent developments at the 10th European Conference on Continuous Casting on behalf of Sapotech Oy.

Figure 2. Antti Lassila presents recent developments and innovations in the Streaming Slush 2021 on behalf of Luxmet Oy.

WORK PACKAGE 1
MEASUREMENT AND MONITORING

Summary

The main target of WP1 was to develop new measurement and follow-up tools for steelmaking, continuous casting, hot rolling, and pre-fabrication lines to enable better control of the processes as well as to ensure high-quality production. Despite the challenges posed by the Covid-19 pandemic, several solutions were developed and tested during the project. Unfortunately, the development and implementation of measurement solutions for pre-fabrication lines suffered in this project. The project provided the consortium partners the possibility to continue and further develop the cooperation and co-creation model in which steelmaking companies will provide the testing and validation platform for SMEs and research institutes.

New developments in AMET vary from different kinds of optical solutions to the highly specialised usage of optical emission spectrometry and accelerometers. In addition, new measurements and modelling methods were used to ensure optimal operating conditions. The solutions developed will cover almost the entire process chain from blast furnace raw material charging to the final stages at a hot rolling mill.

A machine vision-based monitoring tool was developed to distinguish fine-grained particles from the iron ore pellet charge at SSAB Raahe's blast furnaces. The benefit of the system is that unstable operation of blast furnaces can be avoided, improving production stability. A novel method for on-line water analysis was tested in blast furnaces to monitor metals in the washing water of an exhaust gas scrubber. Correlations were observed between the online measurements and process events, which may provide a novel tool for control. A vibration measurement system of an injection lance was piloted in the hot metal desulphurisation station, and the possibility of detecting variations in the composition of a lime-based desulphurisation reagent from the vibration of the submerged lance that vibrates in the metal bath during reagent injection was investigated. At Ovako Imatra, a 3D camera system for scrap batch volume measurement in an EAF was developed and tested. By measuring the scrap charge volume, it was possible to further develop the scrap charging optimisation algorithm.

Several measurement solutions were also tested in later process stages in continuous casting and hot rolling. A mould oscillation monitoring system was designed for the continuous caster 6 at SSAB Europe's Raahe works, and two comprehensive measurement campaigns were organised. An additional image processing algorithm was developed to detect oscillation marks and measure the spacing between them from slab surface images provided by Sapotech Reveal CAST. Several surface and quality inspection solutions were tested in continuous casting and hot rolling. The final goal was improved surface quality tracking throughout the process chain. In total, 21 different applications were developed as a result of this work package.

Agne Bogdanoff, SSAB Europe Oy
Hannu Suopajärvi, Sapotech Oy

INTEGRATION OF NEW MEASUREMENT METHODS INTO STEELMAKING

1 3D-CAMERA SYSTEM FOR MEASURING SCRAP BATCH VOLUME

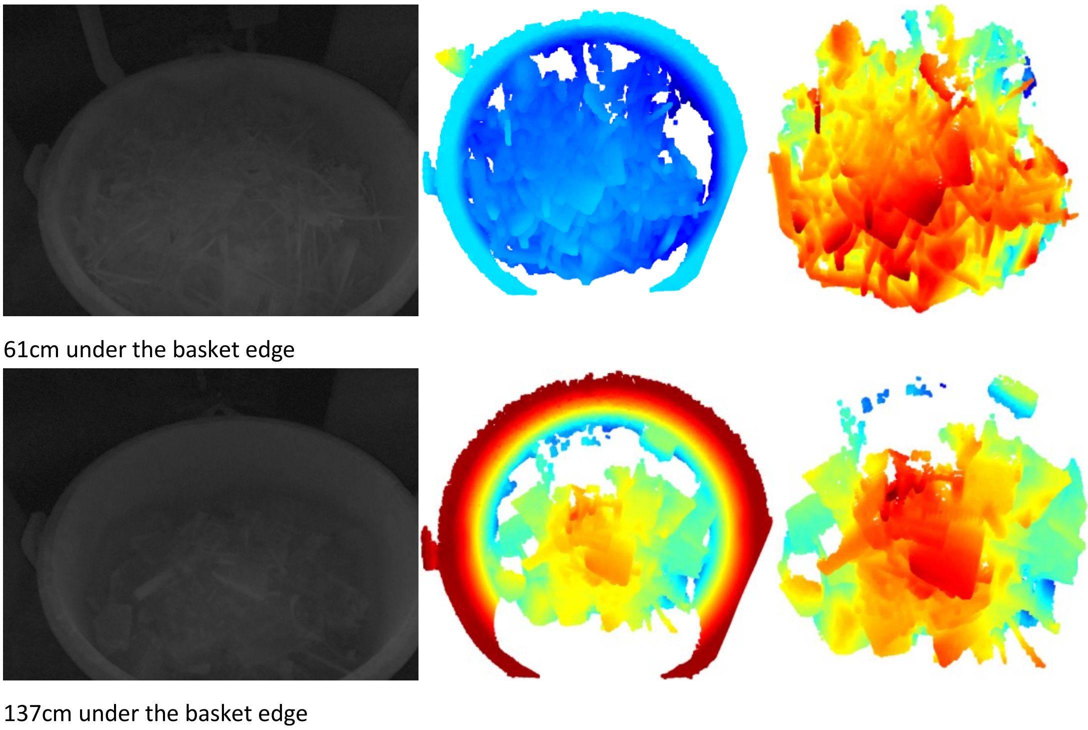


Figure 3. 3D camera images of the scrap layer from two different sized scrap charges at Ovako Imatra.

Description

Scrap baskets charged to EAF have a different amount of scrap inside. When charging the baskets to EAF, the correct charging time depends on the volume of the scrap inside the basket. To combine the scrap volume information with the EAF basket charging optimisation software, the surface of the scrap inside the basket was measured with a 3D time-of-flight camera (ToF). This information could then be combined with the progress of scrap melting inside the EAF.

Application

Three ToF cameras were installed on the scrap basket tracks at Ovako Imatra. The cameras were fixed to railing and aimed down towards the basket. The cameras were protected in the factory environment with steel casings.

Software for handling the 3D camera data was developed. The software started the acquisition of images when the basket arrived at the position underneath the cameras. Point cloud data were automatically obtained and normalised based on the position of the basket sides. The point cloud coordinates were transferred to x-y coordinates, and the average distance of points to the top level of the basket was calculated.

Results

The 3D camera system implemented was found to work well in industrial conditions. The scrap filling level was automatically acquired for each basket and transferred to a basket charging optimisation algorithm. The images and 3D point clouds obtained from the scrap charge were compared to the automatically calculated scrap filling level to validate the procedure. The calculated scrap filling level showed good correspondence to the manually defined filling level determined from the point clouds and scrap basket images.

Impact

By measuring the scrap charge volume, it was possible to include this information in the charging optimisation algorithm. This enabled the accurate timing of the EAF basket charge. Furthermore, obtaining the numeric value of the scrap charge allowed the documenting of scrap charging, which previously was only operators' practical knowledge.

Publications

M. Aula, T. Veijola and **M. Jokinen**, "Measurement of EAF scrap charge volume with 3D cameras", AMET Webinar, 2021.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO STEELMAKING

2 MACHINE VISION SOLUTION FOR EAF ELECTRODE MONITORING

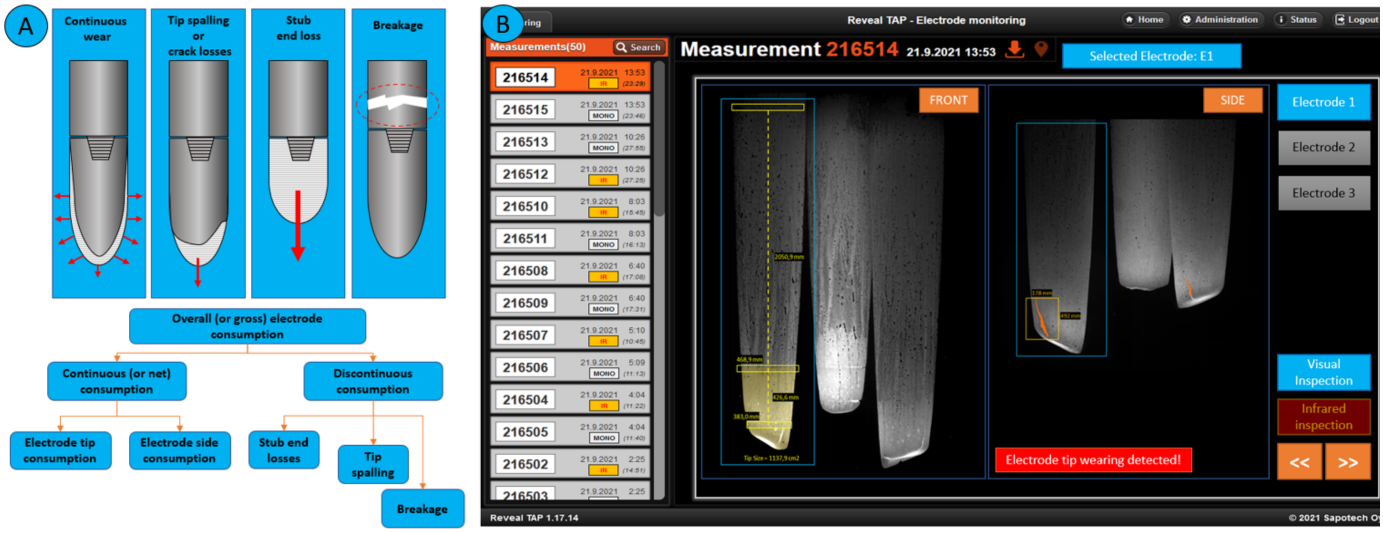

Figure 4. Types of graphite electrode wear mechanisms (A) and user interface from electrode monitoring solution (B).

Description

Graphite electrodes are used in electric arc furnaces (EAF) to melt the steel scrap and in ladle furnaces to heat the melt to the correct casting temperature. The typical electrode consumption in EAFs is 1.0 kg/t steel or more, making electrodes a significant cost item in EAF steel production. Electrode wear is a sum of "normal", continuous consumption and discontinuous consumption (Figure 4A). Both consumption patterns could be better understood if there was a system that automatically measured the electrode wear between the melting phases. Although there have been some attempts in the past to monitor the electrode wear, commercial technologies are yet to be fully exploited.

Application

Sapotech's Reveal TAP machine vision system was first tested at the Ovako Imatra EAF. Based on the successful test results, a longer industrial trial was planned and designed. The system configuration is based on two monochrome cameras, field enclosure, a 4G connection, and the Sapotech Platform. The locations of the cameras were carefully selected so that the electrodes were visible to the cameras.

The system has been calibrated for both camera distances, so that any dimensional measurements can be conducted. The sequence for automatic imaging is under development to capture the electrode images when they are in the correct position. Then the system compares the consecutive electrode images and can measure the tip and side consumption of the electrodes. Algorithms have been developed for crack detections and for discontinuous electrode wear cases.

Results

The electrode wear monitoring system has been operational for a few months. Imaging campaigns have been conducted remotely and a lot of material has been collected. The user interface (UI) has been designed and a cloud-based Reveal Platform has been enabled. The first results show that the electrode image quality is more than sufficient to make the dimensional measurements and to detect cracking of the electrodes. All the conducted measurements are shown in Reveal TAP UI (Figure 4B).

Impact

Increasing the on-line information from the EAF steelmaking process enhances the possibilities to optimally control the process. Monitoring the electrodes after each scrap charging brings an interesting tool to monitor the continuous wear of electrodes, but to also find the possible causes for process disturbances originating from abnormal electrode consumption. Sapotech solutions make it possible to standardise the procedures between operators and shifts. In addition, the electrodes from different lots and suppliers can be compared to find the optimal cost-quality ratio. The measurement result archive can be used as a support for improvement in electrode design.

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Ovako Imatra Oy AB

INTEGRATION OF NEW MEASUREMENT METHODS INTO STEELMAKING

3 PARTICLE SIZE MONITORING IN BLAST FURNACE BELT CONVEYOR WITH CAMERA-BASED SOLUTION

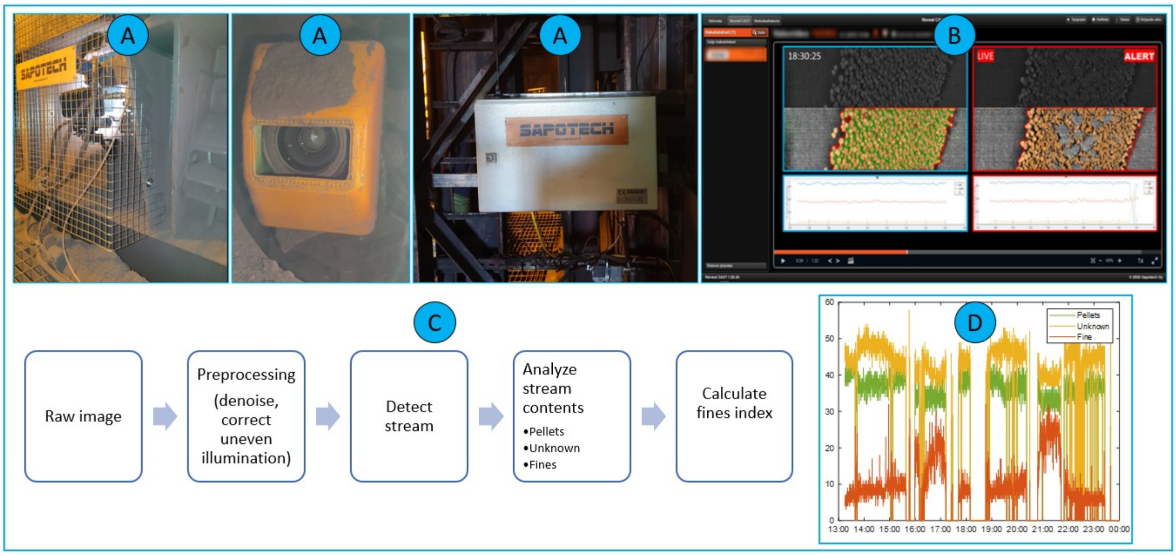

Figure 5. System hardware (A), user interface (B), measurement and analysis sequence (C) and stream analysis (D).

Description

The iron and steel industry uses material conveyors to transfer solid materials from one place to another. In blast furnace and submerged arc furnace processes, the particle size distribution of the materials being charged is an important factor affecting the efficiency of the furnace. In particular, the share of smaller particles (fines) should be kept as low as possible to enable adequate gas permeability in the furnace. The existing solutions for particle size monitoring on belt conveyors are mainly based on laser triangulation from a top-down perspective over the conveyor belt, which makes detection of fines difficult because of the tendency of fines to generate dust and sediment to the bottom layer of the material on the belt.

Application

In the context of the AMET project, Sapotech developed a camera-based solution to measure the particle size distribution from a discharge site on the end of a blast furnace iron ore pellet belt conveyor. The system was comprised of a monochrome camera, LED illumination, and a field cabinet with the required technical infrastructure for data storage, sharing, and remote access. Special emphasis was placed on the HW protection from the dust with air knives and proper sealing of the enclosures.

Images are analysed in real time on a PC using custom software, which categorises the material as either pellets, unknown, or fines. Pellets are detected using a watershed algorithm, and dark areas shadowed by pellets are labelled as unknown. Finally, the fines are detected by subtracting the pellets and unknown areas from the net material stream area. The relative number of fines in the material flow is then sent to the plant control system as an analogue signal.

Results

The system has worked reliably in a challenging environment for several months, requiring only pressurised air supply to HW and occasional cleaning operations due to a build-up of fines in the camera field of view.

Fine detection results from images correspond to silo discharge profiles and findings downstream from the conveyor line.

Impact

Compared to the top-down perspective and/or laser triangulation-based methods, our system can detect fines from the material discharge at the end of a conveyor belt, regardless of dust or sedimentation.

Measuring the share of fines in the furnace charge material can be used to improve the blast furnace performance. Measurements can reveal disturbances in the storage silos and their emptying/dosing, and they can also be used to predict the required screening time. The system can also be modified for particle size measurement tasks such as pellet size distribution.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO STEELMAKING

4 STRUCTURE OF MOTION METHOD APPLIED IN LADLE REFRACTORY MEASUREMENT

	Digital photography	Thermal imaging	Laser measurement	Hybrid systems
Safety increase	Low	Good / Possibility of false interpretations	Good / Possible unseen areas	High
Usability	Moderate	High	High	High
Applicability	High	Very high	Medium	Excellent
Receivable information	Very low	Medium	Good-Excellent	Good-Excellent
Swiftness	Fast	Fast	Low-Medium	Fast
Accuracy	Very low	Good / Depends on modelling	High	High-Moderate
Reliability	Very low	Medium	High	High
Upkeep and maintenance needs	Low	Low	Low	Low
Price	Cheap	Affordable	Expensive	Affordable

ACT PHAST4.0 Photonics Innovation Incubator

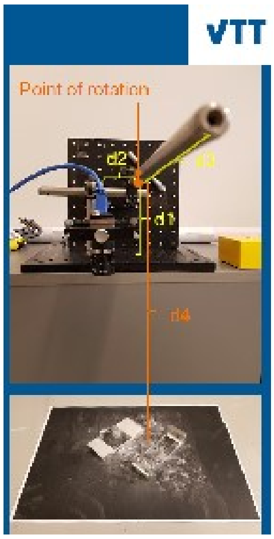

Figure 6. As the Total Refractory Management concept also needs to be introduced, and most of the refractories still lack solutions, there is a need to develop and test new technologies specifically for the monitoring of refractories.

Description

Our current refractory solutions are already using hybrid laser technologies to monitor refractories. We are the only one to provide such a system. We now need to make a mobile demo unit to make testing available to customers globally. With the University of Oulu, we have previously implemented a comparison of different refractory monitoring methods. Based on these studies we were able to convince the EU to fund VTT to test our ideas further as part of the ACTPHAST project. The main reason for us to develop such a system is that Reveal 360 is the solution for monitoring all inner surfaces (and only one to do all possible furnaces) of metallurgical units in high temperature conditions.

Application

Sapotech has developed specific machine vision systems, where the customer need of additional measurements and information has been proven to help the customer automate refractory control even further. These projects could easily generate “immediate” CO_2 reduction opportunities. Making innovative applications in this area is an attractive opportunity. The main saving potential is easy to estimate, because the total costs in the maintenance of refractories are typically tens of millions of euros/year/mills, meaning even moderate improvements (the estimated improvement for some producers is 30 % or more) in procedures can lead to significant cost reductions.

Results

We have reviewed several commercial solutions to monitor refractories in high temperature processes. Sapotech’s main idea is to always include high-resolution images from objects and include these with other measurement data to perform an analysis of high temperature surfaces. During testing and having contacted other Oulu-based companies and VTT, we believe the groundwork for future needs for refractory monitoring is possible. We are also already quite far on the way to have even more cost-effective solutions to make our customers’ work easier and more environmentally reasonable.

Impact

Although we aim to use our unique laser illumination-based imaging solution, there may be some cases where other laser-based solutions are required. Combining these data with new algorithms is necessary. Many similar algorithms and hardware are available on the market for other needs where photonics is applied. In this project, we tested and chose some of these with very promising results. These will be applied in our future solutions.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO STEELMAKING

5

3D-MEASUREMENTS IN QUALITY CONTROL SOLUTIONS FOR FERROUS AND NON-FERROUS INDUSTRIES

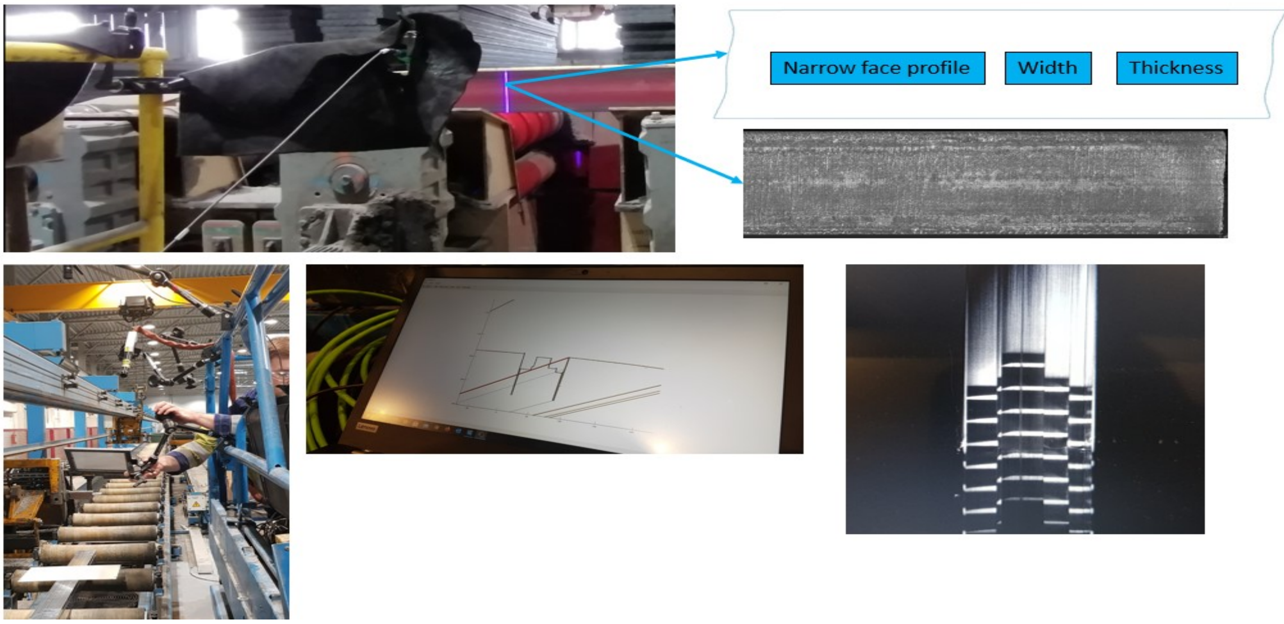

Figure 7. Several measurements for known customer needs were identified, and technology solutions on the market were evaluated for the identified 3D measurement needs. The Total Quality Management concept was introduced and evaluated for these needs, including the required 3D measurements.

Description

An increasing number of measurements is required for metallurgical processes to fulfil even more demanding needs. It is therefore necessary to make systems that provide more precise information from shape and dimensional measurements. Full quality inspection is still done mostly manually, even though automated measurement systems are available. The main reason is that many of the needs require highly customised and tailored solutions, but customers still insist on existing vast references from suppliers. Therefore, with relatively new technology, no suppliers with feasible references exist for the hot and niche needs of metallurgical industries.

Application

Sapotech has developed specific systems where the customer need of additional 3D measurement is proved to help the customer automate quality control even further. These projects could easily generate "immediate" CO_2 reduction opportunities, because bad quality always means additional costs, and in the metallurgical industry, this immediately entails additional melting and operations that will inevitably cause additional emissions.

Results

We have reviewed several commercial 3D measurements and technologies to provide the most cost-effective dimensional solutions while being also very tolerant to extreme hot processing conditions or other challenging needs. Sapotech's main idea is to always include high-resolution images from objects with other measurement data (like 3D data). During testing and having contacted other Oulu-based companies and VTT, we believe the groundwork for future needs for 3D measurements in metallurgical solutions has even identified solutions to achieve patents that will be able to be manufactured in the near future. Work to find reference customers and further testing will continue.

Impact

Although we aim to use our unique laser illumination-based imaging solution, there may be some specific cases where 3D measurements add value to the system. We can now offer 3D measurements as an option for our customers to solve even more specific customer needs. We thus offer solutions for a huge variety of customer needs and offer solutions running on our Reveal Platform for most quality assurance needs.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO STEELMAKING

6 ON-LINE EAF OPTIMISATION WITH PROCESS MODELS AND NOVEL MEASUREMENT SYSTEMS

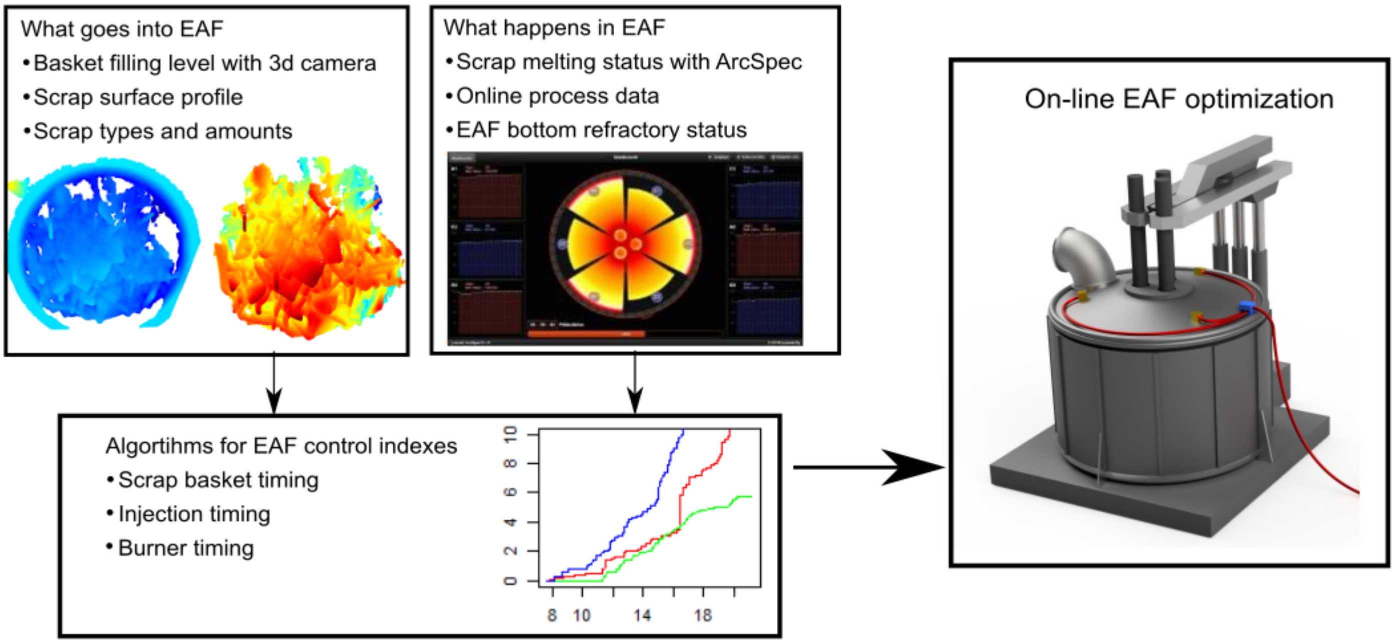

Figure 8. On-line EAF control logic.

Description

The electric arc furnace (EAF) as a process is affected by constantly changing scrap supply. The changing composition and size of the scrap affects the melting speed in the EAF. Many process actions should be performed only when a certain level of scrap melting has been reached. The problem with the current practices is the limited amount of information available from the EAF. To alleviate this problem, Luxmet has developed a system for measuring scrap melting based on the light emitted from the furnace. To obtain an accurate description of the state of the EAF process, Luxmet measurement data are combined with other available on-line process data and a 3D camera measurement of the scrap charge volume.

Application

To achieve accurate process control, all relevant data sources should be combined. The light data from Luxmet ArcSpec were combined with the process information supplied by Ovako Imatra in a software block coded in Python. The data from the implemented 3D camera about the filling level of the scrap basket were also included in the consolidated data.

The utilisation of Python allowed a flexible calculation of process indicators based on the consolidated data. Control routines for adjusting the timing of second basket charging, the injector, and burners were developed. The results from the process modeling performed at the University of Oulu were used in the definition of the control algorithms.

Results

The system was implemented for Ovako Imatra's EAF. The basket charging data were conveyed to the process operators through UI, and the timing of baskets was adjusted. The results of the measurement campaign were compared against a reference period.

Impact

With more accurate timing of basket charging, energy efficiency increased by 2.7 % compared to the reference period. The developed injector timing algorithm enabled oxygen injection that was between 1.2 and 1.6 minutes faster.

Publications

E. Rontti, "Optimization of Electric Arc Furnace Injectors Based on Optical Emission Spectrum Measurements", 2019. Master's thesis, University of Oulu.
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INTEGRATION OF NEW MEASUREMENT METHODS INTO STEELMAKING

7 MONITORING PELLET FINES FORMATION IN BLAST FURNACE IRONMAKING

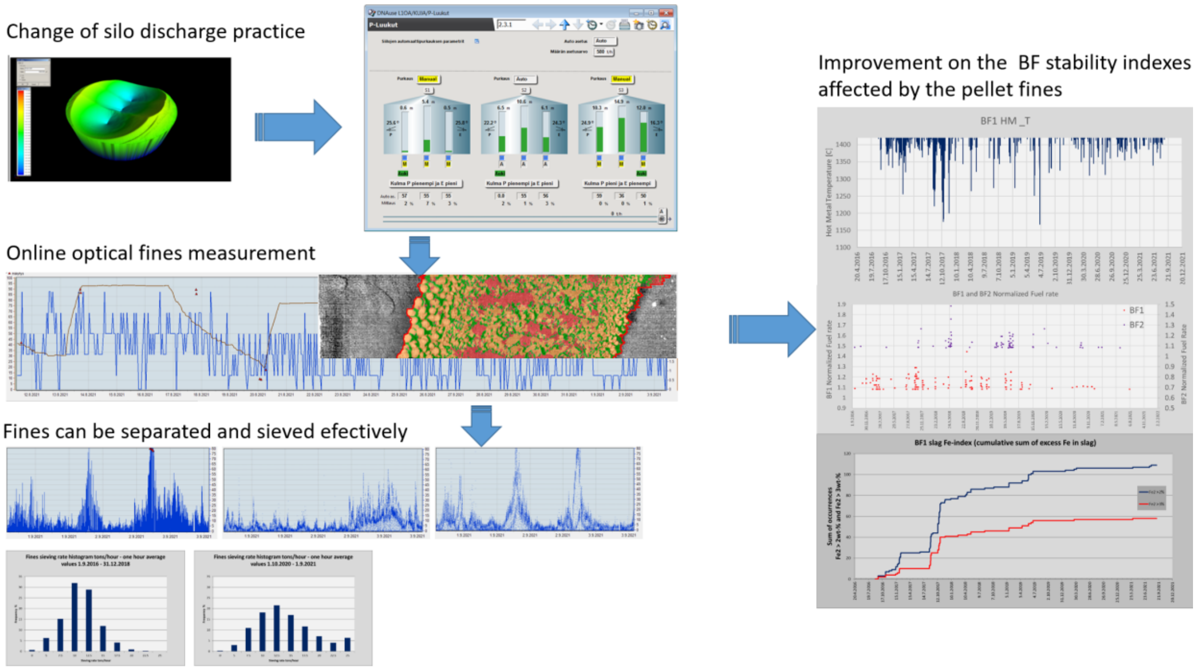

Figure 9. Pellet fines monitoring and the impact of actions.

Description

Blast furnace raw materials containing fines need to be sieved before being used in the process. To ensure as good a sieving result as possible, the automated discharge protocol of large storage silos, the optical measurement system of fines in the pellet stream, and the separation of fines originating from different qualities and intermediate storage in the stock house were developed.

Application

Large pellet storage silo discharge outlets were programmed to imitate a mass-flow type discharge pattern using all discharge points in a predetermined sequence. This ensures a controlled outflow of fines enabling even fines content in the pellet stream entering the blast furnace stock house. The discharged fines content can be optically measured. With even fines content in the pellet stream, the sieving machines can be fine-tuned for optimal performance in the BF stock house.

Results

The pellet surface shape in the large storage silo follows the shape of the material pile, with the surface angle slightly lower than the natural angle of repose during the silo discharge. This minimises the drop height and maintains the location of the fines column. It also prevents the long-lasting continuous discharge of the centre fines column. The separation efficiency of fines has increased over time, and a larger quantity of fines can be separated on a one-hour average. Different pellet qualities can be separated using the developed delay model. The quality of improvement actions can be followed.

Impact

The fines-related impact on the blast furnace can be seen in the variation of the hot metal temperature, slag Fe content, and in the overall fuel rate. The blast furnace operation stability has increased during the improvement actions. Using the constant and controlled discharge procedure of the storage silo, changes in the quality of imported pellets can also be seen.

Publications

O. Mattila, L. Halonen, I. Salmela, J. Roininen, H. Saxén and **T. Paananen**, "Computer aided multidisciplinary approach to monitor and control pellet fines flow in pellet Blast furnace ironmaking", 8th ECIC, 2022.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO STEELMAKING

8

DETECTION OF GAS-FORMING COMPOUNDS FROM THE VIBRATION OF A SUBMERGED LANCE IN HOT METAL DESULPHURISATION

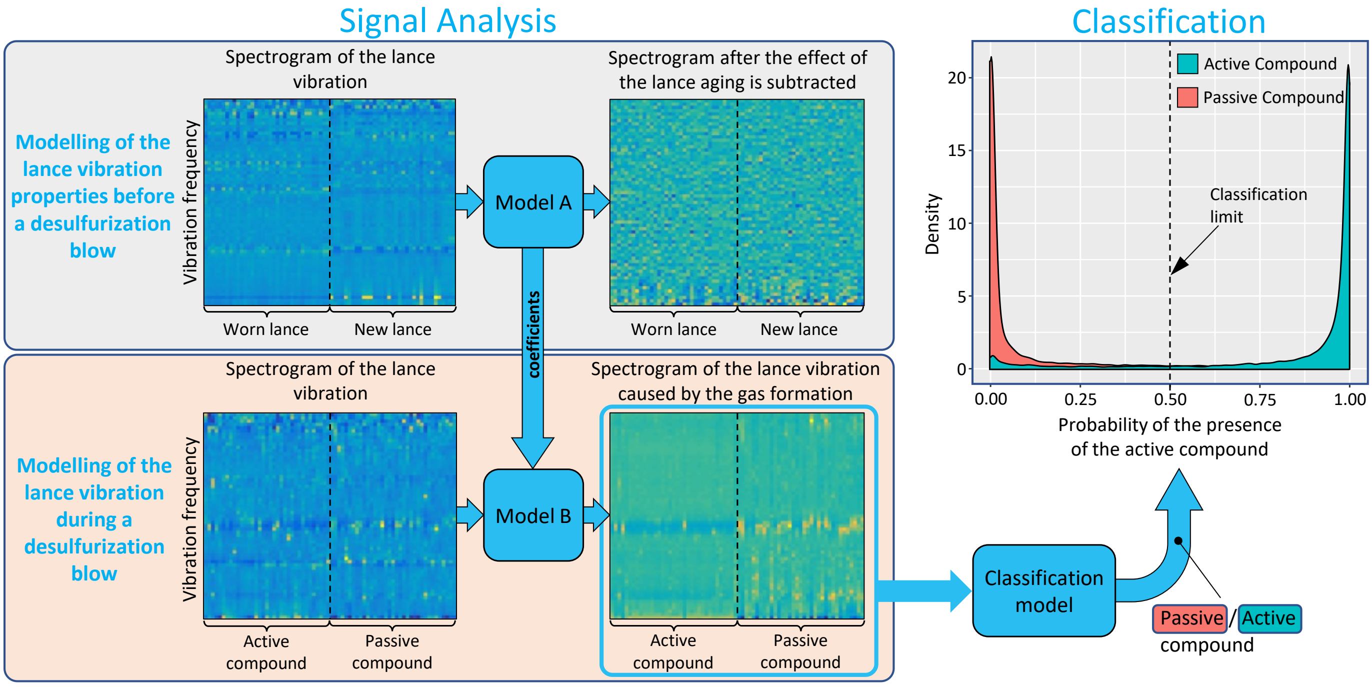

Figure 10. An illustration of signal analysis and modelling in the detection of the gas-forming compound.

Description

A vibration measurement system of an injection lance was piloted in the hot metal desulphurisation station at SSAB Europe's Raahe Works. The purpose of this work was to investigate whether it is possible to detect variation in the composition of a lime-based desulphurisation reagent from the vibration of the submerged lance, which vibrates in the metal bath during reagent injection. A two-day measurement campaign was carried out using two reagents, i.e. with and without gas-forming compound (soda). A high sampling frequency of 25.6 kHz was used for vibration measurements.

Application

Two triaxial piezoelectric accelerometers were installed on the lance surface, one at the top of the lance and another closer to the metal bath. The former location was found to be more feasible due to less aggressive thermal conditions. Due to lance ageing, i.e. erosion and sculling, its vibration properties change over time. Thus, the ageing effect was modelled from the lance vibration data before the actual desulphurisation, as shown by Model A in Figure 10. The coefficients of Model A contain information on the vibration properties of the lance and were utilised in Model B, where the effect of lance ageing was subtracted from the vibration data recorded during desulphurisation. The residual vibration consists of information on the actual gas formation and thus allows visibility for the behaviour of the gas-forming compound during desulphurisation. Such vibration information is shown in the spectrogram as the result of Model B in Figure 10 and was used as input in the binary classification model to predict reagent activity.

Results

Detection of variation of the gas-forming compound from the vibration of the submerged lance during the desulphurisation was proved possible when the effect of lance ageing on vibration is modelled. This is reflected in the double-density plot in the upper right-hand corner of Figure 10, where the classification probabilities are far from the classification limit.

Impact

Vibration analysis with high sampling frequency enables process monitoring over a wider frequency band. This allows online measurement of variation and inhomogeneity of the reagent caused by segregation. The measurement system can immediately warn of excessive gas formation, to which the process control can react in time to avoid splashing. Real-time information on the reagent composition can also be used as input for online metallurgical models used in the hot metal desulphurisation process.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO STEELMAKING

9 REAL-TIME ANALYSIS OF METALS IN FLUE GAS SCRUBBER WASHING WATER

Figure 11. Top row, from left to right: mobile measurement trailer, µDOES® Multi-metal Water Analyser, monitoring dashboard. Bottom row, from left to right: measurement environment, large number of solids calls for system robustness, results validation.

Description

Water quality in industrial processes is still typically monitored with manual sampling followed by off-line laboratory analyses. Novel online water measurement solutions open a new view of process dynamics. Real-time water quality data on process events allows immediate corrective actions and optimisation with associated financial benefits.

Application

Sensmet Ltd.'s new µDOES® Multi-metal Water Analyser was utilised for 24/7 monitoring of metals in the washing water of an exhaust gas scrubber at SSAB Raahe's steel plant in Finland. The goal of a 1-month measurement pilot was to validate the system operation and performance in very demanding process water, with high and varying solids content of several grams per litre and a temperature of up to 50-60 °C.

The measured water matrix and measurement conditions represented the most demanding application for the Sensmet Multi-metal Analyser so far. The exhaust gas scrubber application gave a lot of useful information for developing and increasing the robustness of the online sampling system and analyser.

Results

The developed online sampling system and the µDOES® analyser successfully monitored the concentrations of seven metals: zinc, iron, manganese, and lead were quantitatively measured, and sodium, potassium, and calcium were qualitatively measured to monitor their trends. Promising correlations were observed between the online measurement results, reference laboratory analyses, and process events (see results validation graph above).

Impact

New advantages in online water analysis pave the way for improved future monitoring and optimisation of industrial processes. Reliable real-time monitoring provides data, that may be usable to optimise the use of raw materials, energy, and chemicals, as well as securing the compliance of water quality with the requirements.

In this work, we have shown that the modern online water analysis of multiple metals can be performed 24/7, even in the harsh exhaust gas scrubber's washing water. The results show that it is possible to simultaneously extract several water quality parameters from demanding industrial processes in real time. Such data may allow identification of new correlations and cross-dependencies in manufacturing processes.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO STEELMAKING

10 OPTICAL EMISSION SPECTROSCOPY IN ELECTRIC STEELMAKING

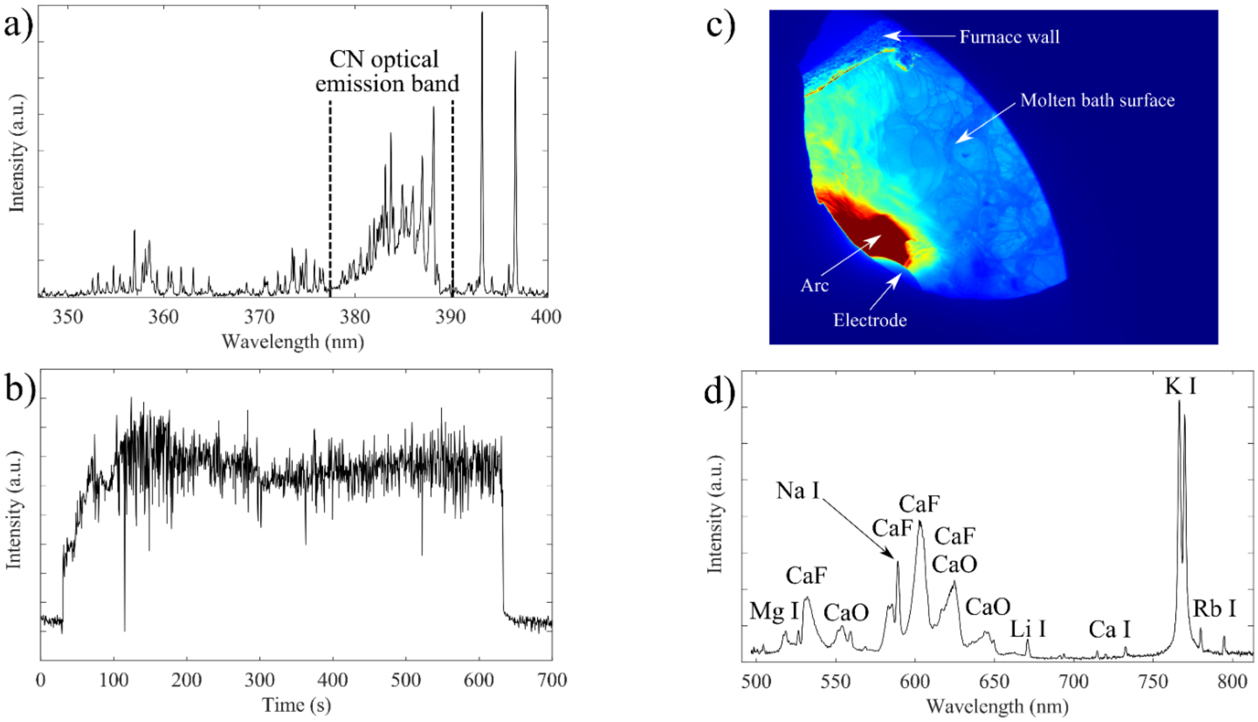

Figure 12. a) CN molecular optical emission band, b) temporal evolution of CN intensity in OES spectra, c) top-view into the pilot-scale electric arc furnace, and d) spectrum from an industrial ladle furnace with identified optical emissions marked.

Description

Optical emission spectroscopy (OES) was used in a pilot-scale electric arc furnace (EAF) and an industrial ladle furnace (LF). Species that radiate in the electric arc and the molten bath can be identified from these spectra due to the characteristic optical emissions of each particle.

Application

In the pilot EAF, the spectrometers were installed on the roof of the furnace, whereas in the industrial LF, they were installed outside the furnace. The OES spectra were analysed with a self-developed algorithm to investigate the temporal evolution of the optical emissions and to relate the data to the slag composition.

Results

In the pilot EAF study, the temporal evolution of CN could be retrieved from the spectra related to the plasma temperature and studied further with equilibrium composition computation. The industrial LF campaign allowed the identification of molecular optical emissions from CaO and CaF and to relate them to the slag composition analyses.

Impact

The identification of CN and its temporal evolution based on the OES spectra provides a tool for assessing the behaviour of CN, which can be a problematic compound in many applications utilising arcs. The industrial LF study further validates OES as a potential solution for online slag composition analysis for EAFs and LFs, which would in the long run result in a significant improvement in resource use and energy efficiency in electric steelmaking.

Publications

H. Pauna, A. Tuomela, M. Aula, P. Turunen, V. Pankratov, M. Huttula and **T. Fabritius,** "Toward On-Line Slag Composition Analysis: Optical Emissions from Laboratory Electric Arc", Metall Mater Trans B, 2022. https://doi.org/10.1007/s11663-021-02382-5

H. Pauna, M. Aula, M. Huttula and **T. Fabritius,** "Quantifying the CaO and CaF_2 content of industrial ladle furnace slag with optical emissions measured through the casting spout", Steel Research International, 2021. https://doi.org/10.1002/srin.202100519

H. Pauna, T. Willms, M. Aula, T. Echterhof, M. Huttula and **T. Fabritius,** "Cyanide recombination in electric arc furnace plasma", Plasma Research Express, 2021. https://doi.org/10.1088/2516-1067/abfc2a

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INTEGRATION OF NEW MEASUREMENT METHODS INTO CONTINUOUS CASTING

11 OSCILLATION MEASUREMENT OF CONTINUOUS CASTING MOULD

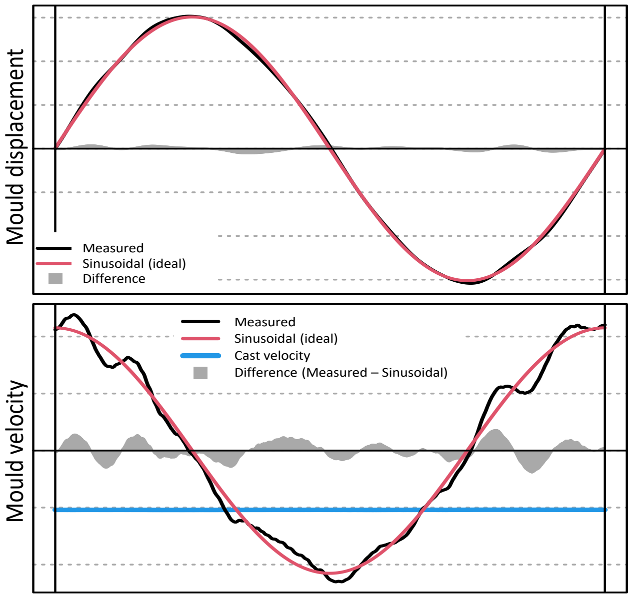

Figure 13. Numerically integrated displacement and velocity signals from a single oscillation cycle compared to theoretical sinusoidal signals.

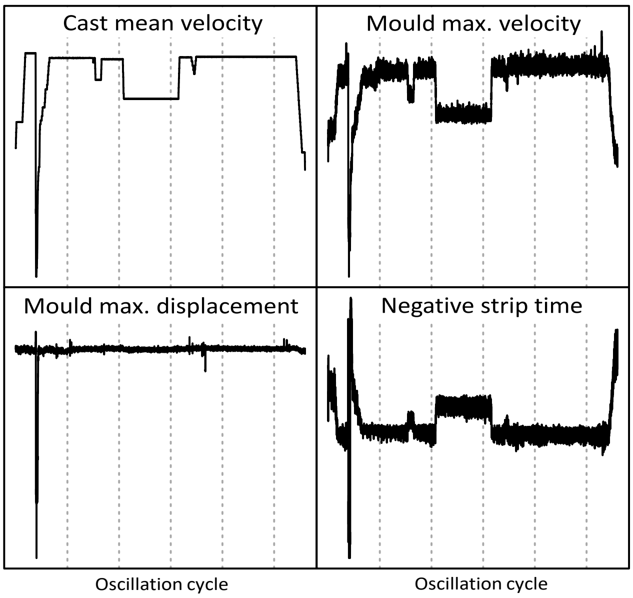

Figure 14. One feature time series from a single casting sequence. A slowing of cast speed caused a quality deviation which was also observed in a photo of the slab.

Description

A mould oscillation monitoring system was designed for the continuous caster 6 at SSAB Europe's Raahe Works, and two comprehensive measurement campaigns were organised. A high sampling frequency of 25.6 kHz was utilised. In the first campaign, the main objective was to compare new measurement points from the oscillators to previously used measurement points from the mould. It was observed that the mould oscillation could be monitored using the new measurement points which were safer for the accelerometers and did not require reinstallation every time the mould was changed. The second campaign demonstrated for a period of nearly four months that an online measurement of mould oscillation was feasible, and it provided valuable information about the casting process.

Application

Triaxial piezoelectric and MEMS accelerometers were calibrated for low-frequency mould oscillation monitoring. High-quality MEMS accelerometers typically have a very linear response at low frequencies and do not necessarily require such extensive calibration. The raw acceleration data were grouped to individual casting sequences. Velocity and displacement signals were created using numerical integration. Individual oscillation cycles were identified from the displacement signals, and multiple different features from these cycles were calculated. For example, these included short-time Fourier transforms, negative strip time, and certain features which identify how much the oscillation differed from the intended pure sinusoidal shape.

Results

New sensor types and measurement locations were proved useful for the accurate and real-time monitoring of mould oscillation. The measurements were further processed to features related to various physical phenomena in the casting process, providing more real-time insight into process quality.

Impact

The calculated feature time series can be compared to slab quality data, for example. The high sampling frequency opens visibility over a wider frequency band and more possibilities for real-time friction monitoring. This information enables the development of a higher-level expert system which can give early warnings of quality deviations, abnormal friction, and equipment failures. The measurement of the shape of the oscillation can also be used for the development of non-sinusoidal oscillation practices. The system can also be used for the condition monitoring of the oscillators.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO CONTINUOUS CASTING

12 MEASUREMENT OF OSCILLATION MARK SPACING WITH IMAGE PROCESSING

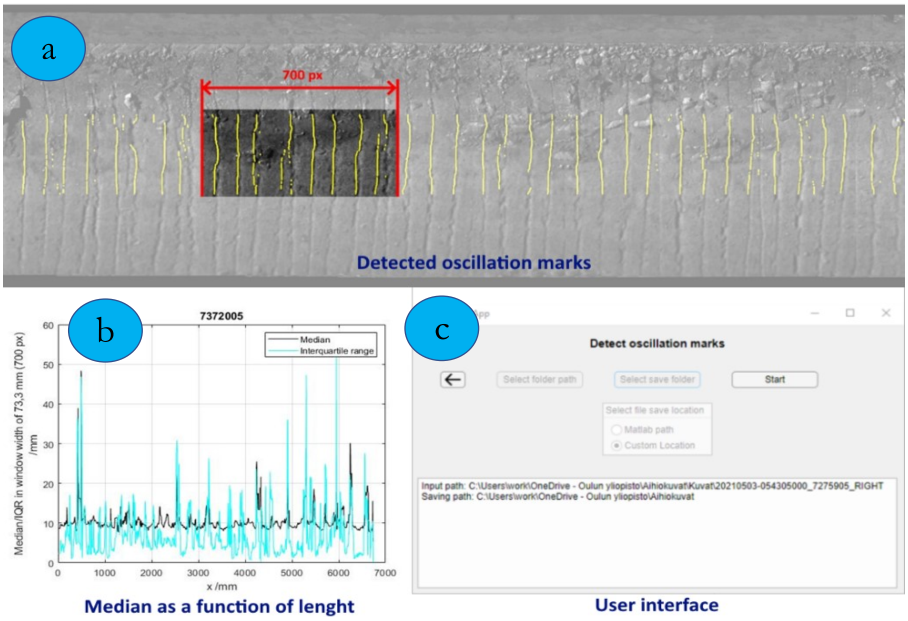

Figure 15. a) Illustration of the detected oscillation marks within the inspection window, b) graph presenting the median spacing as a function of slab length, c) user interface.

Description

Due to the oscillation of the mould in the continuous casting machine, oscillation marks are formed on the surface of the steel strand. Oscillation marks are clearly visible, particularly in the narrow faces of cast slabs. An image processing algorithm was developed to detect oscillation marks and measure the spacing between them.

Application

The analysed images were exported from the Sapotech Reveal CAST platform, showing the narrow faces of slabs of continuous casting machine No. 6 at SSAB Raahe's steel plant. The Sapotech system is set to take images with predetermined intervals and merge them to include one slab in each image. The oscillation marks were detected using MATLAB's image-processing toolbox and morphological image-processing operations. The developed algorithm proceeded by sliding an inspection window with a width of 700 pixels - see Figure 15a. The window was moved with 50-pixel intervals throughout the slab, and the calculation procedure was carried out in each step. The detected oscillation marks were used to determine the slab-specific median spacing of oscillation marks. The median spacing was also determined as a function of slab length (Figure 15b).

Results

When the slab is of the correct size, and the oscillation marks are clearly visible in the images, the algorithm detects the oscillation marks well. The detection algorithm works reliably when the slab height is 210 mm, and the width is 1830–1870 mm. Alternative slab sizes may need some calibration to provide the correct results. However, if the slab surface is covered by scale, for example, the algorithm is unable to detect the marks. Undetected oscillation marks correspond with spikes such as those in Figure 15b.

Impact

The algorithm results are used together and compared with the oscillation measurements carried out by the Intelligent Machines and Systems Research Unit at the continuous casting machine no. 6. at the SSAB Raahe steel plant. In addition, the coupling of various measurements to the casting defect database offers profound information on the defect formation.

The developed algorithm for oscillation mark frequency measurement can be fully integrated with Sapotech's Reveal CAST system. Through the further development of dedicated process indicators, process deviations may be observed, resulting in better casting performance.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO CONTINUOUS CASTING

13 EFFECT OF CALCIUM AND SULPHUR LEVELS ON NON-METALLIC INCLUSIONS IN VACUUM TREATED STEELS

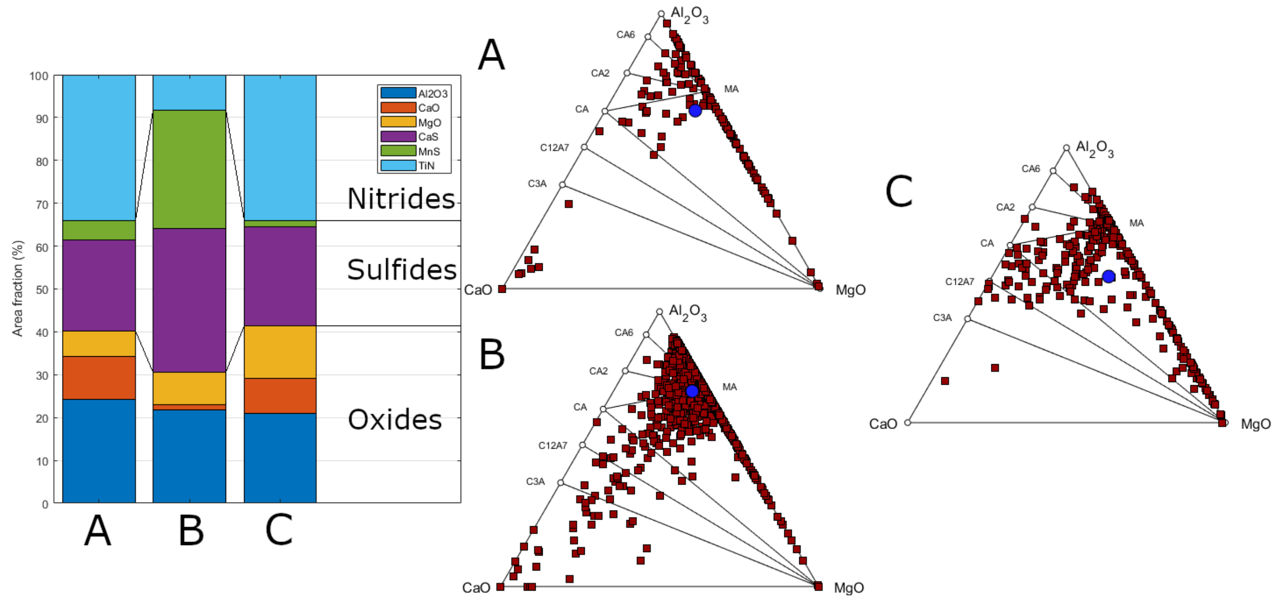

Figure 16. Left: Area fractions of inclusions, allocated to the components used in the classification. Right: Oxide compositions of inclusions containing oxide and CaS phases, plotted on ternary diagrams. Average compositions marked with blue circles.

Description

Inclusions are non-metallic, micrometre-scale particles within steel, often oxides, sulphides, or nitrides. Above all, the composition of non-metallic inclusions depends on the total composition of the steel. Deoxidation and alloying practices therefore play a significant role in non-metallic inclusions. For example, calcium treatment is carried out to transform solid Al_2O_3 inclusions into calcium aluminates which are molten at steelmaking temperatures, and to minimise the occurrence of MnS inclusions.

Here, heats with varying calcium and sulphur levels were selected for inclusion analyses with scanning electron microscopy. Non-metallic inclusions in hot rolled steel samples from SSAB Raahe Works were analysed. The samples are denoted as **A**: Reference material; **B**: Low Ca/S ratio; and **C**: Low Ca & Low S levels.

Application

The hot rolled steel samples were analysed with the Field Emission Scanning Electron Microscope (FESEM) Zeiss Ultra Plus. In the scanned area, inclusions were automatically detected, and their properties saved. The size and shape of each inclusion were obtained with image analysis. Simultaneously, the elemental composition was acquired with EDS (Energy-Dispersive X-Ray Spectroscopy).

Based on the EDS analyses, the fractions of oxide (Al_2O_3, CaO, MgO), sulphide (CaS, MnS), and nitride (TiN) components were calculated for each inclusion. This allowed the classification of inclusions and plotting of the oxide composition in the Al_2O_3-CaO-MgO ternary diagrams to estimate the phases present in the steel samples.

Results

In Figure 16, the leftmost stacked bars show the overall composition of inclusions as fractions of components used in the classification. While the reference material (A) and Low Ca & Low S (C) samples show similar compositions, the Low Ca/S ratio sample (B) is characterised by larger sulphide fractions as well as lower CaO content in oxides. On the right, ternary diagrams show the oxide composition of inclusions containing both oxide and CaS phases, thus accounting for the majority of inclusions in the samples. The ternary diagrams show that the average composition of oxides is near $MgAl_2O_4$ spinel, denoted as MA in the diagrams.

Impact

The strict control of calcium and sulphur makes it possible to transform solid Al_2O_3 inclusions to molten calcium aluminates and to avoid excess formation of MnS, often elongated during hot rolling. Thus, the impact toughness values could be improved. The current target at the steel plant is to reduce the minimum accepted calcium levels without detrimental effects on process control or steel quality. Based on the results, decreasing the calcium content requires a sufficiently low enough sulphur level to be ensured.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO CONTINUOUS CASTING

14 OPTIMISATION OF IMMERSION DEPTH OF SUBMERGED ENTRY NOZZLE AND ARGON FLOWS

Figure 17. Continuous casting at SSAB Raahe.

Description

In addition to phenomena during further processing, the surface quality of the hot rolled product is strongly affected by mould phenomena during the continuous casting process. Slag defects, longitudinal and transverse cracks, can be reduced by means of appropriate mould flows. Optimal mould flows can be achieved by combining the suitable immersion depth of the submerged entry nozzle (SEN) and argon flow with different casting parameters. Immersion depth refers to the distance of the upper edge of SEN discharge gates from the steel surface in the mould.

Application

A CFD model was created by SWERIM to describe the mould flows and slag intake of continuous casting machines 4 and 5. Combinations of casting parameters provided by SSAB Raahe were used to adjust the immersion depths and argon flows. The model can be applied further to other casting circumstances. A water model has been used as a validation method for the CFD model. Another task during the project was to build immersion depth control, but because of difficulties in finding a suitable technology, this work will be continued later.

Results

Illustrative maps were constructed on the grounds of the modelling results. The maps present optimal combinations of casting parameters, including SEN immersion depth and argon flow, to avoid slag intake to the slabs. The project improved knowledge of mould phenomena.

Impact

The maps created can be utilised to design different immersion depths for different kinds of casting sequences. Knowledge of optimal immersion depths can be applied in practice by using an immersion depth control system. The surface quality of slabs can be improved by using optimal immersion depths. Additionally, the proper control of immersion depths offers opportunities to lengthen casting sequences by lengthening the lifetime of the SEN.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO CONTINUOUS CASTING

15 NEW ONLINE OES-PDA SYSTEM FOR FAST DETERMINATION OF STEEL CLEANNESS AND STATUS OF INCLUSIONS

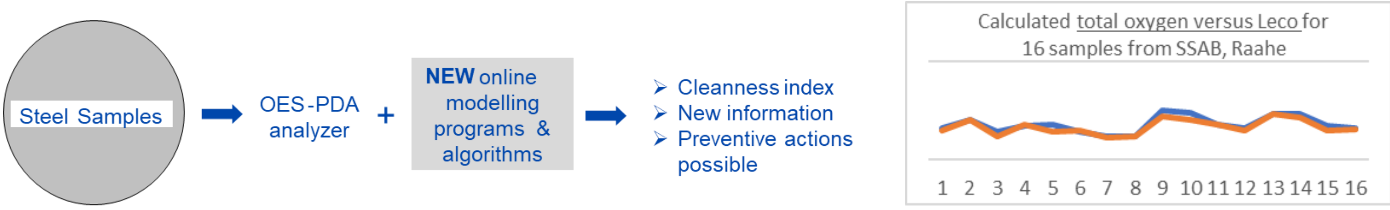

Figure 18. Left: New online modelling tools for OES-PDA analysis systems have been developed for more accurate and robust control of steel cleanness and states of inclusions in continuous casting including the ladle operations before casting. Right: Results of total oxygen content (TOC) measurements used in validation.

Description

The development of the new OES-PDA system has been carried out by Casim Consulting in close cooperation with SSAB Raahe, the University of Oulu, and with active international cooperation with two European steel plants. A fully automatic online determination of different micro cleanness parameters of steel plant production samples was the final target. The commercial tools available today are not sufficiently accurate and robust for online applications. Improved tools need to be developed, and many steel plants have started to develop improved inhouse systems.

<u>Typical micro cleanness parameters are:</u>

- Amounts of inclusion, types, sizes
- Total oxygen content (TOC)
- Composition of main inclusion types

<u>The main developments carried out:</u>

1. Improved pre-handling. Incorrect data need to be detected and removed or handled correctly. Incorrect data can originate from various factors:
    - Entry of the top slag during sampling
    - Reoxidation during sampling with air inside the sampler
    - Sample surface contamination
    - Porosity or holes in the sample
    - PDA single sparks igniting incorrectly, etc.
2. The sample needs to be representative. Indicators have been developed to detect if the sample is not representative, i.e. taken too early after ladle treatments where alloying elements are added as FeSi or CaSi or too early after vacuum treatment.
3. Special treatments for Ca and Mg inclusions and separation of CaS from CaO and in general sulphides from oxides. In practice, all Ca and Mg are bound to inclusions in the cooled samples, so special treatment is needed for these elements.
4. Many other developments have been carried out, such as the separation of endogenous from exogenous inclusions and calculating total oxygen separately for these different oxide groups. In clean steel, the exogenous oxygen should be close to zero, and the endogenous oxygen low. Inclusion sizes are calculated using the ablated mass of the spark and concentrations of the elements in this mass.

Application

The new tool and system have been validated with many validation samples from SSAB Raahe. Samples have been taken from the ladle and casting machine mould. The new tools are now in the online installation stage in SSAB Raahe to obtain a fully automatic, robust, and accurate new online OES-PDA system. The developed model considers many elements like Al, Ca, Mg, Si, Mn, Ti, Cr, etc., their inclusions and precipitates. With Al killed steels, one of the main aims at SSAB Raahe is to calculate the amounts and size distribution of Al_2O_3 oxides.

Results

The validation of the new tool and system has been carried out mainly by comparing the calculated total oxygen content (TOC) with Leco measurements. Good agreements have been obtained. We also observed the importance of good pre-handling procedures, as well as the procedure to separate exogenous from endogenous inclusions. With these procedures, even dirty samples can be saved and used, making the system more robust and accurate.

Impact

- Preventive actions are possible
- Cleanness and state of inclusions can be controlled better
- Many kinds of quality and practical problems can be solved
- Saving the output datasets in a databank system for longer-term statistical analysis of quality and effect of changes made in the processes on the quality
- Even dirty samples can be saved and used.

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", 10th CLEANSTEEL, 2018.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO CONTINUOUS CASTING

16 CORNER CRACK VISUALISATION AND DETECTION IN CARBON STEEL SLABS

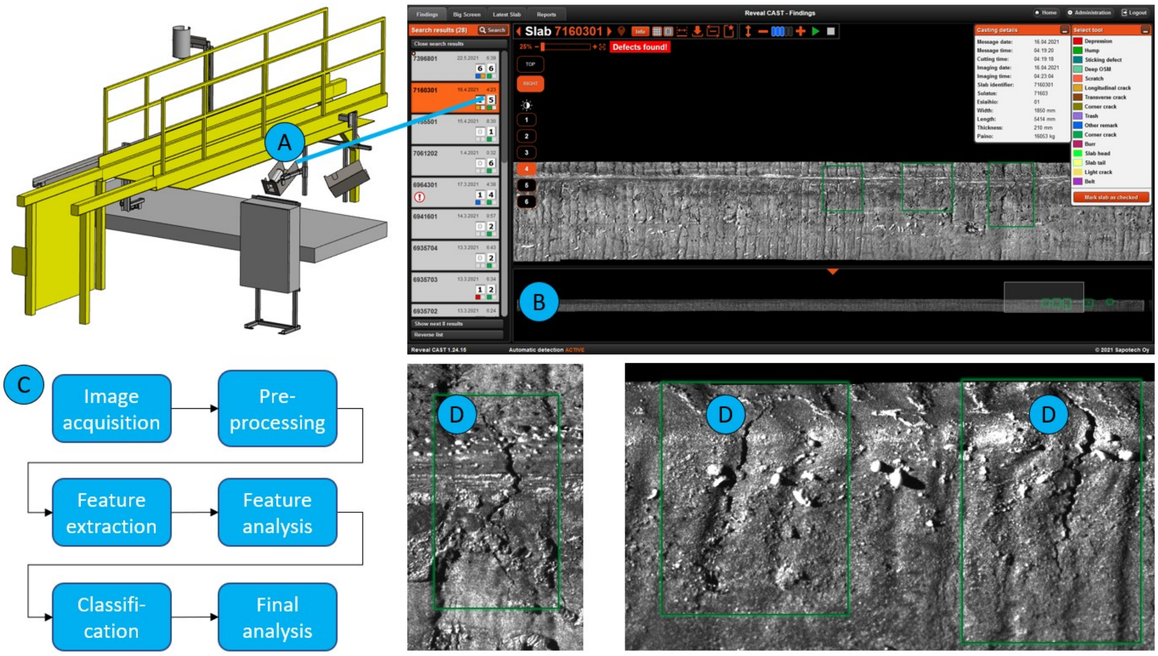

Figure 19. Configuration of slab corner inspection and some detected corner cracks.

Description

Transverse corner cracks are one of the most harmful surface defect types encountered in the continuous casting of steel. Typically, corner cracks are small and are often hidden under the oxide scale layer formed before the manual inspection takes place. This means that defects are difficult to spot, resulting in yield losses in production.

Based on the market and technology analysis, a novel solution that can visualise and detect corner cracks online during the casting of the semi products is required.

Application

Based on the modular Reveal CAST surface inspection technology, Sapotech has developed the “corner” imaging approach, where a single camera with laser illumination is targeted directly at the corner area of a semi product. In the AMET project, the corner inspection system was installed on a carbon steel slab caster to monitor one top corner (Figure 19A) of a slab. Individual images taken from the corner area are combined into a whole length image of the slab corner area (Figure 19B). The image acquisition and algorithmic processing is described in more detail in Figure 19C. To maximise the imaging performance, cameras are directed specifically to image the corner, ensuring that as much image (pixel) data as possible are captured. The system can be enhanced with automation to move the camera according to changes in slab width or slab height.

In general, scale on the surface can cause visual artefacts that resemble corner cracks. Specific algorithmic filtering tools and maximised imaging resolution enable Reveal CAST to distinguish scale artefacts from actual corner cracks.

Results

Corner cracks down to 150 µm can be visualised with Sapotech’s solution (Figure 19D). The first releases of the algorithms have been deployed and their performance is being evaluated.

Impact

Corner cracks are a serious quality issue for low-alloyed steels. Installing a surface inspection system in the production line means corner cracks can be detected, and the subsequent processing can be better planned. This could also entail reduced manual inspection work, yield improvements, and semi product conditioning based on actual surface quality. Importantly, automatic inspections provide feedback for the casting process to further optimise the casting conditions for better semi product quality.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO CONTINUOUS CASTING

17 WIRELESS SOLUTION FOR STEEL LADLE TRACKING COMBINED WITH OTHER MEASUREMENTS

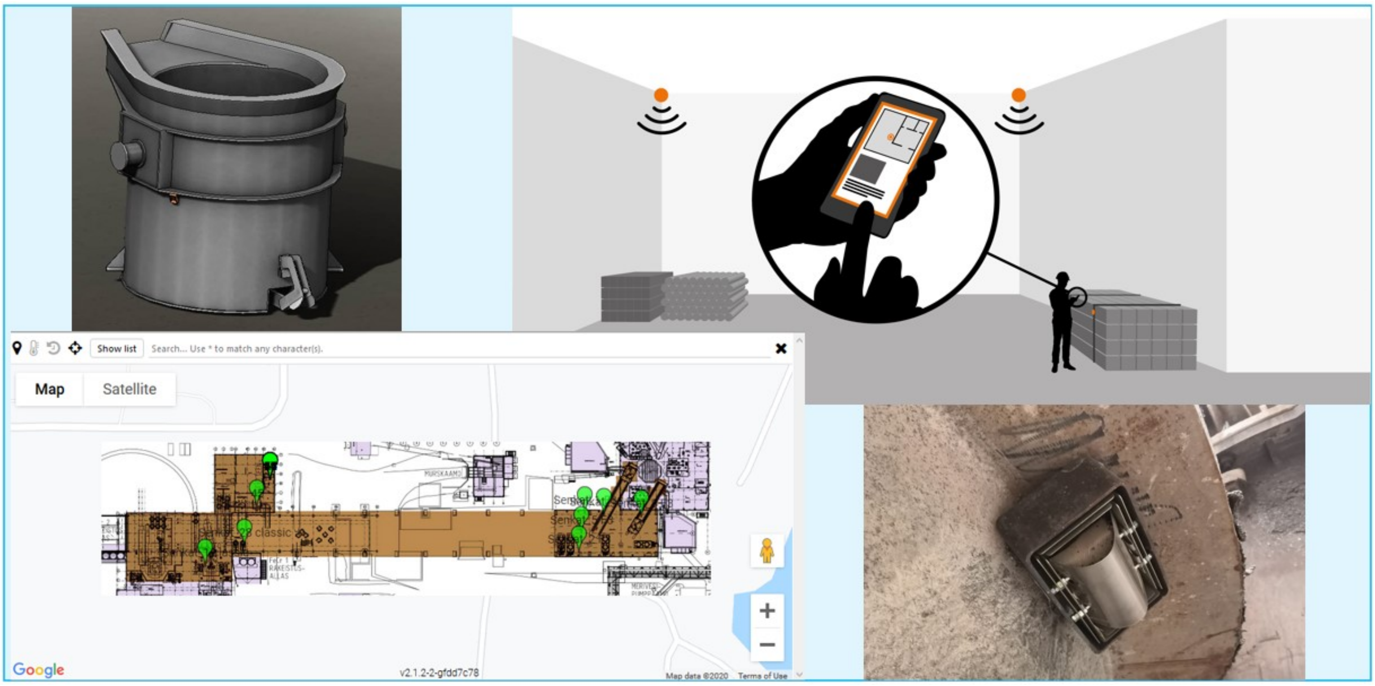

Figure 20. Tracking real time location of an asset in a steel mill is challenging, as all vessels are used at high temperatures and tracking is needed in multiple locations (all locations affect temperature flow of vessels).

Description

Some metallurgical processes lack critical location-based data, and innovations are needed to fulfil ever more digitalised positioning requirements. There is a need for real-time accurate location data and solutions to track location, combining complex temperature models of tracked objects. The aim is to model the thermal state to monitor how the refractory material wears off as a function of time and the location of tracked objects. The construction of the temperature model also utilises the Reveal TAP solution to measure the temperature of the outer surface of the ladles and provide information about current operations of certain processes. It is thus easy to launch complex temperature models to track refractory wearing.

Application

Sapotech has developed camera-based solutions to make steelmaking safer for operators. The time that ladles spend heating is also monitored. This information is not available in all steel plants, but beacons used in Reveal TRACE can be integrated into the heating places so that the time spent heating becomes available. This makes it possible to monitor the movements of the ladle at the steel plant, as well as the temperature of the ladle at each process phase. The more data the system collects, the more information the customer receives.

Results

The primary results achieved so far are economic benefits and a safer working environment. There is a need to collect more accurate data, and we are now aiming to improve the solution based on the gathered information. The system is relatively easy to deploy, and positioning information can be shared on cloud-based platforms. The project has proved there is a need for projects like AMET, where SME companies can help other SMEs apply their solutions in cooperation to make even more demanding solutions and systems.

Impact

Refractory wear is a significant cost and ecological impact factor in manufacturing. To achieve savings in refractory wearing with digitalised solutions, we can help steelmakers achieve even lower emissions overall.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO CONTINUOUS CASTING

18 TRACING SLAB SURFACE QUALITY FROM CONTINUOUS CASTING TO PLATE MILL

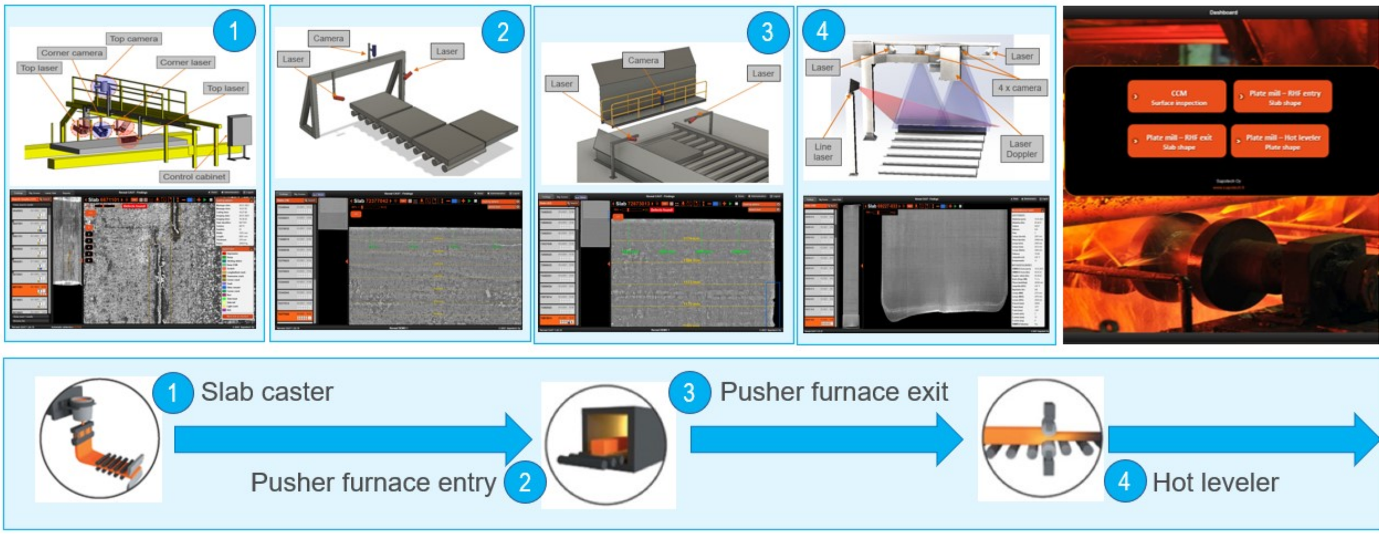

Figure 21. Reveal CAST surface inspection systems in carbon steel production.

Description

Today, most surface quality monitoring of cast, conditioned, and rolled semi products is still conducted visually by steel industry operators. Automatic surface inspection could provide an approach to ensure surface quality without extensive personnel involvement. To take this further, having inspection systems throughout the production chain would afford many advantages to enhance the quality and yield of production.

Application

In the AMET project, Sapotech showcased the implementation of Reveal CAST surface inspection system for different stages of production. An industrial trial unit was installed in the carbon steel slab caster, and a demo unit was used to capture slab surface quality at the entry and exit of the pusher furnace. Data from the existing system after the hot leveller complemented the analysis.

Results

Top broad face surface defect inspection and slab top corner visualisation were realised in CCM as an on-line application. The algorithms for typical defects were fine-tuned, and dimension and shape measurements were developed. Both demos were successfully conducted, and image data taken during the campaigns were post-processed with defect detection and dimension measurement algorithms. Surface images of hot plates taken with the system located after the hot leveller were also utilised in this project. All the results were combined on the Reveal Cloud Platform, which can be accessed through a web browser.

Impact

Sapotech's Reveal CAST provides immediate feedback regarding surface quality and dimensions. This can be converted to benefits in terms of better process control, yield, and optimised downstream processing. In an ideal situation, there would be a surface inspection system at every stage of production. Through system integration, it would be possible to trace the surface quality throughout the process chain and identify the root causes of surface defects. Furthermore, it would also provide more applicable information for predictive production planning, based on the surface quality data of all the previous process phases.

With Reveal CAST, it is therefore possible to build a total surface quality monitoring solution in which the slab created in continuous casting is inspected until it has been packed for shipping to the customer. The surface quality information is integrated and stored on the Reveal Platform, providing a digital process memory.

Publications

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S. Kaukonen, H. Suopajärvi and **P. Parhi,** "Sapotech Reveal Platform – Machine vision based solution platform for digitalization of metallurgical processes", 10th ECCC, 2021.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO HOT ROLLING

19 SOLUTION FOR SHAPE AND PROFILE MEASUREMENT OF A STEEL COIL

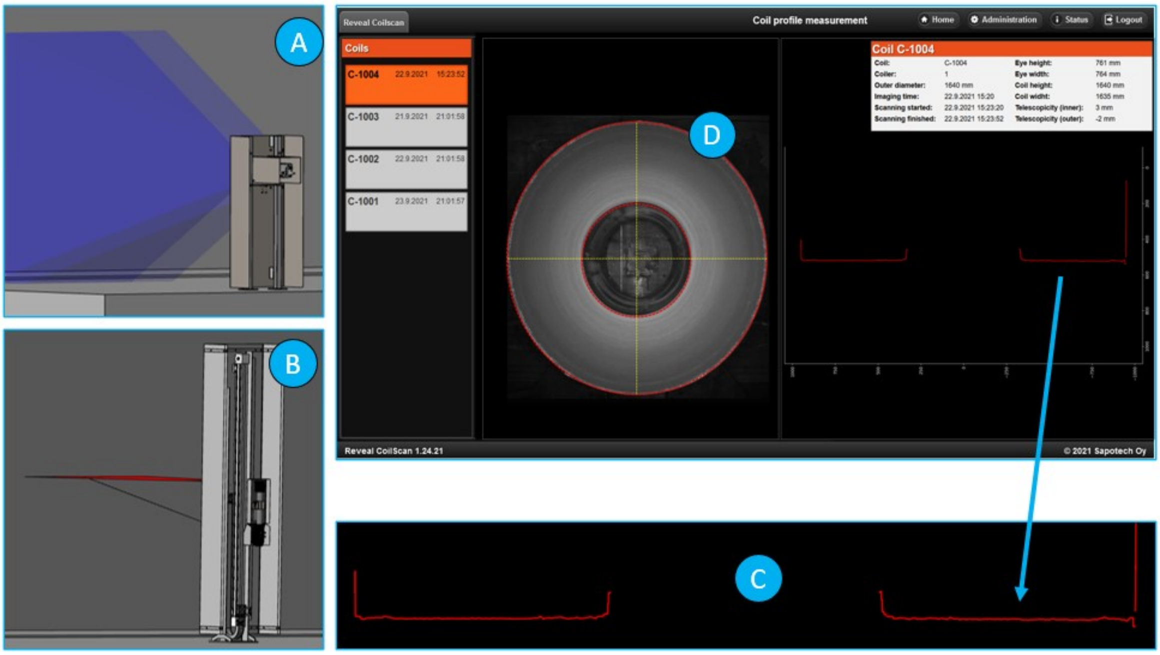

Figure 22. Hot rolled coil shape measurement system.

Description

The hot rolled coil is the final product leaving the hot strip mill either to post processing lines or to customers. It is therefore of the utmost importance that the quality of the coil is at an acceptable level to avoid any issues from the customer side. Coil quality monitoring in terms of shape and dimensional tolerances can also provide important feedback for the winding process. The shape inspection of the hot rolled coils is a resource-demanding task if it is done completely in manual mode. An automated measurement system for coil shape quality would ease the task with a digital memory.

Application

Sapotech developed automatic hot rolled coil shape measurement system in the context of AMET project. The system comprises of two different measurements which are combined in the final evaluation stage. Camera-based system (Figure 22A) images the front face of the coil when it passes the system. Powerful LED illumination assures that imaging conditions remain unchanged. The camera itself has an auto focus and programmable zoom to ensure high quality of captured image data. Laser scanner technology (Figure 22B) is used to measure the profile of the coil face. Line laser is projected on the centre of coil in horizontal direction, and it scans the topography as the coil passes the system. Both sensors are calibrated for different coil shapes.

Results

The coil shape measurement system provides many KPIs from the coils. The dimensions of the coil, the shape of the outer perimeter, the shape of the coil eye, and different profile measurements (Figure 22C) can now be conducted automatically. High-resolution images from the coil faces (Figure 22D) are taken and are stored in Sapotech's Reveal database along with the measurement data.

Impact

Sapotech's coil shape measurement system enables 100% automatic quality control of the hot rolled coils before they are dispatched to customers. In principle, this means that customer complaints, devaluations, price reductions, and re-deliveries can be completely avoided.

In addition, the system can provide feedback for the winding process to control the parameters based on coil side profile measurements. Also, by providing the coil dimension and profile measurement data to cold rolling mill, possible issues in unwinding can be avoided.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO HOT ROLLING

20 MODELLING OF BACKUP ROLL SPALLING

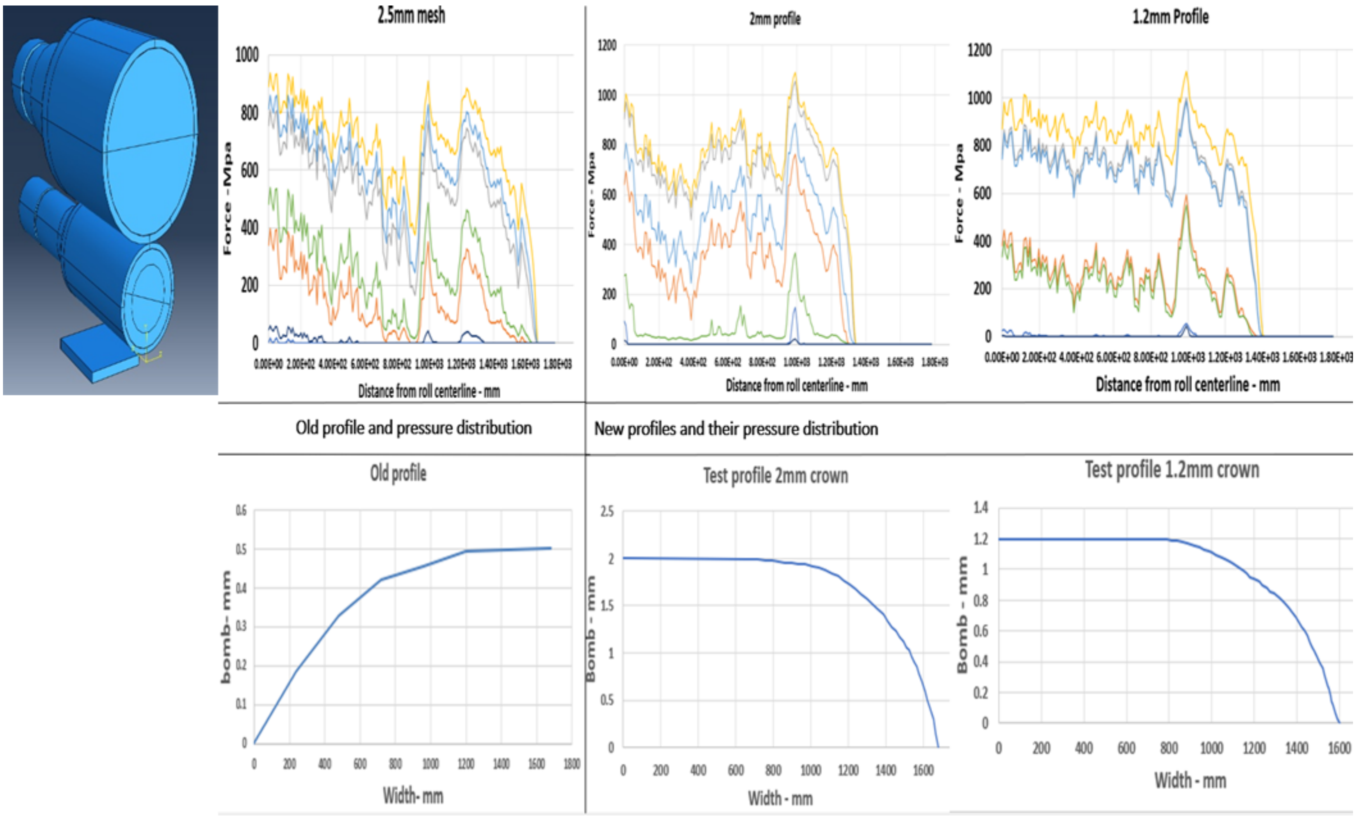

Figure 23. Hot rolling mill contact pressure and new profiles.

Description

The aim of this study was to develop a model from the SSAB Raahe hot rolling mills' pressure distribution and geometry of work and backup rolls for reducing force peaks. The intention with this model was to prevent roll spalling, leading to unstable rolling conditions, quality problems and deterioration of surface appearances.

Application

A Finite Element Analysis (FEA) of the rolling process was utilised to define contact pressure distribution on hot rolling rolls. The model was made from a work roll that had been in use and had some wear in the profile. The backup roll had a grinded profile.

Results

Spalling is a common problem with casted rolls. With this analysis, we have verified the spalling area and made test profiles to obtain pressure distribution evenly in the work area. By applying these test profiles, we have obtained better pressure distribution in the work area. There are still spikes near the slabs' edges, but pressure is mostly distributed evenly with a 1.2 mm profile.

Impact

Spalling in cast backup rolls is a common problem, but with these simulations, we have gathered data which show that changing the backup roll profile contour could provide an effective solution to prevent spalling in the future.

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INTEGRATION OF NEW MEASUREMENT METHODS INTO HOT ROLLING

21 INVESTIGATION OF LENGTH AND WEIGHT ACCURACY OF PLATE SLABS

Figure 24. Mother slab cutting at continuous casting at SSAB Raahe.

Description

Measurement accuracy is a major factor in the efficient use of material. Inaccurate measurements can lead to larger material losses due to scrapping. Partly rolled plate dimensions are computed using plate slab dimensions and weight. Plate slabs are not weighed. The weight of the plate slab is a calculation multiplying cut slab length and weight per metre of mother slab. Mother slab length is measured during casting, and weight immediately afterwards. Possible conditioning losses are calculated using constants.

Application

Research methods included statistical data analysis, which was executed in Minitab. Mother slab length measurements from different process points were combined and compared. Manual measurements were taken to evaluate the length accuracy of the plate slabs. The difference between the calculated and measured area of the partly rolled plate was used as a response to evaluate the variables influencing the weight accuracy of the plate slabs.

Results

Differences in the length measurements were found. Continuous caster measurement converted from hot to cold varied from the measurement taken from cold slabs at the slab halls. The hot to cold coefficient can be altered to achieve a better match. Laser length measurement at the CC6 roller conveyer was found to be too inaccurate to follow the accuracy of length measurement.

The material loss of the conditioned slabs is calculated using assumed thickness losses. It was observed that conditioned slabs were heavier during rolling than was reported, while assumed conditioning losses were assumed to be thicker than they were in practice.

The length accuracy of machine scarfed slabs and the last slabs of the sequence was observed to have the biggest inaccuracies. Manual placing of the laser, which is harder with a rougher edge, probably caused this.

Impact

Variables influencing the weight accuracy of the plate slabs were found. Plans to make alterations to the hot to cold coefficient and conditioning losses to the databases were made. Problems in the measurement accuracy of some slabs during slab cutting were found, and improvements will be considered. The influence of timely calibration and control of measurements became more evident.

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WORK PACKAGE 2
PHENOMENON-BASED MODELS AND AI

Summary

Physical, mathematical, and statistical models can be integrated to create a basis for machine learning algorithms and corresponding artificial intelligence applications. A combined approach, including both data-driven and phenomenological modelling, can thus be defined as intelligent modelling. The assessment of an individual phenomenon with a physical model does not always have the necessary practical applicability, providing a further rationale for the intelligent modelling approach. Ultimately, the goal is to broaden the understanding of the dynamics of the studied process with a novel approach, which often becomes increasingly difficult when the complexity of the phenomena increases.

When multivariate and complex phenomena are present in metallurgical processes, the formulation of phenomenological prediction or inference approaches becomes challenging because of the process characteristics and the required assumptions or simplifications. It is also possible that either an individual phenomenon or the cumulative effect of simultaneously occurring phenomena has yet to be explicitly defined or is otherwise unknown prior to the analysis, necessitating the use of data-driven modeling together with models that describe the relevant physical or chemical characteristics. For example, the quality of the cast product in continuous casting is known to depend on the steel composition, casting parameters, process irregularities and the casting process's overall trajectory. However, these data entities are not applicable in prediction or modelling purposes as such, but they must instead be used as input variables in modelling tools that consider the actual physical phenomena. With combined and intelligent modelling approaches, accounting for the unknown behaviour in the process and possible correlations or collinearity of the relevant phenomena becomes feasible.

The methods and results related to measurement and monitoring that were realised in WP1 were further utilised in WP2, with the theme "Phenomenon-based models and AI". The target of WP2 was to develop new models for iron and steelmaking for more intelligent process control and enhanced production efficiency. The research work was mainly carried out by the University of Oulu and Åbo Akademi University, with close collaboration with the steelmaking partner SSAB Europe. Close collaboration with SMEs makes it possible to implement the models quickly in the existing technology platforms. The topics of WP2 can be divided into different unit processes, from ironmaking to melt metallurgy and ending with the cooling and coiling after rolling processes. Åbo Akademi University conducted simulations concerning ironmaking, including the optimisation of hot stove heating cycles with modelling and analysis, as well as blast furnace-related topics such as the interpretation of dynamics in top gas. In relation to the electric steelmaking route, the thermodynamic-kinetic model for the electric arc furnace was further developed at the University of Oulu in collaboration with Outokumpu Stainless and RWTH Aachen. Novel measurement methods developed by SMEs in the WP1 were utilised in the development of the EAF process model.

The successful production of new steel grades requires advanced models for the simulation of continuous casting as well as predictive control during the casting process. As the product portfolio of steel grades becomes more extensive, it is increasingly important to know and utilise the thermochemical properties of the steel predicting the solidification and microstructural phenomena in cast slabs. Various phenomenological modules for continuous casting were developed during the AMET project. These include the thermodynamic model for slag, which can be used to assess the risk of the submerged entry nozzle clogging during casting. To decrease the defect formation, research on quality prediction in the continuous casting of steel was carried out. As a direct result of quality prediction research, proposals for corrective actions concerning defect formation were presented to the industrial partner SSAB Europe. In topics related to continuous casting, IDS and CastManager software tools were utilised in close collaboration with Casim Consulting SME.

The hot rolling section was divided into five stages: roughing; hot strip rolling; cooling; coiling; and coil cooling. All stages were modelled separately and coupled into a virtual rolling model. For each section the background of the development work lies in advanced measurement and monitoring of process data using the advanced technology developed by several SMEs. This data was utilised to develop and validate individual hot rolling process models. During the computing of a rolling model, measurement data from FEM (Finite Element Method) sensors are used to control the virtual rolling process. The hot strip rolling model is thus controlled and adjusted by the same principles as an industrial rolling process. Integrated rolling automation is implemented by calculating setup values and controlling the virtual rolling using FEM sensor data.

Microstructural evolution was studied experimentally using the stress relaxation test and simulated with several models. Static recrystallisation (SRX) and grain growth (GG) were the focus of the study. SRX kinetics and GG rate were studied with mean field models, as well as a Cellular Automata model, which produces grain size distributions for more diverse data analysis. Finally, the mean field models were coupled in the virtual rolling model.

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COWPER MODELLING AND ANALYSIS

22 SIMULATION AND ANALYSIS OF MEASUREMENTS FROM HOT STOVES

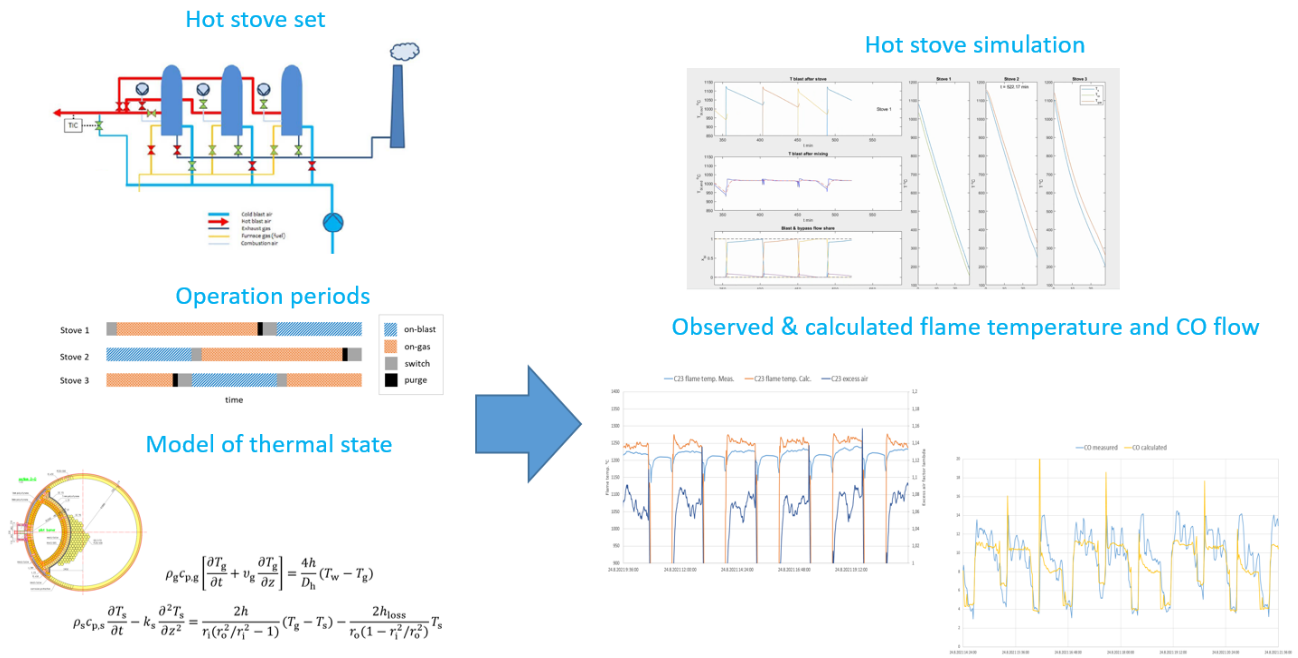

Figure 25. Simulation-based analysis of the operation of hot stoves for improved thermal efficiency.

Description

The operation of the regenerative preheaters of the combustion air for the blast furnace, i.e. the hot stoves, is quite complicated due to partly overlapping periods and complex switching phases. This, with the lack of reliable measurements of the stove states and a fluctuating composition of the fuel gas, makes it difficult to guarantee an efficient preheating of the blast. The project studied the thermal state of the stoves and the use of new measurements for controlling the combustion process.

Application

The thermal state of the hot stoves was described by a simulation model that considered the vertical temperature distribution in the gas and checker work, and the combustion of the fuel gas. Using newly installed measurements of the gas composition in the stack, the combustion in the individual hot stoves was studied to assess the efficiency and find possible inconsistencies in the signals.

Results

A dynamic simulation model of the hot stove set was developed in MATLAB, considering the vertical temperature distribution. Changes in the temperatures in the radial direction around the gas channel were neglected due to small gradients in the stove. The simulation captures the complex operation of the stove set well and can be applied to evaluate different operation strategies. New measurements in the joint flue gas stack of the hot stoves were analysed by mass- and energy balance-based methods. In addition to detecting some errors in the signals, the analysis revealed potential ways to enhance the preheating of the blast by an adjustment of the excess air coefficient during the heating stage.

Impact

The work has revealed several interesting aspects of the operation and control of the hot stove set in a steel plant, including the effect of the excess air coefficient on the combustion efficiency. The models have made it possible to increase the blast temperature and have given a deeper insight into the relevant complex system. Some errors in the present signals and routines have also been found. In addition, a potential leakage of air from the blast to the flue gas channel has been detected.

Publications

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INTERPRETATION OF DYNAMICS IN BLAST FURNACE TOP GAS WITH AI

23 MODELLING OF BLAST FURNACE HEARTH WEAR AND OPERATION

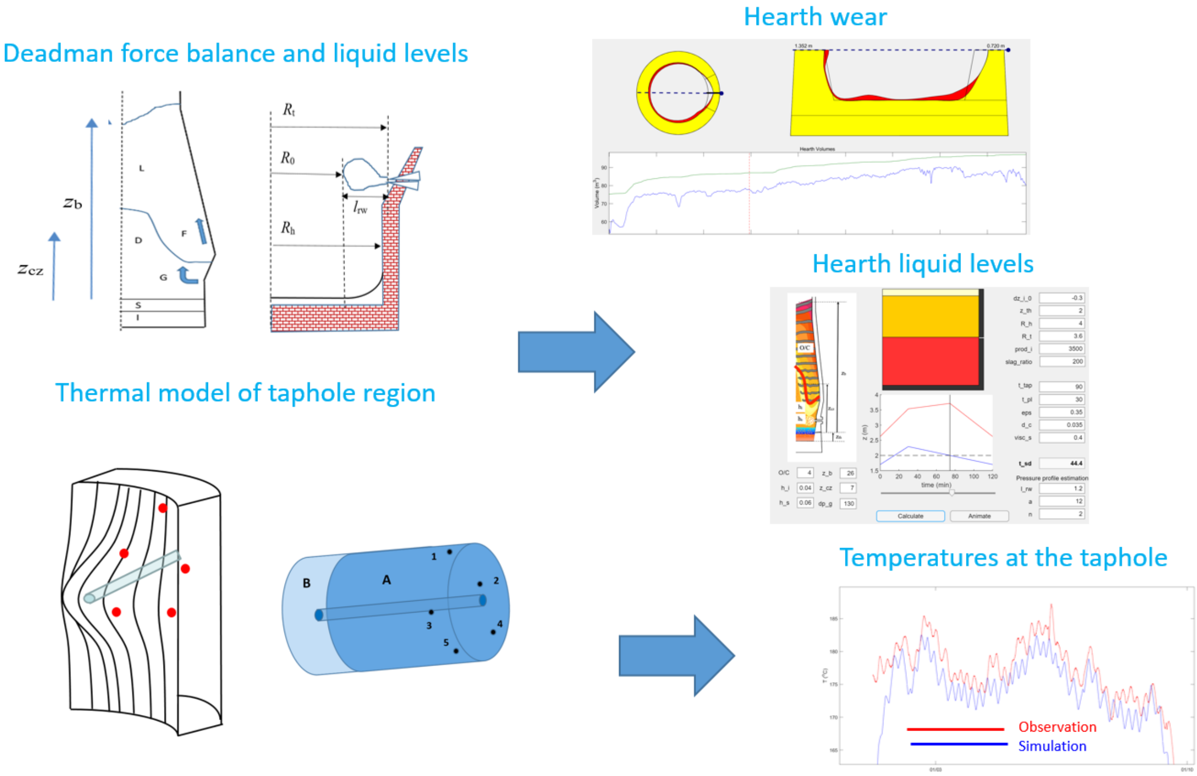

Figure 26. Mathematical models of BF hearth wear, liquid levels, and temperature distribution around the taphole.

Description

The blast furnace hearth is the most inaccessible part of the process but remains a crucial element for the BF campaign length, because repairs can only be undertaken during long stoppages when the furnace is emptied. To monitor the evolution of the hearth state, a set of mathematical models was developed. These helped interpret measurements and provide a view of the in-hearth conditions.

Application

The state of the blast furnace hearth affects the drainage of the furnace and the hot metal temperature and chemistry, but only indirect measurements from the region are available. The project extended an existing hearth wear model, developed a liquid-level model for the case where the hearth coke ("deadman") might float, and a two-dimensional dynamic model of the state of the lining/taphole clay around the taphole based on tapping information and thermocouple readings.

Results

A liquid level model of a BF hearth with a coke bed that might float was developed based on a balance of the forces that acted on the "deadman", including gravity, gas drag, and buoyancy. The levels vary depending on the in- and outflow of the liquids and "deadman" motion, which suppresses or accepts hot metal from/to the coke-free zone. An online hearth wear model provides information about the geometry, i.e. average diameter and sump depth, which is required for the simulation. The model of the taphole region, which captures the dynamic state of the lining with fluctuations induced by the irregular tappings, was found to reproduce the thermocouple measurements accurately, as seen in the lower left part of Figure 26.

Impact

The hearth wear model plays an important role in predicting the extent of the campaign and the need for maintenance. The liquid level model can be applied to estimate the state of the hearth coke by comparing the predicted drainage with the observed one, e.g. the length of the iron-only flow period. It also quantifies the effect of the ore-to-coke ratio and gas pressure drop on drainage. The taphole model provides online predictions of the taphole length that can be used to monitor the taphole region for preventing breakouts or other disturbances caused by excessive lining wear.

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INTERPRETATION OF DYNAMICS IN BLAST FURNACE TOP GAS WITH AI

24 SIMULATION OF GAS FLOW IN THE BLAST FURNACE THROAT

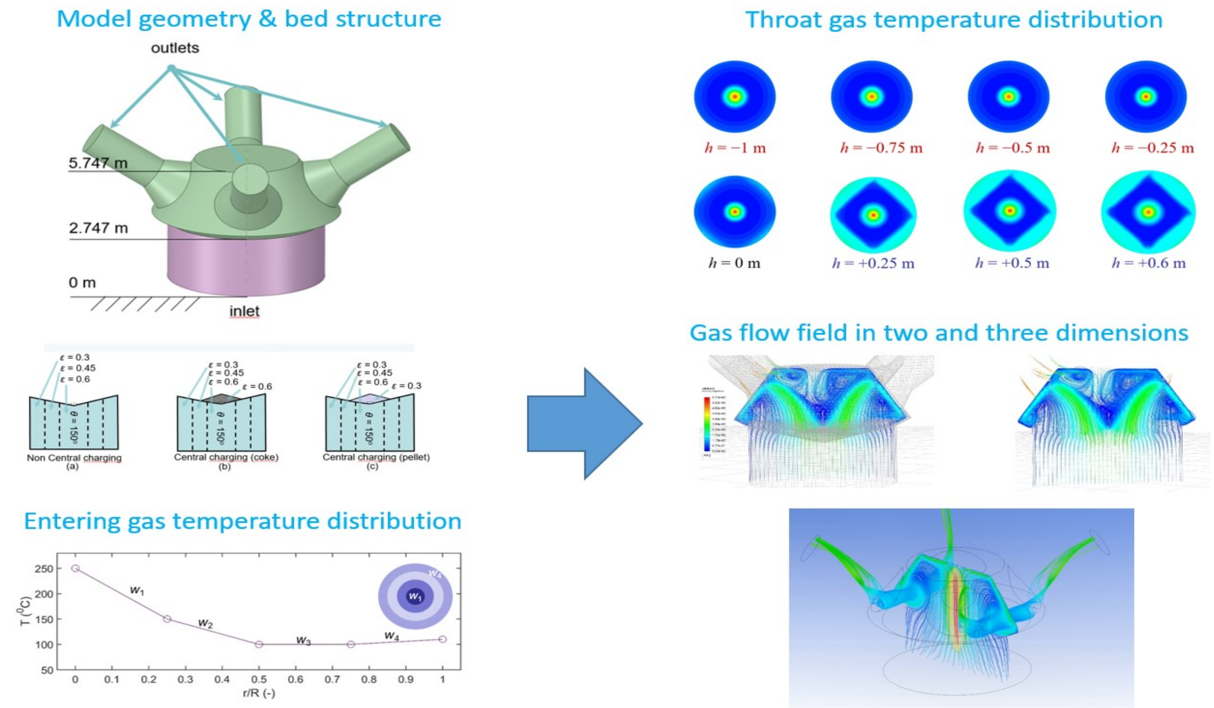

Figure 27. Simulation of gas flow and temperature field in the upper part of the blast furnace.

Description

The flow of top gas in the blast furnace throat is complex, because it enters from a packed bed with an inclined surface and exits through four distinct gas uptakes. An understanding of the flow patterns is essential to interpret gas temperature measurements in the throat, e.g. using new acoustic techniques.

Application

The flow of gas in the uppermost part of the blast furnace shaft and throat region was studied by computational fluid dynamics (CFD). To consider the complex flow patterns, a three-dimensional domain was modelled, focusing on the behaviour of the gas above the burden surface, where measurements of the gas temperature were taken. The simulated flow patterns provide a means of interpreting new two-dimensional gas temperature measurements by acoustic techniques, also revealing possible recirculation of the gas that affects the measurements.

Results

The simulations with ANSYS revealed complex flow patterns mainly caused by the four discrete outlets (gas uptakes) and the redistribution of the gas that flows from the burden to the empty throat region. For inclined burden surface profiles, a clear acceleration of the gas towards the centre was observed, with an extent depending on the gas velocity distribution in the bed. A strong recirculation in the regions between the gas uptakes was also observed, which yielded a disturbed temperature field that did not reflect the temperature distribution of the gas leaving the burden. Dynamic simulations revealed a complex and possibly fluctuating circulation of the gas that was further disturbed by the charging of the burden. The results showed that the acoustic measurements should be taken as close to the burden surface as possible to avoid the negative impact of gas circulation and redistribution.

Impact

The findings of the work have highlighted several problems in the interpretation of gas temperatures measured in the blast furnace throat, including the effect of gas redistribution and backflow. The results show how gas with a certain flow and temperature distribution in the bed is mixed above the burden surface, depending on the surface profile. The findings also give an idea of the dynamic behaviour of the gas flow after disturbances, and that the flow paths towards the gas uptakes may change with time.

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THERMODYNAMIC-KINETIC EAF MODELLING

25 MATHEMATICAL MODELLING OF THE EAF PROCESS

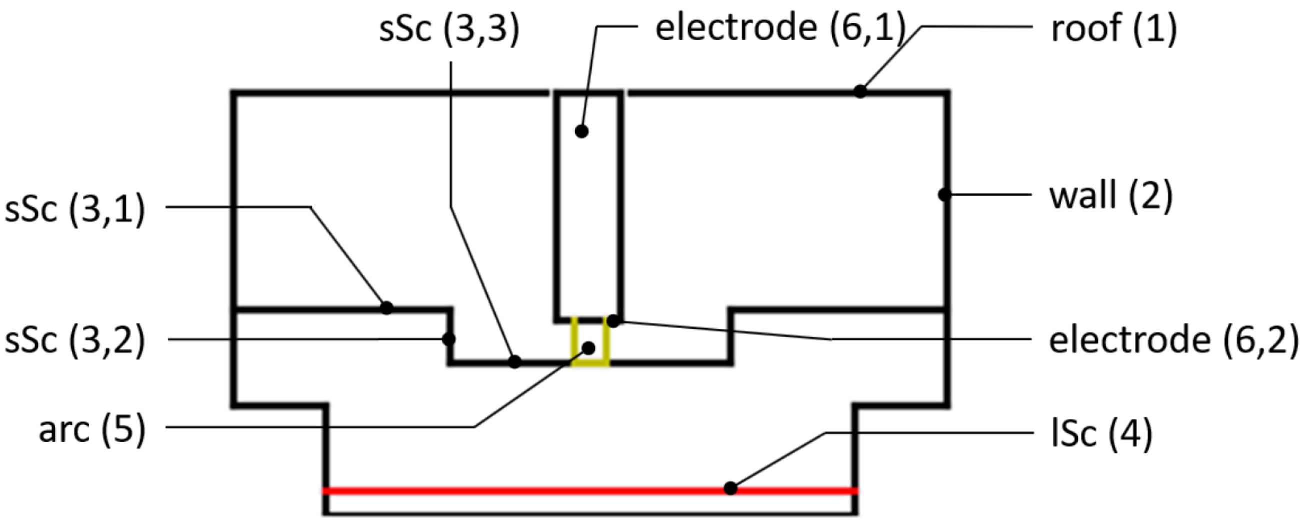

Figure 28. Schematic illustration of the zones of the scrap melting module.

Description

This study aimed to develop a mathematical model for the online prediction of scrap melting, composition changes, and temperature changes in the EAF process.

Application

Model development is based on a modular structure that can be adapted for a given process environment (e.g. carbon steelmaking or stainless steelmaking). Three standalone modules have been developed during the AMET project: 1) scrap melting; 2) gas-phase reactions in the freeboard; and 3) metal–slag reactions. The scrap melting module is based on the calculation of heat transfer from electrodes and burners to different zones of a simplified EAF geometry. This module is coupled with an inhouse thermochemistry package to calculate the main thermochemical properties at a given temperature. The gas-phase reaction module is based on a Lagrangian method for Gibbs energy minimisation in the freeboard of the EAF, while the metal–slag reaction module employs the effective equilibrium constant method to predict the rate of competitive mass transfer controlled reactions.

Results

Concerning the scrap melting module, the view factor calculation for radiative heat transfer was found to be in good agreement with CFD modelling. While only a qualitative validation has been carried out for the scrap melting rate, it was found to be in reasonable agreement with that observed in plant practice. A functional validation of the gas-phase and metal–slag reaction modules has been conducted using literature data. The predicted gas-phase equilibria were found to be in near-perfect agreement with earlier studies and commercial software (HSC Chemistry 9). The metal–slag reaction module showed some discrepancies and thus further validation is required.

Impact

The next steps are to couple the standalone modules together, use the model to predict complete heats from charging to tapping, and validate the model with plant data. The model is then ready to be tested for the online prediction of the EAF process and can also be used as a basis for model predictive control applications.

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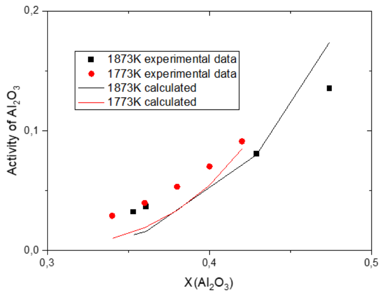
DEVELOPMENT OF PHENOMENOLOGICAL MODULES FOR CONTINUOUS CASTING

26 SLAG THERMODYNAMIC MODEL

Thermodynamic model (cell model)



Activities of $CaO-Al_2O_3$ slag

Reactions

$[Al]+[O]=Al_2O_3$
$[Ca]+[O]=CaO$
$[Ca]+[S]=CaS$
$[Mg]+[Al]+[O]=MgAl_2O_4$
$[Ca]+12[Al]+19[O]=CaAl_{12}O_{19}$
$[Ca]+4[Al]+7[O]=CaAl_4O_7$
$[Mg]+[O]=MgO$
Reaction between steel and liquid inclusion

Inclusion prediction

Steel composition(in wt%):
Steel 1: [Al]:0.13 ,[S]: 0.011,[C]: 0.11, [Si]: 0.28,[Mg]: 0.0001, [O]: 0.0010, [Mn]: 0.9

[Ca]>0.112ppm precipitation of $CaAl_{12}O_{19}$
[Ca]>0.48ppm precipitation of $CaAl_4O_7$
[Ca]>3ppm precipitation of liquid inclusion
[Ca]>14ppm precipitation of CaS
[Ca]>35ppm precipitation of CaO

Nozzle clogging prevention by calcium treatment:

For steel 1: 3ppm<[Ca]<14ppm, full liquid aluminate without CaS and CaO

Figure 29. Inclusion prediction by in-house slag thermodynamic model.

Description

An inhouse thermodynamic model tool for metallurgical slag in the Al2O3-CaO-MgO-MnO-FeO-SiO2 system was developed based on the concept of the cell model. Combined with the thermodynamic model of liquid steel, the slag thermodynamic model can predict the inclusion phases in steel. The range (window) of total calcium concentration in the formation of liquid inclusions can be determined for the guidance of calcium treatment.

Application

Many applications of inhouse slag thermodynamic model can be found in steel refining and casting. The thermodynamic model of slag can be applied in constructing an online model for the evolution of steel, slag, and inclusions during ladle treatment, which can serve as a tool to control the steel chemistry and cleanliness in the ladle. Another application for the slag thermodynamic model is that it can be combined with a thermodynamic model of steel and thermodynamic data to calculate the optimal calcium addition to obtain fully liquid inclusions, which is critical for the prevention of nozzle clogging during casting.

Results

The inhouse thermodynamic slag model was developed, and model parameters were optimised using experimental thermodynamic data from the literature. The calculated activity of Al2O3 in CaO-Al2O3 are compared with experimental data. As shown in Figure 29, the calculated activity values are in good agreement with the experimental data. The precipitation reactions for solid inclusions such as Al2O3, CaO, CaS, MgAl2O4, CaAl12O19, CaAl4O7 and liquid inclusions were considered, and thermodynamic data for reactions were assessed from thermodynamic data books and the relevant literature. Combined with a thermodynamic description of the liquid steel phase, the equilibrated inclusion types and amounts can be predicted based on equilibrium calculations. The inclusion prediction has been validated by comparing the results with those from the commercial thermodynamic database, e.g. FactSage. The influence of calcium addition on the inclusion phase formation was investigated with the model, and the optimal amount of calcium addition was determined.

Impact

The process models for steel refining and casting contribute to the digitalisation of steel production and provide an impetus for the transformation of the steel industry towards the Industry 4.0. The thermodynamic models have been widely applied in the process model of steel refining and continuous casting. Compared with a commercial thermodynamic package, an inhouse, standalone thermodynamic model can be more intimately incorporated in the process model to control the steel composition, cleanliness and castability.

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DEVELOPMENT OF PHENOMENOLOGICAL MODULES FOR CONTINUOUS CASTING

27 QUALITY PREDICTION IN CONTINUOUS CASTING OF STEEL

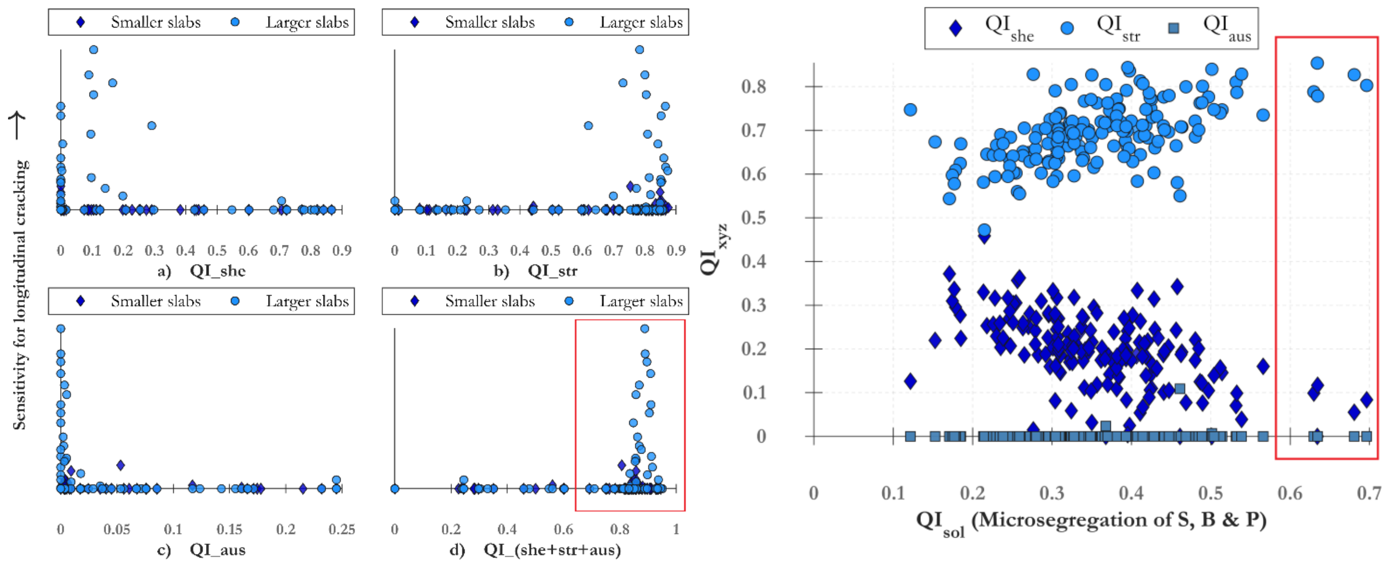

Figure 30. Phenomenological quality indices applied to defect sensitivity assessment and quality prediction. Longitudinal cracking sensitivities in various steel grades and an area with the highest defect sensitivity in an individual steel grade are well identified.

Description

This task focuses on offline quality prediction, more specifically an assessment of defect formation sensitivities in different steel grades during the continuous casting process. Whether a defect of a certain type will form is theoretically known to depend on both compositional and process-related factors. The composition of the steel grade mostly determines the phenomena during solidification in continuous casting. Furthermore, process irregularities and infeasible operational practices can encourage the negative effects of these phenomena. Because of the significance of the metallurgical phenomena in defect formation, it is justified to consider the effects of compositional factors before proceeding to quality prediction with machine learning approaches that incorporate both compositional and process-related features.

Application

The studies are conducted with an advanced simulation tool known as IDS, which is applied in the evaluation of solidification, microstructure formation, and metallurgical phenomena during the casting process. Simulations are executed with both nominal and measured compositions for a variety of defect-prone steel grades to generate justified conclusions about defect formation. The simulation results are thoroughly compared with reported defect formation from cast and rolled products at the plant.

Results

The results indicate that there is great potential in the application of quality indices for quality prediction. The quality indices and other simulation results are for many of the steel grades capable of describing the phenomena and their significance in defect formation. It seems that finding the causes of defects commonly requires multivariate analysis, and for some steel grades, measured information from the process is also necessary in the assessment.

Impact

The impact of the results is significant, because corrective actions and new thresholds can be proposed for the studied steel grades. Corrective actions and thresholds are formulated individually according to the nominal composition of the steel grade and previous composition thresholds. In their simplest form, the results can be illustrated as a table, which consists of probable causes of the defect formation and proposals for future defect avoidance. This work will continue soon with even broader defect formation considerations.

Publications

S. Louhenkilpi, A. Laukka, J. Miettinen, J. Norrena, V.-V. Visuri, T. Alatarvas, T. Fabritius and **E. Piipponen,** "Online 3D Heat Transfer and Solidification/ Microstructure models and their Capabilities for Simulation of Continuous Casting of Steel and Quality Prediction"**,** STEELSIM2021, 2021.

J. Norrena, "Quality criteria in continuous casting of steel", 2021. Master's thesis, University of Oulu.

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DEVELOPMENT OF PHENOMENOLOGICAL MODULES FOR CONTINUOUS CASTING

28 CASTMANAGER CLIENT – MONITORING SOFTWARE TO CONTINUOUS CASTER CONTROL ROOM

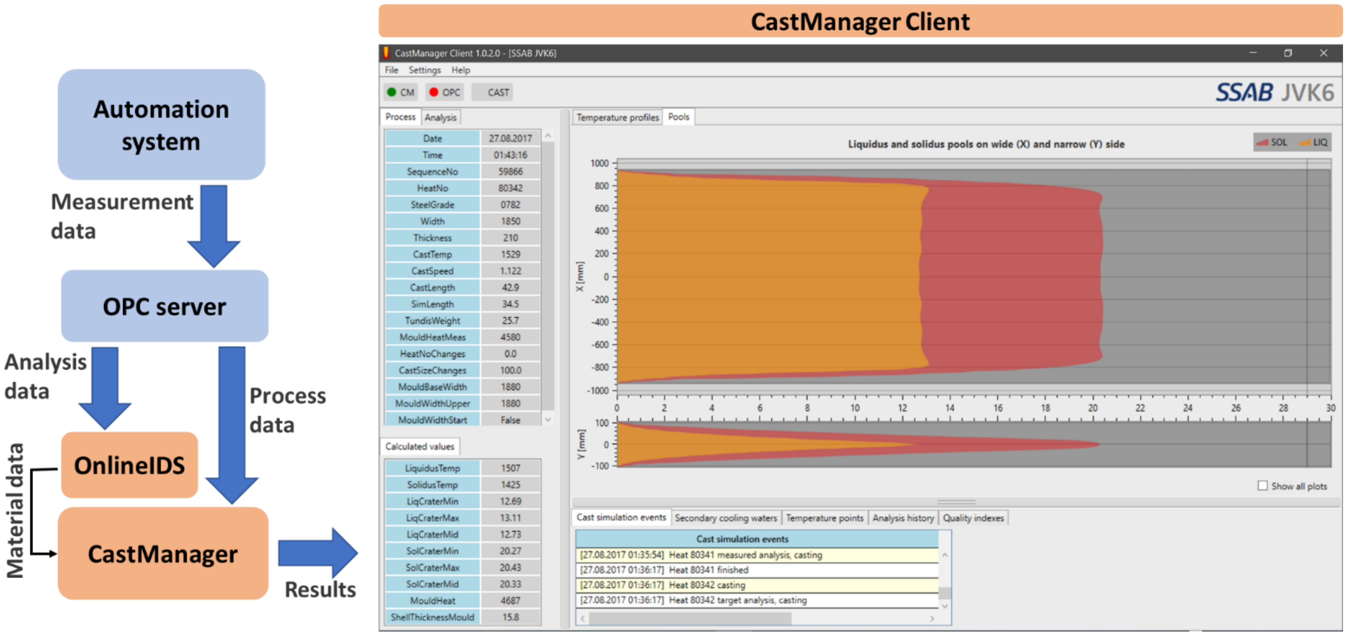

Figure 31. CastManager software system.

Description

The *CastManagerClient* monitoring program for the continuous caster control room was developed for the SSAB Raahe steel plant. The program is part of an online continuous casting simulator that also includes *CastManager* and Solidification and Microstructure Model *OnlineIDS*. CastManager is a Windows service that includes a 3D GPU accelerated heat transfer module. It retrieves the required process data from the factory automation system and calculates 3D strand and mould temperature distributions as a function of secondary cooling components, steel grade, strand and mould geometry, and casting variables. OnlineIDS calculates material data for every heat using analyses measured from the tundish.

Application

Every certain cycle, CastManager Client requests the latest process data and calculation results from the CastManager service, which returns them as an XML message. This message is parsed, and results are visualised for the user. These results include strand temperatures and temperature-related data such as solidus and liquidus pools and longitudinal temperature profiles from the meniscus to the machine end. Values of casting variables, secondary cooling waters, cast events, and steel analysis history among others are included in the process data.

Results

CastManager Client has been successfully tested in a test environment on continuous casters CCM4, CCM5, and CCM6, simulating real casting trials. The next step will be to install the program in the control room of CCM4.

Impact

Monitoring of steel solidus length is important to ensure that the strand is fully solidified when it exits the casting machine. Visualisation helps the operators see the ongoing situation and understand the influence of process variables on the solidification length.

Publications

S. Louhenkilpi, A. Laukka, J. Miettinen, J. Norrena, V.-V. Visuri, T. Alatarvas, T. Fabritius and **E. Pipponen**, "Online 3D Heat Transfer and Solidification/ Microstructure models and their Capabilities for Simulation of Continuous Casting of Steel and Quality Prediction", STEELSIM2021, 2021.

S. Louhenkilpi, J. Miettinen, J. Laine, R. Vesanen, I. Rentola, J. Moilanen, V.-V. Visuri, E.-P. Heikkinen and **A. Jokilaakso**, "Online Modelling of Heat Transfer, Solidification and Microstructure in Continuous Casting of Steel", IOP Conference Series: Materials Science and Engineering, 2019. https://doi.org/10.1088/1757-899X/529/1/012051

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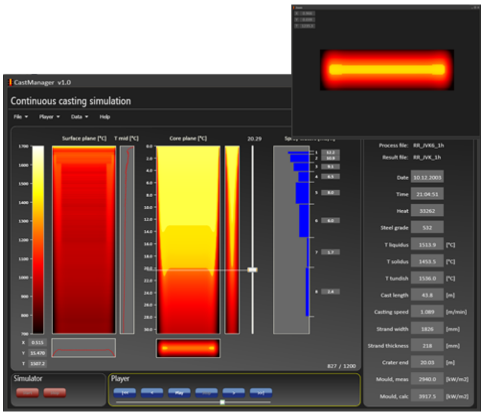
DEVELOPMENT OF PHENOMENOLOGICAL MODULES FOR CONTINUOUS CASTING

29 VALIDATION OF THE ONLINE CASTMANAGER HEAT TRANSFER TOOL FOR CONTINUOUS CASTING



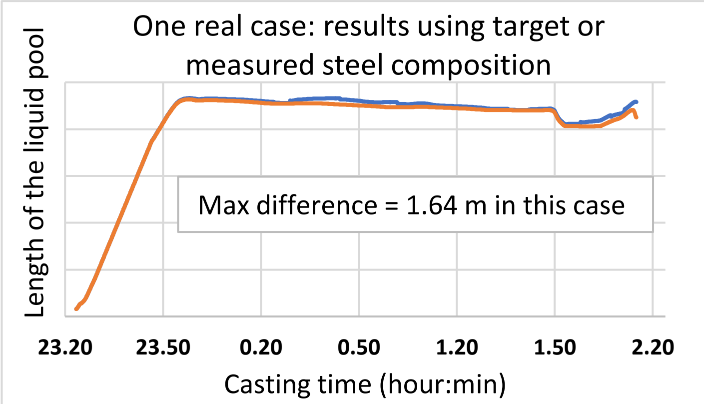


Figure 32. Left: CastManager is online 3D heat transfer tool for continuous casting. Right: simulated length of the liquid pool using “modified” target steel composition from the ladle compared with the actual measured steel compositions from the caster.

Description

CastManager is a 3D online heat transfer tool for continuous casting. It is coupled with the online IDS tool. IDS is a solidification tool, and it calculates the important fundamental phenomena during solidification and cooling, such as phase transformations, elemental microsegregations, inclusions, precipitates, and thermophysical material properties. All these are calculated as a function of steel composition and cooling pattern. Today, a module with quality indices has also been implemented for online quality prediction purposes. The online system CastManager + IDS runs in three slab casters at SSAB Raahe steel plant. The CastManager and IDS tools have been developed in Finland by Casim Consulting Oy in close cooperation with University of Oulu, Aalto University, and the Finnish steel industry.

Application

The present aim was to validate the CastManager tool. The results were compared with another, similar online heat transfer tool (CHTT) also installed in SSAB Raahe’s caster No. 6. IDS calculates the material data for CastManager; CHTT is coupled with another material data tool. The tools, CastManager and CHTT, are based on the similar main partial differential equations. In any case, it was impossible to know the model parameters in the CHTT tool, such as Leidenfrost curves, the effective thermal conductivity formula, correlation equations between spray cooling and spray heat transfer equations, width change or grade change algorithms, and many others. Despite all this, the agreement between the tools was usually very good. However, in some situations, small differences could also be observed. More than 6000 casts were compared. The material data tools provided almost identical material properties. It was found later that the tools in SSAB Raahe use slightly different steel composition data. The material data therefore also varied. CHTT used the “modified” target steel composition from the ladle. CastManager also used this at first, but when available, the actual measured steel compositions from the casting machine were used. Selected cases with differences were compared. In these cases, the maximum difference in the liquid pool length was 1.64 metres.

Results

The tools (CastManager and CHTT) seem to give very similar results when the steel compositions are equal. Using the actual steel compositions from casting machine provides more accurate results than using target compositions, but it is important to develop an automatic algorithm to correct the possible measurement errors in the measured steel compositions from the caster online.

Impact

The accurate online calculation of the liquid pool end position and control of the strand temperatures are very important for avoiding defects and thus increasing the steel quality, as well as yield and productivity.

Publications

S. Louhenkilpi, A. Laukka, J. Miettinen, J. Norrena, V-V. Visuri, T. Alatarvas, T. Fabritius and **E. Piipponen**, ”Online 3D Heat Transfer and Solidification/ Microstructure models and their Capabilities for Simulation of Continuous Casting of Steel and Quality Prediction, STEELSIM2021, 2021.

S. Louhenkilpi, J. Miettinen, J. Laine, R. Vesanen, I. Rentola, J. Moilanen, V.-V. Visuri, E.-P. Heikkinen and **A. Jokilaakso**, “Online Modelling of Heat Transfer, Solidification and Microstructure in Continuous Casting of Steel,” IOP Conference Series: Materials Science and Engineering, 2019. https://doi.org/10.1088/1757-899X/529/1/012051

J. Miettinen, S. Louhenkilpi, V.-V. Visuri and **T. Fabritius**, “Advances in Modeling of Steel Solidification with IDS”, IOP Conference Series: Materials Science and Engineering, 2019. https://doi.org/10.1088/1757-899X/529/1/012063

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AI-BASED EXPERT SYSTEM FOR CONTINUOUS CASTING

30 ROADMAP TO AN AI-BASED EXPERT SYSTEM FOR CONTINUOUS CASTING OF STEEL

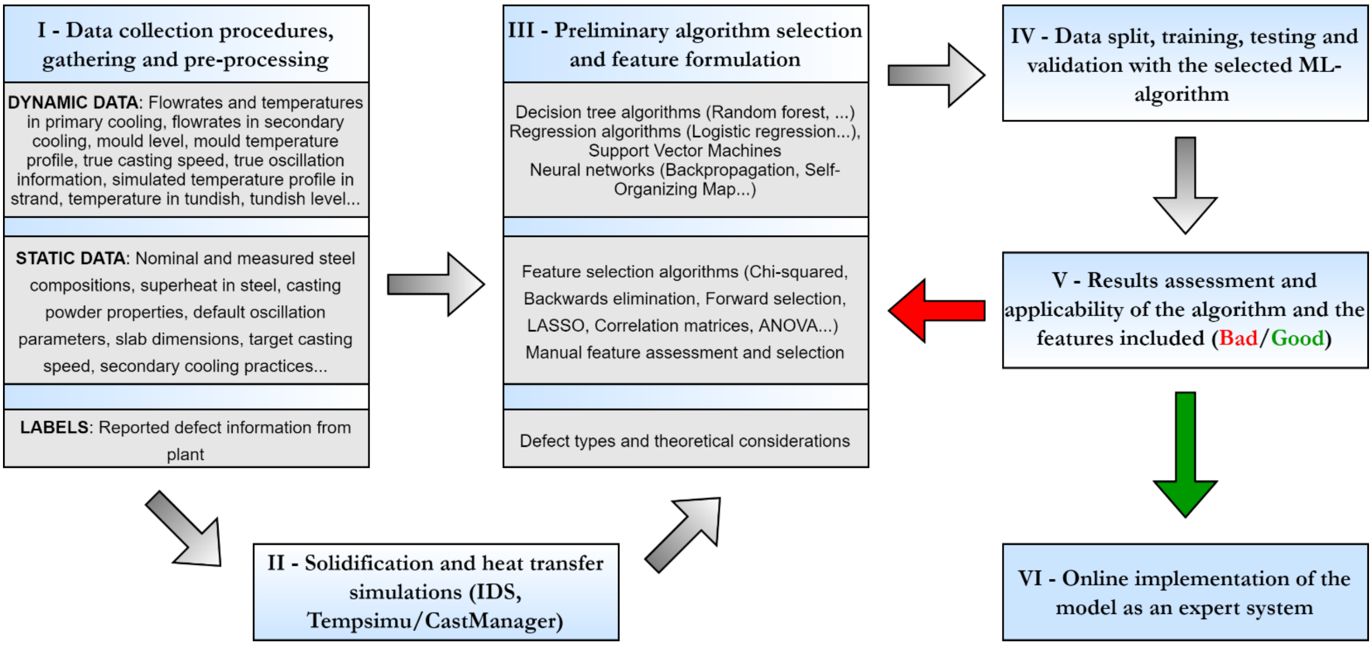

Figure 33. Stepwise detailed work plan for the development of an expert system for continuous casting of steel.

Description

In this task, a roadmap is formulated for future work in the field of online quality prediction in continuous casting. According to the literature and knowledge gained during AMET, the required information for quality prediction includes at least composition data, measured information from the casting process, casting parameters, and reported defects. Additionally, empirical knowledge from the plant may be necessary. Defects in continuous casting are categorised into their own groups, and even if process irregularities and some composition factors are known to encourage defect formation in general, a different subset of factors must be defined for each defect type, increasing complexity substantially. Machine learning is selected as the methodology because of the complex and multivariate mechanisms of defect formation.

Application

The methods and work stages necessary in the development of an expert system include data gathering, analysis and pre-processing, simulations with tools that are applied to describe the relevant phenomena in continuous casting, statistical methods, and eventually the formulation of a machine learning model including model selection, feature selection, and the actual training, testing, and validation steps before any online application development.

Results

Recent results from defect sensitivity assessments and offline quality prediction in **Steps I-II** during AMET are promising, and it is probable that an online expert system can indeed be formulated in the future by proceeding stepwise with **Steps III-VI** in the future.

Impact

A validated expert system in continuous casting of steel is beneficial in both the offline and online prediction of defect formation in the cast product. The advantages and benefits of such a system include defect formation avoidance during casting, increased hot charging possibilities, and the allocation of inspections to cast products with a high predicted defect formation probability. Energy consumption and production costs will decrease, while an increase in the quality of the cast product is expected. Furthermore, new steel grades or other changes in the steel compositions could cause challenges in the casting process because of the missing empirical knowledge, which can be supplemented with offline predictions before casting.

Publications

S. Louhenkilpi, A. Laukka, J. Miettinen, J. Norrena, V-V. Visuri, T. Alatarvas, T. Fabritius and **E. Piipponen**, "Online 3D Heat Transfer and Solidification/ Microstructure models and their Capabilities for Simulation of Continuous Casting of Steel and Quality Prediction, STEELSIM2021, 2021.

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MICROSTRUCTURAL MODEL FOR ROLLING OF STRIPS AND BARS

31 SIMULATION OF MICROSTRUCTURAL EVOLUTION OF STEEL DURING THERMO-MECHANICALLY CONTROLLED PROCESSES

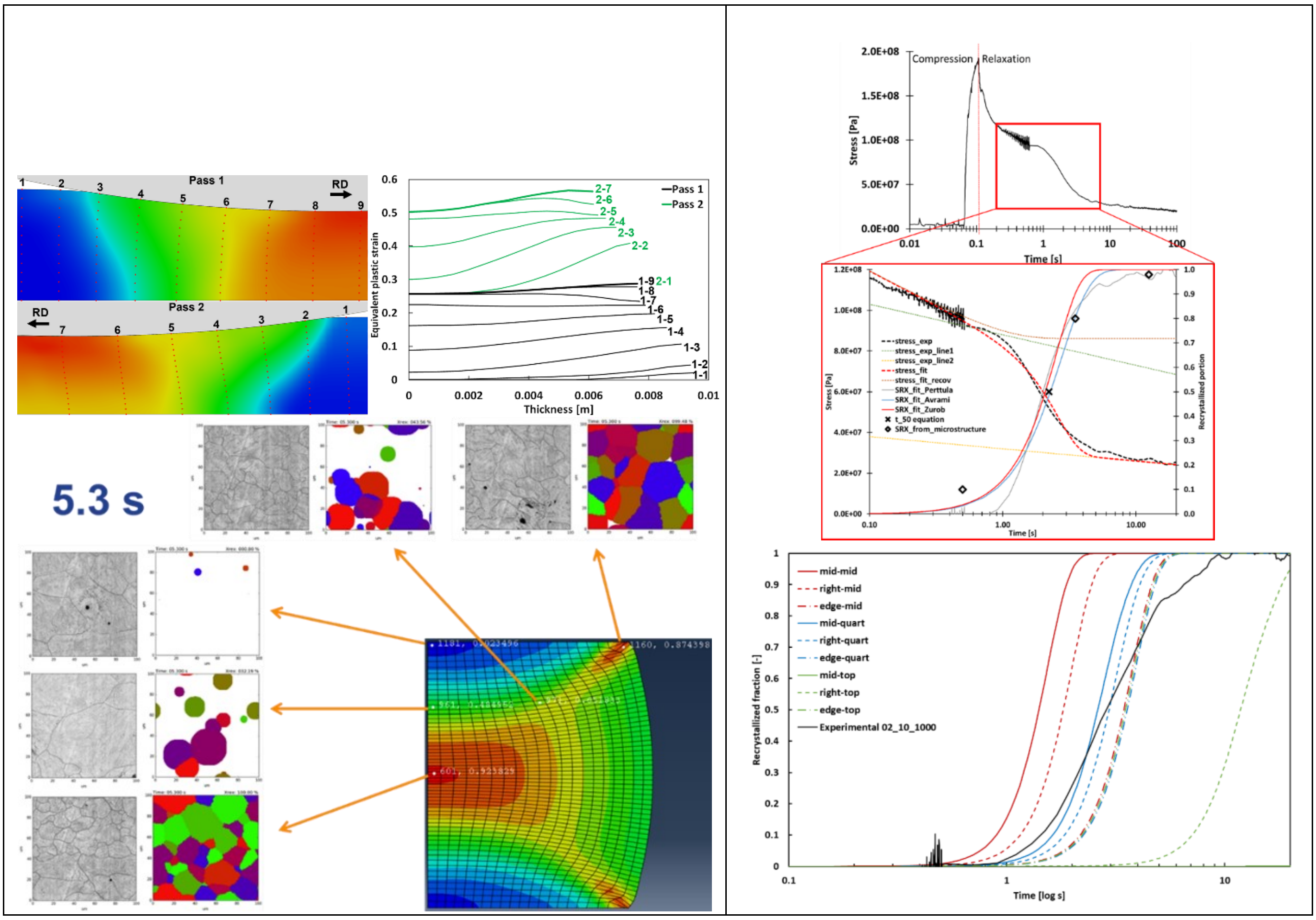

Figure 34. Top left: simulation of 2 roughing passes; bottom left: SRX+GG simulation of a Gleeble 3800 test; top right: SRX-kinetics from a relaxation test; bottom right: SRX-kinetics in the cross-section of a Gleeble test piece.

Description

Static recrystallisation (SRX) and grain growth (GG) during TMCP (namely roughing) are studied to understand and model the phenomena. Physical simulations are used to obtain experimental data, which are used to fit the models and predict microstructural evolution. Roughing is also studied to model the thermomechanical behaviour of the slab and rolling mill.

Application

A 2D thermo-mechanical FE-model is created to simulate multi-pass roughing and the ability to calculate SRX+GG equations is coded. Gleeble 3800 is used to study the SRX and GG kinetics, while model fitting is done with the mean field and CA models. This eventually leads to a coupled FE model, where the effect of SRX+GG can be accounted for in slab's the thermomechanical behaviour.

Results

The FE model works and has been published. SRX+GG modeling is ongoing. Good models have been found and tested but require more experimental data to reliably simulate microstructural evolution.

Impact

The finished model can be used to simulate microstructural evolution of steel during roughing, which can be used along with results from Tasks 32-34 (p. 47-49) to simulate the thermomechanical properties of steel and rolling mills in roughing and hot strip rolling. Finally, this information is critical to properly predict the mechanical properties of steel.

Publications

O. Seppälä, J. Ilmola and **J. Larkiola,** "Industrial Fe-Simulation of Roughing Using an Automatic Solver Shifting Technique", Materials Science Forum, 2021. https://doi.org/10.4028/www.scientific.net/msf.1016.1312

O. Seppälä, A. Pohjonen, J. Ilmola, A. Jokiranta, A. Kaijalainen, M. Somani and **J. Larkiola,** "Simulation of deformation and static recrystallization in the stress relaxation test", Journal of Physics: Conference Series, 2019. https://doi.org/10.1088/1742-6596/1270/1/012027

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OPTIMISATION OF WATER COOLING IN ROLLING OF STEEL STRIPS

32 FAST TEMPERATURE MODEL FOR STRIP ROLLING AND COOLING

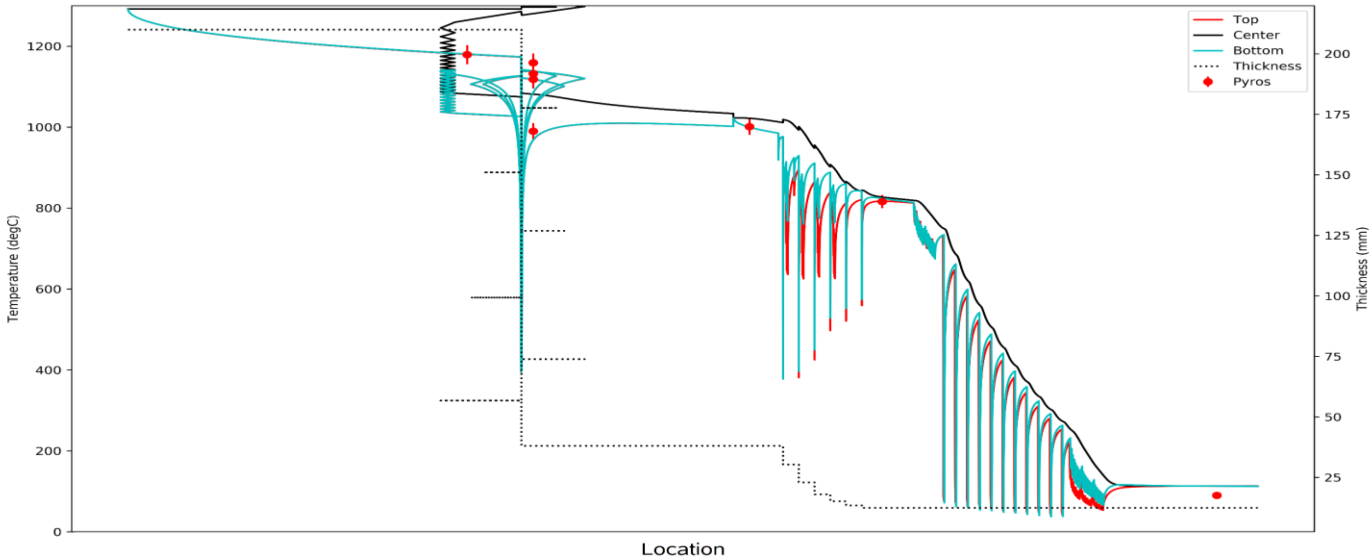

Figure 35. Temperatures on top, bottom, and centreline. Pyrometer measurements are taken on the bottom surface. The dotted line represents thickness. Note that the strip goes back and forth through the roughing roller.

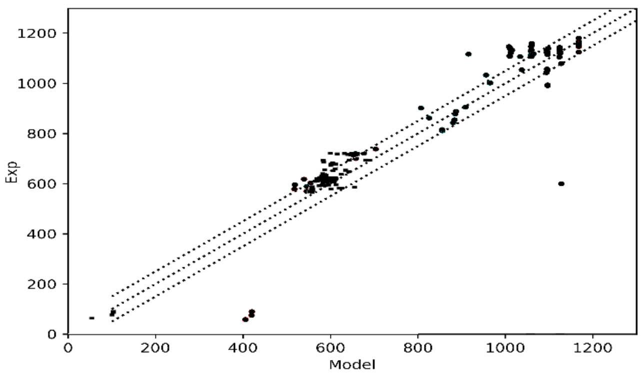

Figure 36. Correlation between temperatures measured by pyrometers (Exp) and modelled temperatures at pyrometer positions (Model).

Description

The properties of modern steels are usually a result of thermomechanical rolling and controlled cooling. Although many different phenomena are involved in rolling, the single most important factor remains the temperature that determines the conditions for metallurgical phenomena, i.e. whether there is enough time for recrystallisation between rolling passes, or how big the grain size will be on the coil box, depends mostly on the temperature, though alloying is also important factor. In this project, a one-dimensional temperature model was developed for the whole strip production line, from walking beam furnaces to strip coilers. However, some de-scalers and their effects are neglected in the model, and the model for the coil box is drastically simplified.

Application

The model can be used to study the effect of process parameters such as pass schedule and cooling water fluxes on temperature evolution on the entire strip production line. It can be used not only to model what happened in the produced coil, but also to find extremes and test what different temperature paths are even theoretically possible to obtain on the strip production line.

Results

The model aimed to take all the different factors that affect the cooling conditions and thus the temperature profile into account. The model therefore has a significant number of different parameters, and proper validation would have required a much larger experimental dataset. However, it was tested that the model gave reasonably accurate results on varying grades with different pass schedules and cooling schemes (Figures 35 and 36).

Impact

This model provides an essential backbone for the future development of fast strip rolling models and a great foundation on which to build more profound metallurgical models.

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PREDICTION OF STRENGTH IN STEEL STRIPS

33 MODELLING OF COILING AND COIL COOLING OF STEEL STRIPS

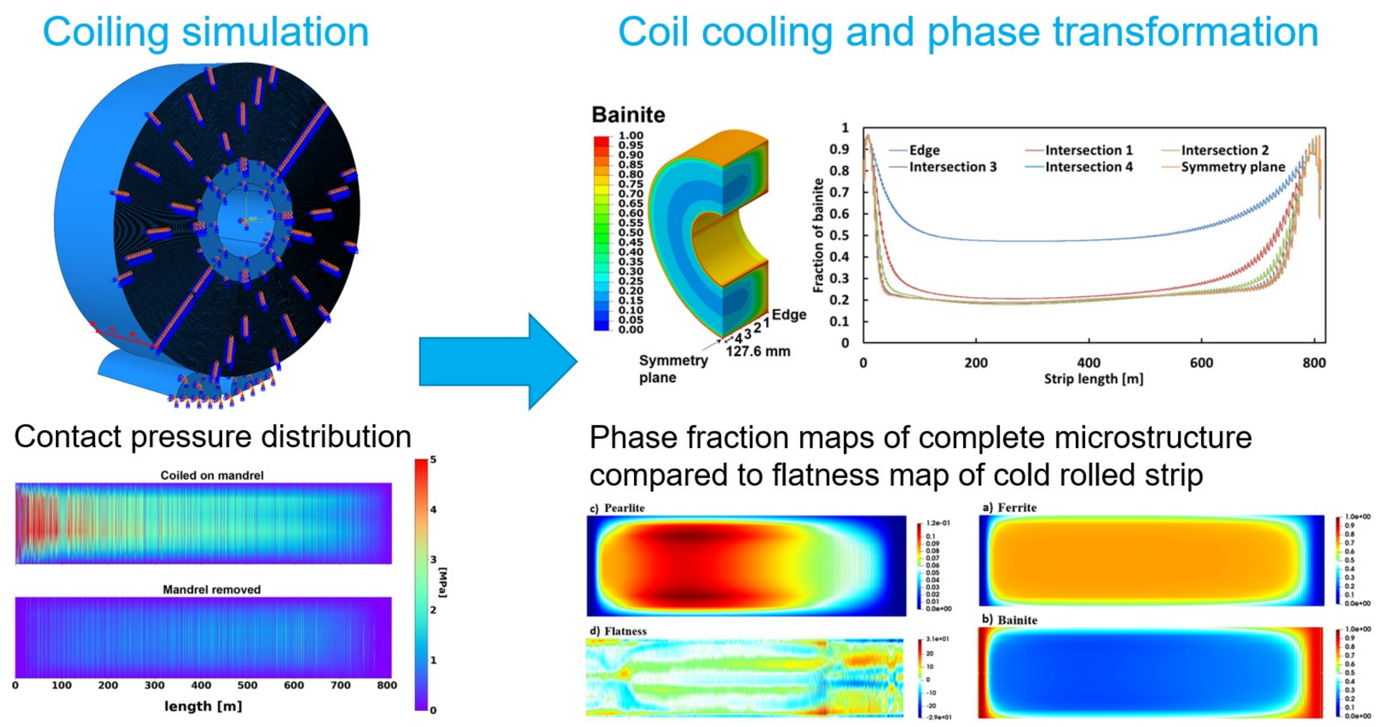

Figure 37. Coiling and coil cooling with coupled phase transformations.

Description

The final microstructure of a dual-phase steel was modelled during coil conveyance and coil field cooling. These steels are generally coiled with a fully austenitic microstructure and ferritic phases transform in coil cooling. Diverging thermal conditions around the coil lead to an uneven phase fraction distribution due to differing cooling rates.

Application

A Finite Element Analysis (FEA) of the coiling process was utilised to define the internal contact pressure distribution inside the coil. Contact pressure was considered in thermal contact conductance between strip layers in the coil. A coupled microstructure model calculated transformed phase fractions in the coil during the cooling process. Arbitrary coil conveyance paths and thermal conditions can be simulated with the developed model.

Results

Rotationally asymmetric phase fractions in the steel coil were discovered with the developed model. This unequal phase fraction distribution caused stability issues in the further cold rolling process, producing thickness deviations in the cold rolled strip. The final phase fraction distribution can be calculated in 3D for any steel strip when phase transformations occur during coil cooling.

Impact

The root cause of the thickness deviations in cold rolling of dual-phase steels was modelled successfully, and a tool for simulating coil cooling was created. The model is also utilised to simulate alternative coil conveyance practices to avoid inhomogeneous phase fraction differences. Cooling paths for different steel grades are simulated, and the effect of water-cooling ramps are studied.

Publications

J. Ilmola, A. Pohjonen, S. Koskenniska, O. Seppälä, O. Leinonen, J. Jokisaari, J. Pyykkönen and **J. Larkiola,** "Coupled heat transfer and phase transformations of dual-phase steel in coil cooling", Materials Today Communications, 2021. https://doi.org/10.1016/j.mtcomm.2020.101973

J. Ilmola, A. Pohjonen, O. Seppälä and **J. Larkiola,** "The effect of internal contact pressure on thermal contact conductance during coil cooling", Procedia Manufacturing, 2020. https://doi.org/10.1016/j.promfg.2020.08.076

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PREDICTION OF STRENGTH IN STEEL STRIPS

34

ARCPRESS SETUP CALCULATIONS AND VIRTUAL MANUFACTURING OF HOT STEEL STRIPS

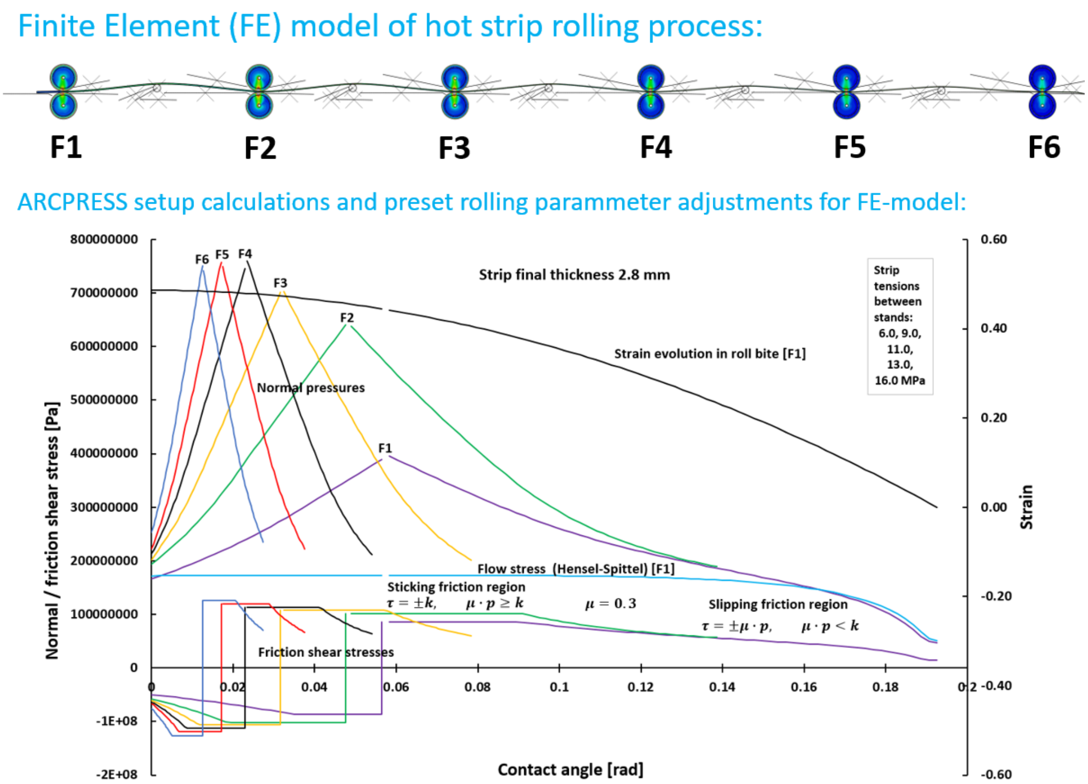

Figure 38. Calculations of contact pressures for 6 stands hot strip rolling process. Contact pressure calculation is utilised to predict roll force and work roll flattening. Pre-set adjustments of FE-model are set based on ARCPRESS setup calculations.

Description

ARCPRESS setup calculations are utilised in roll force predictions, roll flattening, and the pre-set adjustment of the roll gap in the FE model of hot strip rolling. Normal contact pressure and frictional shear stresses between a strip and work roll are considered, as well as entry and exit strip tensions and the effect of the friction coefficient.

Application

The ARCPRESS model is implemented in a virtual rolling automation system of the FE model of hot strip rolling. The ARCPRESS is also coupled with static recrystallisation model introduced earlier (p. 46). Moreover, it can be exploited as an individual model to calculate roll gap parameters and flow stress. The entire hot strip rolling manufacturing process can also be modelled when coupled with the fast temperature model described earlier (p. 47). Together, these three models constitute a digital platform for the virtual manufacturing of the hot steel strip.

Results

All the rolling parameters required for setting up the rolling automation for the incoming slab can be calculated with ARCPRESS. Normal pressure distribution considering sticking and slipping friction shear stresses in the roll gap are used to predict roll force.

Impact

The model (with coupled models mentioned earlier) can be utilised to model and simulate hot strip rolling, metallurgical phenomena and accelerated water cooling. The process and strip properties can be optimised and improved by investigating phenomena in the model which cannot be measured from the process.

Publications

J. Ilmola, J. Larkiola, O. Seppälä and **J. Jokisaari,** "Roll gap calculations for automation integrated finite element analysis in multipass hot strip rolling simulations", KomPlasTech2019, 2019.

J. Ilmola, J. Larkiola, A. Pohjonen, O. Seppälä and **J. Jokisaari, "**Implementation of process setup calculations and automation controls in finite element analysis of hot steel strip rolling", 11th IRC, 2019.

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WORK PACKAGE 3
NEW BUSINESS BASED ON PLATFORM ECONOMY

Summary

Traditionally, the challenging conditions of high-temperature processes are considered barriers of market entry for small and medium-sized enterprises (SMEs). In addition, the offering of small companies may be insufficient compared to the needs of typical large metal industry customers.

This work package (WP3) aimed to make the market entry easier by bringing products to global markets through the platform economy. With the aid of the platform economy, the SMEs can offer their products as a service, allowing easy and cost-effective access for customers to innovative products. On the other hand, a networked business could enable SMEs to enter the global markets at lower costs but with a more extensive joint offering together.

In the project, the SMEs were proposed a new ecosystem business model to shift from delivering single measuring devices to delivering comprehensive systems. The SMEs' capabilities of scalability were analysed, and a productisation model was developed to ensure the systematic growth of business. Standardisation, systematisation, and modularity inside the operations and the service offerings were identified as key components of scalability. Flexibility and connectivity are also needed to adapt to changes in future customer needs. In the future, common platforms offer easier ways to productise SMEs' innovations.

***Toni Laurila**, Sensmet Oy*
***Erno Mustonen**, University of Oulu*

PRODUCT PORTFOLIO MAPPING OF THE PLATFORM ECONOMY COMPANIES

35 DEVELOPING A BUSINESS MODEL FOR THE IOT PLATFORM ECOSYSTEM

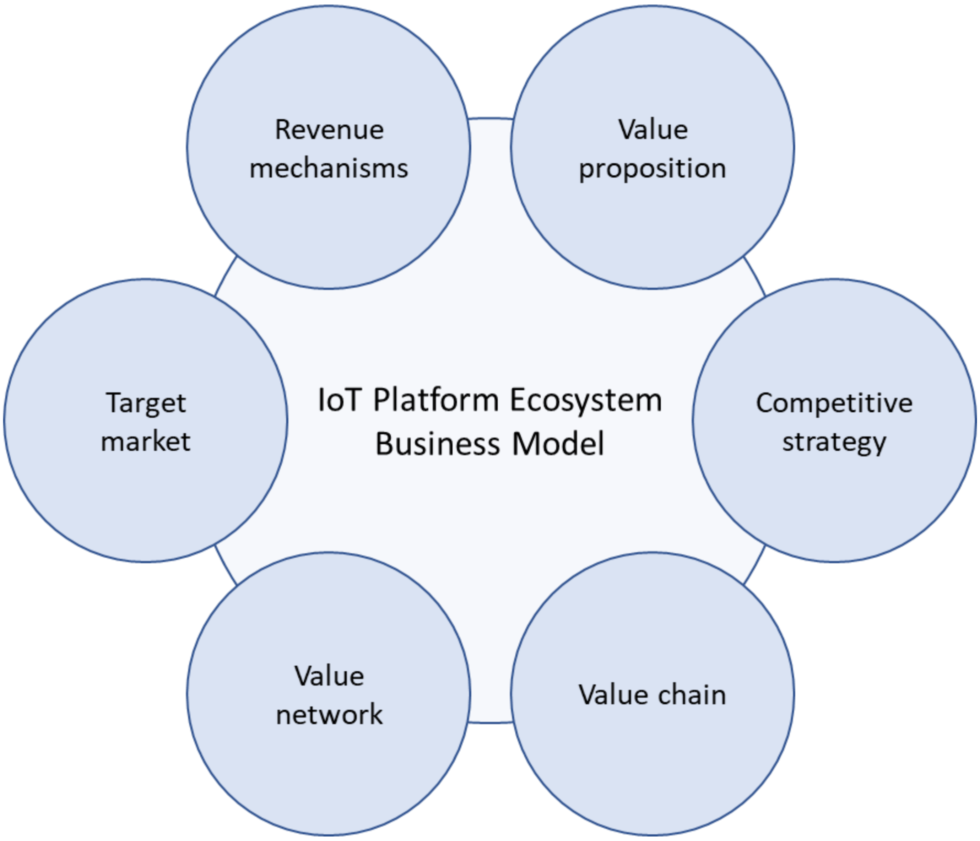

Figure 39. Key Issues and Managerial Areas of IoT Platform Ecosystem Business Model.

Description

IoT platform ecosystem companies' current product offerings and their value creation were modelled and analysed. The companies' current business models were analysed from an IoT platform ecosystem's perspective, and proposals for developing an IoT platform ecosystem business model were presented.

Application

The IoT platform ecosystem business model framework was applied to model and plan the potential ecosystem business that would be formed by companies working through a common IoT platform.

Results

The results propose targets for development in eight areas to build a shared IoT platform ecosystem business model: value proposition; revenue mechanisms; value chain; value network; competitive advantage; and target market.

Impact

Generally, the results will help companies move the business thinking from individual companies and their independent business models towards cooperation and a shared IoT platform ecosystem business model. The development targets should be approached and planned in cooperation from the ecosystem's perspective. At the detailed level, the results can support companies build the shared ecosystem business model block by block.

Publications

M. Mirzaei, "Developing a Business Model for the IoT Platform Ecosystem", 2021. Master's thesis, University of Oulu.

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A CASE STUDY ANALYSIS OF CONNECTING TECHNOLOGIES WITH SERVICES

36

IMPROVING SERVICE SCALABILITY IN IOT PLATFORM BUSINESS

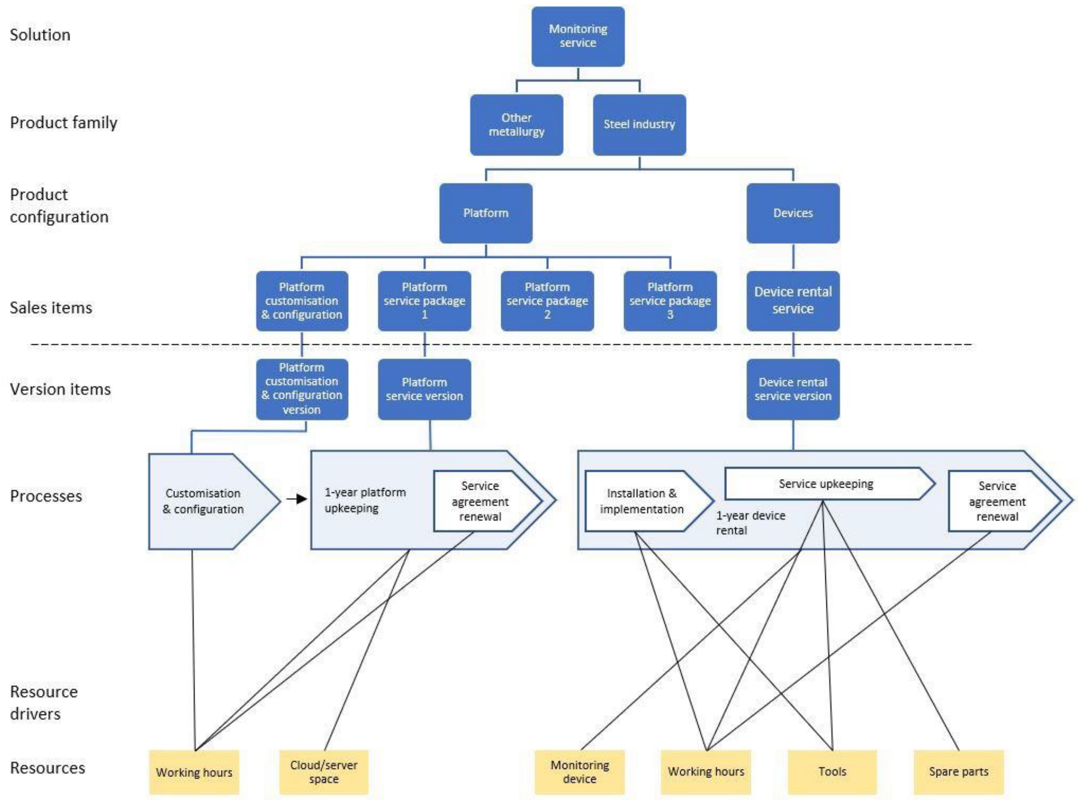

Figure 40. Productised service portfolio for scalability.

Description

Challenges of scalability were identified in companies working in the IoT platform business. Based on the challenges, a productisation model was developed to improve service scalability in the IoT platform business. The model utilises a generic product structure that acknowledges the commercial and technical sides of an offering and the related resource drivers.

Application

The offerings of companies working in the IoT platform business were modelled with the developed productisation model. The modelled offerings varied in how the devices and the platforms were offered to the customers. The offerings included devices sold as physical goods and as a service, and platforms sold as a time-based service ran on cloud or on premise.

Results

Generic representations of the productisation model for two different scenarios were constructed. The model considered both the physical and service attributes of an offering. In the first scenario, the devices were sold as physical goods and the platform as a monthly-based service. In the second scenario, the devices were rented, and the platform was sold as a use-based service.

Impact

The model supports gaining a uniform understanding over what is sold to the customer (commercial view of the offering) and how it is delivered (technical view of the offering). By linking the service processes to the required resources via resource drivers, companies can better understand, analyse, and plan the scaling of their service production.

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