UNIVERSITY OF OULU

IOB Department for Industrial Furnaces and Heat Engineering | RWTH AACHEN UNIVERSITY

5th European Academic Symposium on EAF Steelmaking

05 - 07 June 2023

EASES

Abstract booklet

Content

Session on Process control and sensors

Session chairs: Matti Aula and Henri Pauna

Electric steelmaking process monitoring with optical emission spectroscopy – An in-depth review

Arto Rautioaho, Henri Pauna, Ville-Valtteri Visuri, Marko Huttula, Timo Fabritius, University of Oulu

Electric steelmaking is one of the key factors in the future of environmentally friendly steelmaking where the carbon footprint has to be reduced and processes need to be both energetically and economically feasible. As the capacities of electric furnaces and usage of e.g. low-grade recycled material can be expected to increase, the importance to optimize the process practices and enabling flexibility of the processes becomes paramount. The high-temperature environment of electric steelmaking sets several criteria for the implemented tools, where the equipment has to withstand extreme conditions for long periods of time, have a low maintenance need and cost, and have the capability of real-time data acquisition and analysis.

To address the need for novel process control, optical emission spectroscopy (OES) has been studied in the laboratory, pilot-scale, and industrial furnaces together with existing industrial applications to provide an in situ method for electric arc furnace and ladle furnace process control. Since OES is a method that measures the emitted light from an object, the applications focus on the electric arc plasma, burners' flames, and heat radiation from the molten bath. Due to the nature of material radiating in high-temperature plasmas and flames, the optical spectra hold information on the composition and temperature of the light source as well as the current status of the process. This in-depth review compiles the research and usage of OES as a process control tool for electric steelmaking by focusing on electric arc plasma, burners' flames, and molten bath radiation together with a discussion on how the addition of hydrogen into the processes could be monitored and controlled with OES. Guidelines for further development of existing applications as well as potential new applications in the realm of steelmaking are discussed.

An In-Situ Analysis Method in EAF and BOF Steelmaking

Bernhard Mitas, Henri Pauna, Joachim Feldbacher, Johannes Schenk, K1-MET GMBH

An analysis was conducted to gage the feasibility of using a spectroscopic method to determine the chemical composition of the liquid metal phase in EAF and BOF steelmaking. The hypothesis that certain radiation intensities found in UV- and UV-near regions of the hot-spot spectrum in the BOF and the impingement area of oxyfuel burners in EAF steelmaking can be used for analysing the chemical components present in the aggregate is tested. Significant lab-scale experiment results and the conclusions regarding industrial scale implementation are presented.

Soft sensor approach for continuous estimation of EAF bath temperature

Aljaž Blažič, Igor Škrjanc, Vito Logar, University of Ljubljana

Electric arc furnaces (EAFs) are widely used for recycling steel scrap, and achieving the proper tapping temperature is critical for the process. However, accurately measuring the melt temperature is challenging due to the complex and dynamic nature of the process, which requires advanced measurement equipment. Therefore, most EAFs rely on multiple temperature samples taken prior to tapping the melt to verify that the temperature is within the desired range. These measurements are taken with disposable probes, but require the furnace to be switched off, resulting in longer tap-to-tap time, increased energy losses, and reduced efficiency.

To address this problem, this paper proposes a novel approach to estimating the EAF bath temperature using a soft sensor fuzzy model. The model is constructed using the Gustafson-Kessel clustering method for the input data and the least squares method to estimate the consequent parameters. It utilizes the temperature measurement as the initial condition and the measurements of EAF inputs to continuously estimate the bath temperature throughout the refining stage of the recycling process. The results demonstrate that the proposed model has high prediction accuracy and meets the required tolerance band.

The model is designed for parallel implementation in the EAF process to achieve fewer temperature measurements, shorter tap-to-tap times, and reduced energy losses. Continuous monitoring of the bath temperature allows operators to adjust the EAF control to achieve optimal tapping temperature and higher efficiency.

In summary, the proposed soft sensor approach provides a practical solution for continuous measurement of the melt temperature in the EAF recycling process. The high accuracy of the model, parallel implementation, and potential for improved efficiency make it a valuable tool for the steel industry."

Determination of the Hot Heel in an Electric Arc Furnace Using Computer Vision

Amit Sharma, Thomas Echterhof, Herbert Pfeifer, RWTH Aachen University

Industrial process monitoring constitutes an integral part of the Electric Arc Furnace (EAF) operations. Integrating modern, state-of-the-art techniques for monitoring these processes has made major advancements in improving process optimization and productivity. Computer Vision, an advanced image processing technique, has found its way into several dynamic EAF processes, the determination of Hot Heel being one of them. The conventional method of determining Hot Heel levels encompasses using pervasive methods like sensors dipping into the liquid steel, which has its drawbacks such as high wear and tear due to high operating temperatures inside the furnace. Using computer vision can be a feasible alternative for a number of reasons, such as its non-intrusive nature and low maintenance costs. Installing cameras at appropriate positions on the furnace provides an ample amount of data to carry out image analysis by means of the pixel values of the images. Appropriate pre-processing of data could indicate the presence of a region of interest (ROI). The acquired region of interest could easily be extended to inherit pixel locations and embedded information. Further advancements in the techniques are possible in the areas of sensors and process controls. Low maintenance costs and high adaptability would increase the overall acceptance of the incorporated technique.

A Decision Support System for Optimizing Electric Arc Furnace Operations using Mechanistic and Data-driven Models

Simon Tomažič, Vito Logar, Igor Škrjanc, University of Ljubljana

We present a novel decision support system specifically designed for electric arc furnace operators to improve the efficiency and effectiveness of their decision-making process. Our system uses advanced mechanistic and data-driven models trained on historical data to simulate planned batches based on real-time data, providing operators with valuable information that can help them make decisions about furnace settings. One of the key objectives of our system was to develop and implement a user-friendly graphical interface that uses the Siemens MindSphere cloud service for interactive management with the operator support system. With this interface, operators can easily analyse past batches and compare them with simulated batches using different input data and melting parameter settings. By analysing the simulation results and different melting scenarios, operators can identify optimal settings, resulting in improved process optimisation and lower operating costs. Our decision support system is a powerful tool that enables electric arc furnace operators to make efficient and informed decisions, ultimately leading to more sustainable and cost-effective operations.

Session on Process modelling and simulation I

Session chairs: Alberto Conejo and Chuan Wang

Simulations of 3D Hydrogen Electric Arc and Effect of External Magnetic Field on Arc Flow Dynamics

Mohamad Al-Nasser, Abdellah Kharicha, Hadi Barati, Menghuai Wu, Andreas Ludwig, Christian Redl, Bertram Ofner, Anton Ishmurzin, Nikolaus Voller, Gernot Hackl, University of Leoben

Steel produced by Electric arc furnace (EAF) exceeded 29% of the total steel production in the world by the year 2018. The growth in the utilization of EAF shows an increasing rate every year. EAF attempts to reduce carbon emissions in steel production by using green electricity instead of fossil fuel. Reducing carbon production during EAF operations is an inevitable course of action which is in harmony with global measures to cut down carbon, on the top of which sits the renewable energy. The switch to EAF operation might also utilize green hydrogen technology in steel reduction instead of carbon reduction, a fact this leads to almost carbon emission-free process. Hydrogen is mixed with other inert gases and used as a reducing agent in the reduction of iron oxides. The electric arc behavior is highly complicated and experimental measurement is not achievable due to extreme conditions inside the furnace. Numerical simulations provide a powerful tool to predict the arc behavior and estimate the flow and temperature fields in the furnace.

In this work, a 3D numerical model is presented; it is capable of simulating hydrogen arcs in 3D in addition to simulating other gases inside the arc mediums. The numerical model couples the electromagnetic field with hydrogen plasma arc dynamics (flow and heat transfer). The arc is simulated inside atmospheric pressure of direct current (DC) in hydrogen gas. The model shows that arc instabilities emerge spontaneously near the cathode before propagating downwards along the arc jet. Occurs also a spontaneous splitting into several arcs before instance merging into one arc. The model accounts for the effect of external magnetic field interaction with the arc, and a different external magnetic field yields a different arc behavior. The horizontal magnetic field induces arc skewing and directional flow is observed, while the axial magnetic field induces a rotational flow and arc swirling; this is diverging away from the center of low currents and coverages to the center of domain at high axial magnetic field. This model aims to improve the understanding arc behaviour and predict and prevent possible failures during the operation.

Modelling 3D Electro vortex Flow inside liquid metal and Effect of External Magnetic Fields on Flow Pattern

Mohamad Al-Nasser, Abdellah Kharicha, Hadi Barati, Menghuai Wu, Andreas Ludwig, Christian Redl, Bertram Ofner, Anton Ishmurzin, Nikolaus Voller, Gernot Hackl, University of Leoben

In Direct Current (DC) electric arc furnace (EAF) the current flows from the anode to cathode through the metal and arc plasma. In addition to the arc jet in plasma, the current generates electro vortex flow (EVF) inside liquid metal. EVF is crucial factor inside the EAF to obtain a uniform thermal distribution and adequate chemical mixing inside liquid metal bath. This insures uniform steel quality and avoid any undesirable solidification away from the arc. Although the EVF inside liquid bath is desirable any

excessive or unidirectional flow can result in non-uniform heating or excessive wear on the refractories. Numerical modelling of the liquid metal bath offers a good replacement for experimental measurement due to extreme conditions inside the EAF.

We present a numerical model that simulates the EVF inside liquid metal in 3D. The flow structure and strength of the flow are dictated by the current value and the presence of an external magnetic field. Compared to the 2D axisymmetric, 3D simulations offer more degrees of freedom and introduce different aspect of flow. The results presented reveal a typical electro vortex structure for low currents. Higher currents induce more mixing inside the domain and swirl flow can be observed without any presence of an external magnetic field. Cyclone, Tornado, and rope tornado are observed inside the domain due to current interaction with axial magnetic field. The horizontal magnetic field induces a directional flow. The non-uniform flow inside EAF can result in unbalanced heat distribution or excessive wear on the refractories.

Fluid flow simulation of an EAF with bottom gas injection and coherent jets

Fornah Samuel, Zhu Rong, Wei Guangsheng, Junfeng Yang, Conejo Alberto, University of Science and Technology Beijing

In this work, a three – phase mathematical model for a 100 – ton electric arc furnace (EAF) with combined blown is presented. The combined blow consists of oxygen injection with three coherent jets, as well as bottom gas injection with three tuyeres. The model uses a volume of fluid (VOF) approach to simulate the multiphase flow. For simulating the fluid dynamics of this complex system, the coherent jet fluid flow is calculated apart from the rest of the metallurgical reactor. Then, the results of such calculation are coupled with the EAF simulation to decrease the computational time and increase the solution robustness. The model proves to predict the mean velocity reported by previous models correctly. The calculation results gave valuable information about the EAF combined blown fluid dynamics and can be used to make process decisions and improve their performance.

Hydrogen-Ready CoJet Technologies For EAF Steelmaking

Pascal Kwaschny, Joachim von Scheele, David Muren, Linde AG

CoJet® gas injection technology was developed and first introduced by Praxair (now Linde) in 1996 and has had a significant impact in Electric Arc Furnace (EAF) operation. With more than 170 CoJet® installations world-wide CoJet® technology has become the industry standard for chemical energy input into EAFs.

The Fluidic Burner uses jets, without mechanically moving parts, to deflect the flame and optimize chemical energy input and melting in the EAF. This has been found to be particularly beneficial when installed at the slag door or in the EBT area to cut and melt-in heavy scrap.

Linde’s CoJet® injectors and Fluidic Burner may be operated with hydrogen as a fuel to help decarbonize chemical energy input into the EAF. Experiments show that hydrogen is an ideal fuel, better even than standard fossil fuels, at producing a flame shroud for better jet coherency and yielding longer jets.

The Fluidic CoJet®, in development, adds the fluidic flame capability to the CoJet® technology. The added feature improves heating and melting uniformity, shortens melt-in time thereby increasing productivity and enables a more efficient use of chemical energy.

To further support the optimization of the energy-efficiency, Linde's propriety OPTIVIEW™ technology has now also been adapted to EAFs. OPTIVIEW™ is an image-based system that analyses the flue gas composition.

Based on the analysis, OPTIVIEW™ provides online information to optimize the EAF post combustion to obtain minimum energy losses.

A Review of Thermodynamic and Kinetic Models for the behavior of Nitrogen in an Electric Arc Furnace

Siddharth Nachankar, Thomas Echterhof, Herbert Pfeifer, *RWTH Aachen University*

Depending on the steel grades produced, gases, like nitrogen, dissolved in the melt can be a limiting factor for steel production in the electric arc furnace (EAF). The EAF process does not involve inherent degassing of the melt as in the basic oxygen furnace (BOF); on the contrary, the constant impingement of the arc plasma jet(s) fed from the furnace atmosphere as well as oxygen, coal and lime injectors can influence the amount of dissolved gases. Therefore, steel grades with low nitrogen limits can only be produced in the EAF with an increased and usually costly effort in secondary metallurgy by employing processes such as Argon Oxygen Decarburization (AOD) or Vacuum Degassing (VD). In addition, there are now concerns that switching burners from natural gas to hydrogen fuel could have a negative impact on the hydrogen content of the steel melt.

Dynamic EAF process models can be used to predict the content of dissolved gases in molten steel if they are extended and adapted accordingly. In order to accomplish this, suitable sub-models need to be identified, that can make use of the data provided by the EAF process model like, e.g. the furnace atmosphere composition.

Owing to its inert nature and larger fraction in the furnace atmosphere, nitrogen has been selected for this review. Various thermodynamic models are available in literature predicting the solubility of nitrogen in different compositions of steel alloys. Furthermore, experimental studies have been published to estimate the rate of absorption and desorption of nitrogen gas in molten iron and steel alloys. In this paper, a survey of the most recent thermodynamic models predicting the solubility of nitrogen in molten steel has been conducted. Furthermore, a detailed review of the kinetic studies implemented to understand the pickup of nitrogen gas into the melt has been presented. Finally, the suitability for an implementation within the available EAF process model has been discussed.

Session on Process modelling and simulation II

Session chairs: Vito Logar and Petri Sulasalmi

On the differences of modelling scrap- and DRI-based EAF processes

Ville-Valtteri Visuri, Ilpo Mäkelä, University of Oulu

The steel industry is faced with a challenge to develop new operating practices and production routes to strive towards CO_2-lean EAF steelmaking. Production of direct reduced iron (DRI) by a hydrogen-based reduction in a shaft furnace followed by melting of the DRI in an EAF has been envisaged as a potential route for CO_2-lean production of steel from high-quality iron ores. This paper discusses the differences between modelling scrap- and DRI-based EAF processes from three perspectives: DRI melting, biochar as a foaming agent, and hydrogen burners. The thermal requirements for DRI melting in comparison to scrap melting are exemplified based on enthalpy differences. The prediction of foaming with biochar is discussed using the concept of the foaming index. Finally, hydrogen burners are compared to natural gas burners from thermal effect and offgas composition viewpoints.

EAF process simulation on using hydrochar as a carburization agent

Chuan Wang and Mikael Lindvall, *Swerim AB*

The addition of biocarbon to EAF process will play an important role to facilitate the steel industry for the green transition. Hydrochar is a type of biocarbon derived from low-grade biomass residues via the hydrothermal carbonization (HTC) process, which is suitable to upgrade various locally available wet biomass feedstocks. Compared to biochar produced from the pyrolysis process, hydrochar has lower fixed carbon content and higher volatile content. In this study, an EAF process model was created by using commercial software, Outotec® HSC Chemistry®, to simulate the addition of hydrocar in an EAF testbed. One type of hydrochar was added via both top charging and injection as carburization agents. The reference case is the addition of fossil carbon, one type of anthracite. The simulation model will be presented in detail with some perspectives on further developments.

Coupled dynamic modelling of scrap melting and gas phase reactions in the EAF process

Ilpo Mäkelä, Ville-Valtteri Visuri, Matti Aula, University of Oulu

As the steel industry strives towards new greener operating practices, they will also need process models capable of considering these new methods. Mathematical process models enable the producers to better control and study their processes, however, models capable of considering DRI-based EAF practice relevant for hydrogen-based steelmaking are still few and far between.

This paper showcases our recent developments towards a modular EAF process model. The model is based on previous works by Ringel, Jussila and Hekkala, who developed stand-alone modules for scrap melting, gas phase reactions in the freeboard and metal-slag reactions, respectively. The modular

structure will allow the model to be easily updated, improved, and changed to consider new processing practices or raw materials, making it a versatile platform for future developments.

The aim of this paper was to couple the melting module with the module for gas phase reactions in the freeboard. The melting module considers the significant heat sources and heat distribution between different zones in the furnace. The gas phase reactions module uses the Gibbs energy minimization by White et al. to calculate the equilibrium gas phase composition. Coupling these modules allows the model to consider interaction of gas phase reactions with the melting and heat transfer phenomena in the furnace. Some points of interest would be the CO post-combustion and the effects of different burner fuels on the gas phase.

Theoretical electric arc furnace model for online estimation of the unmeasured process variables

Vito Logar, Igor Škrjanc, University of Ljubljana

Modelling of the electric arc furnace processes has in the last decades become a field of increased importance. Studies of different phenomena on different levels can help the researchers to better understand either various subprocesses or the EAF process as a whole. In the past, our research group developed several versions of the complete EAF model, differing in the level of their complexity, included details, and aiming to achieve different goals. Initial version of the model was intended to learn about the EAF system and its key processes. The following version was developed with an intention of obtaining a universal and accurate EAF model, describing all necessary the processes, focusing especially on chemical reactions, melting geometry, and radiative heat transfers. Intermediate versions were focusing on different details of EAF subprocesses, aiming to achieve greater estimation accuracy. The last version of the model represents a simplified version of the previous model versions and is designed for online parallel simulation with the actual EAF process. Its aim is to estimate the unmeasured and rarely measured process variables, such as energy balance, stage of scrap melting, and bath temperature. The difference between this model and the previous versions is that it is significantly simplified, customized to the client's requirements, and thus introduces several assumptions and simplifications of the main subprocesses, while still maintaining sufficient level of accuracy. In this manner, the complexity of the model’s structure and several of its subprocesses was significantly reduced, such as the number of calculation zones, chemical reactions, melting geometry, and heat transfers. In this presentation, the model is presented in more detail, focusing on customer requirements, model validation with measured EAF data, its implementation into industrial infrastructure, and analysis of the accuracy of the estimated variables. Furthermore, some ideas for further modifications for the model development are given.

Simulation and analysis of the EAF-based steel production process using dynamic models

Dimitra Papamantellou, Saikat Chatterjee, Sourav Panda, Tata Steel

Two dynamic models for the Electric Arc Furnace steel production process are available at Tata Steel Ijmuiden: the Effective Equilibrium Reaction Zone (EERZ) model and the model developed by the Research Center of Metallurgy (CRM – EAF model). These models have been validated with industrial operations data and are able to simulate both the melting and refining aspects of an EAF. Various kind of charge material (such as scrap, HBI/DRI and/or hot metal) as well as different operating conditions (batch / continuous feed, arcing program, burners, oxyjet, etc.) can be modelled. In this analysis, a case with 100% scrap as charge material will be investigated. Hence, only the melting process will be taken into account. A comparison between the results of both models will take place. Furthermore, the advantages and limitations of the two models will be presented. According to the calculations that have been run until today, both the EERZ and CRM – EAF model are capable of reproducing the steel plant data reasonably well.

Session on Slag and by-products engineering, processing and valorisation

Session chairs: Rita Kallio and Davide Mombelli

Software tool to estimate the influence of Cu content of scrap in the scrap mix TCO

Asier Vicente Rojo, Edurne Nuñez, ArcelorMittal Global Research & Development

Scrap is the main raw material of the EAF route of steelmaking, accounting for 50-60% of the production cost, and an important one of the primary route. The decarbonisation commitment acquired by the most relevant steelmaking companies, will only increase the amount of scrap used by both routes, making it a critical component to succeed in the CO_2 reduction challenge.

While being a very relevant material, scrap characterisation is complex due to its heterogeneity, but furthermore, its quality is worsening as its demand increases. This includes the presence of unwanted elements such as copper

Lower quality in scrap comes at a lower price, while scrap with lower cooper content is most costly. Being able to balance the cost and benefit of purchasing scrap with a higher or lower content of copper and higher or lower purchase cost would be of interest to optimise the mix and produce the required quality steel at the lowest possible cost.

The Value In Use (VIU) of scrap is highly used in the daily work of managing scrap yards, purchases and use. It considers the purchasing cost and metallic yield on top of the additional costs associated with the melting of the non-ferrous materials contained in it. However, it does not consider the residual elements, such as Cu, as these do not have a thermodynamic impact on the process.

Nowadays, this cost benefit analysis can only be done by performing TCO calculations that require a lot of information, including complete chemical composition of scrap, market parameters and other relevant data, and involve an arduous process.

Based on a parametric study of the TCO calculation, this work proposes a mathematical model to estimate the TCO of a mix with a given scrap type, thus facilitating the decision making that results less costly by comparing two scenarios. This mathematical model can be easily programmed and requires only 5 parameters to be run, while it provides a low error result.

Evaluating suitability of bricks to be charged to electric arc furnace

Ahmed Abdelrahim, Matti Aula, Timo Fabritius, University of Oulu

Aside from melting steel scrap, electric arc furnace (EAF) can be utilized to melt by-products that would be otherwise difficult to use. Many of the by-products produced in steel industry are in the form of powder, which makes their direct recycling to EAF difficult. The problem of the small particle size can be alleviated by agglomerating the by-products.

Briquettes and pellets have been for long used as a charge material to blast furnace (BF), so their characterization methods for this purpose are well defined. The same is not true for EAF, in which utilizing the by-product agglomerates is not as widely spread. The main difficulty in using the by-product agglomerates in EAF is that they require energy to melt in EAF, which decreases the productivity. This problem is especially pronounced for the most common binder material, cement.

The results presented in this work are based on the EU RFCS-project Fines2EAF, in which cement-free bricks were utilized in recycling the fine-grained waste streams to EAF. When developing agglomerate recipes, the potential recipes need to be screened in order to avoid operational problems in industrial scale, and to focus the trials on the most promising recipes. In this project a test scheme for evaluating the suitability of the potential brick recipes to be charged to EAF was developed.

Separate tests were utilized to evaluate the behaviour of the bricks in EAF from different perspectives. The mechanical strength was evaluated with five meter drop tests, as the bricks were planned to be charged to silo. In EAF the requirement of compressive strength is not as high as in BF due to lower material height, but the compressive strength test was performed for the reference. The thermal stability during heating was tested with optical dilatometry, in which the shape of the cut bricks were observed. The reduction behaviour of the iron oxide containing bricks was tested with thermogravimetric analysis. Lastly, the interaction of the brick and molten slag was tested by charging the cut bricks to molten slag in the chamber furnace.

In the evaluation of the test results two of the original five recipes were deemed most promising for the use in EAF. The results highlight that it's especially important to consider thermal shock resistance and to perform the drop tests from the actual drop height that the bricks will have to withstand, in order to screen out recipes that would produce high amount of dust in the industrial scale.

Laboratory Scale Evaluation of the Slag Foaming Behavior

Andreas Pfeiffer, Kathrin Thiele, Gerald Wimmer, Johannes Schenk, Primetals Technologies Austria / Montanuniversität Leoben

Due to the ambitious climate targets of the European Union, one can expect that the electric arc furnace (EAF) will gain greater importance in the future of steelmaking. Since slag foaming is a decisive factor in an efficient process, understanding this phenomenon is essential when applying hydrogen-based direct reduced iron (DRI). Therefore, a method was developed to check different slag compositions concerning their foaming behavior. Slag samples are melted, and a carbon carrier is added. After a selected reaction time, the crucible is quenched in liquid nitrogen, superficially freezing the state while foaming. Afterward, it is halved, providing metallographic examination and height measurement possibilities. Three slags were tested, MgO-saturated EAF slag, MgO-unsaturated EAF slag, and electrical Smelter-like slag. Digital and scanning electron microscopy with energy dispersive x-ray spectroscopy are used to compare the slags and evaluate the method. The Smelter slag shows no foamability, unaffected by the FeO content. Contrary, good foamability can be observed for EAF slags.

Forecasting slag compositions for the optimal valorisation of electric steelworks slags

Alice Petrucciani, Antonella Zaccara, Ismael Matino, Marco Vannucci, Valentina Colla, Scuola Superiore Sant'Anna

Resource- and energy-intensive industries are experiencing a deep renewal in recent years to reduce their environmental impact and carbon footprint. In particular, the main priorities focus on energy efficiency, waste reduction, and the application of circular economy and sustainability principles. In this context, the steel industry plays a key role as the second-largest industrial consumer of energy, a major contributor to CO_2 emissions, and a producer of a large amount of by-products. Therefore, this sector is undergoing a profound transformation to reduce its impact while maintaining the required quality of end products.

The steel industries produce different types of by-products and slags are the most abundant. They can be reused as a potentially valuable source of secondary raw materials, leading to a substantial reduction use of natural resources and related costs. The reuse and recycling of by-products can thus play a crucial role in avoiding their disposal in landfills and the waste of valuable resources, reducing the exploitation of primary raw materials, decreasing CO_2 emissions, and supporting the implementation of the Circular Economy concept.

The present work is a part of the EU-funded project entitled "Optimising slag reuse and recycling in electric steelmaking at optimum metallurgical performance through on-line characterization devices and intelligent decision support system – iSlag". The main objective of the project is the valorisation of slag generated during the electric steelmaking process, through the definition of optimal practices, the study of new recycling routes, and the promotion of industrial symbiosis solutions. To optimise the management of slags, it is necessary to know rapidly and/or in advance their main features. To this aim, iSlag aims at combining new rapid slag characterisation devices with advanced modelling and data processing tools in order to maximise the reuse and recycling of slag.

The present work focuses on the modelling task as it is a fundamental part of the decision support system (DSS), which is one of the final expected outcomes of the project, and is intended to support operational and management practices. Different approaches have been followed to develop models providing different balances between accuracy and computational burden, which are used for different purposes such as offline scenario analyses and real-time decisions on the path of slags produced during specific production lots.

Manipulation of the leaching behavior of high-alloyed steel EAF slags through the particle size modulation

Davide Mombelli, Gianluca Dall'Osto, Salvatore Cozzo, Carlo Mapelli, Politecnico di Milano

The safe disposal of EAF slag have become crucial due the environmental and health protection regulations. Its direct reuse is hampered by the possible release of toxic elements into the surrounding environment over time. Specifically, EAF slag from high-alloyed steel production could potentially release toxic metals (e.g., Ba, Cr, Mo and V). Currently, the assessment of leaching behavior is carried out according to the EN 12457:2002 standard, which generically specify that the material should not be finely ground, limiting the particle size as much as possible. However, no guidance is given on reducing particle size and handling fine fractions, which could lead to manipulation of data and variability of results. In this work six different fractions (from <4 mm to <63 µm) of EAF slag from high-alloyed steel production were investigated. X-Ray Diffraction, Scanning Electron Microscopy and selective C2S dissolution were used to correlate the leaching behavior with particle size and identify which mineral can alters the release of specific toxic elements. The pH of the water was measured immediately after filtration, and the solution was analyzed by Inductively Coupled Plasma-Optical Emission Spectrometry. In addition, five mixtures were prepared using different mass fractions of the six granular fractions with the aim of unbalancing the mixtures toward coarser or finer fractions, respectively. All the mixtures were subjected to leaching under the same previous conditions and analyzed to evaluate the behavior of the different blended fractions. To investigate the predictability of the leaching behavior of the mixtures, the experimental results were compared with the values predicted by a theoretical model calibrated using the results obtained from the leaching results of the six particle size fractions. The investigation showed that the leaching behavior is negatively affected by the particle size reduction, mainly due to the increase of surface-to-volume ratio, which increases the dissolution rate. Similarly, the mass fraction of the main crystalline phases that regulate leaching (unstable spinels, brownmillerite and larnite) is also correlated with the change in particle size. Consequently, the leaching results for the mixtures highlighted a critical aspect contained in the European standard. Even small changes in particle size can lead to different concentrations of toxic metals in leachates, which can then be manipulated to achieve the desired result.

Session on CO_2 emission reduction and environmental impact

Session chairs: Thomas Echterhof and Simon Tomažič

Pathways for the environmental impact mitigation of the scrap recycling route in Italy

Gianluca Dall'Osto, Giacomo Villa, Davide Mombelli, Silvia Barella, Andrea Gruttadauria, Carlo Mapelli, Politecnico di Milano

Global steel production through scrap recycling is expected to increase steadily in the coming decades, mainly due to the lower direct CO_2 emissions of EAF compared to blast furnace. However, despite the lower emissions, to achieve the goals of mitigating environmental impact set by the European community the steel sector footprint needs to be further reduced. Currently, the three main pathways for reducing emissions from the steel sector are carbon feedstock substitution, substantial upgrading of existing processes, and the use of Carbon Capture and Storage (CCS). Using real data on steel mill production and Best Available Techniques Reference documents for steel, this study focuses on the benefits and critical issues of three different emission mitigation options (use of green H_2, use of biomethane, and CCS retrofitting) applied to EAF. Specifically, four impact indicators (CO_2 emissions, water consumption, electricity consumption and soil exploitation) were used for the assessment. Since Italy represents a special case in Europe, having its production already 80% based on EAF, the overall potential mitigation of emissions at 2030 and 2050 was evaluated and compared with the threshold defined by the Sustainable Development Scenario. In light of the assessment results, green hydrogen is extremely attractive in terms of CO_2 mitigation, particularly if compared to biomethane and natural gas, although dramatic amount of renewable energy demanded for its production appears as an arduous challenge in the Italian context, considering that such production should be realized ex-novo in Italy. The use of biomethane seems to be the most favorable scenario, although penalized by the finding of sufficiently large quantities of gas to support the needs of annual steel production. On the other hand, the recent interest in biomethane production in Italy could ensure the feasibility of this scenario in the coming years. Finally, the use of natural gas and CCS has provided interesting results, especially when combined with biomethane. Moreover, taking into account the expected increase in carbon taxes and the decrease in CCS-related costs expected in the coming years, retrofitting current production sites seems to be the most plausible solution for impact mitigation in the short to medium term.

Decreasing the environmental impact of the electric steel making process through implementation of furnace optimization models

Felix Kaiser, Tim Reichel, Thomas Echterhof, Diana Mier, Iñigo Unamuno, Herbert Pfeifer

Steel production in the electric arc furnace is an energy-intensive process and generates a high amount of climate-relevant CO_2 emissions. During the last decades, various improvements of the furnace and its operation have been developed and implemented, so that the efficiency of modern steel plants has reached a high level. Due to the standardized process flows and high production volumes, even small improvements in resource efficiency can lead to significant savings and improve the environmental impact of the steel production. This paper presents several optimization activities and retrofitting

solutions for the metallurgical sector and in particular for the electric steel route. On the example of a Spanish electric steel plant, a life cycle analysis is carried out to calculate the potential improvements in environmental impacts and compare them with the current state of the art. For this purpose, real process data were collected and transferred to a life cycle assessment model with the use of a material flow analysis. A comparison of the ecological impact categories provides information on which retrofitting solutions can improve the process in the electric arc furnace and ensure a lower environmental impact.

Low impact Electric Arc Furnace: how to combine de-carbonization, energy saving and limited environmental emissions in modern electric steelmaking

Andrea Lanari, Massimiliano Daita, SMS group SpA

The steel production through electric arc furnaces (EAF) plays an increasingly important role in modern steelworks concepts. Today the electric arc furnace steel of the overall steel production in EU-28 is 44% (approx. 67 Mtons/year), being the remaining 56% still produced by the integrated route. A number of major investment in Europe will be based on EAF route, due to the favorable conditions of lower CO_2 emissions, flexibility in raw material utilization and flexibility in operation (an EAF can be switched on/off within a short time).

The challenge posed by the target of climate neutrality by 2050 drives the actual technological changes: the mixed combination of de-carbonization at lower operational costs in a dynamic environment where the CO_2 per ton cost fluctuates has forced the OEM to invest in new solutions to overcome the limitation of the conventional EAF design and process.

The presentation introduces a variety of technical solutions developed by SMS in order to cope with the above challenges: power feeding technology for installation of big size EAF in weak electric grids, hydrogen utilization in the melting process, reduction of NO_x emission in the ambient, optimization of the charging mix for high quality grades.

Target is decreasing the carbon footprint of a ton of steel from the actual 1’500 kg (integrated route) to a value constantly below 80 kg (95% reduction). Introduction in the process of alternative material to fossil carbon is also in the picture, another important step along the path of CO_2 neutral steel.

Biochar as a slag foaming agent in EAF – A novel experimental setup

Eetu Hoikkaniemi, Petri Sulasalmi, Ville-Valtteri Visuri, Timo Fabritius, University of Oulu

Slag foaming practice is employed widely in electric arc furnace steelmaking to improve the energy efficiency, protect the furnace structures and reduce noise pollution. Slag foaming is typically launched by injecting fossil-based carbonaceous material (e.g. coke dust) into the melt. Using fossil carbon as a foaming agent produces fossil-CO_2 emission. The typical amount of injected carbon for slag foaming purposes is 5-10 kg/ton of steel, which results in CO_2 emissions of 24.2 kg kg/ton of steel, on average. By replacing fossil-based carbon with biochar has a potential of reducing direct CO_2 emissions of EAF process by 25%.

In this study, a novel laboratory-scale experimental setup was used for studying the substitution of fossil carbon by biochar as slag foaming agent. The equipment was equipped with an injection device for feeding carbon and a camera system for observing the foaming phenomenon and recording the process.

A set of experiments was conducted for studying the foaming in slag-carbon systems using two carbonaceous materials: 1) coke dust was used as a reference material and 2) a high-quality biochar was used a possible replacement. In the experiments, sufficient foaming was achieved with both carbonaceous materials. The biochar produced almost equal foaming behaviour as coke dust. The results confirm that biochar has a great potential for slag foaming application.

Application of hydrogen operated burners in the electric arc furnace

Lilly Schüttensack, *Thomas Echterhof*, Herbert Pfeifer, RWTH Aachen University

In the steelmaking industry electric arc furnaces are mainly used for the scrap melting. The main energy source in the electric arc furnace is electric energy. Therefore, the EAF is in comparison to other aggregates in the steel production, for example the blast furnace, low in CO_2 and other green house gas emissions. This advantage makes the EAF interesting for future applications in the steel industry. Still, the amount of process relevant CO_2 emissions is relevant and the elimination of all unnecessarily produced CO_2 is a great challenge. One CO_2 source are the auxiliary burners used in the EAF to increase the energy input in the furnace and heat “cold spots”.

The EAF operation is a very complex system with a lot of variety in the operation parameters such as the scrap composition. Due to the high temperatures in the EAF a continuous measurement of the operation parameters (e. g. melt temperature or composition) is not possible. The usage of an EAF process model can overcome this problem and give an insight on the processes inside the EAF. The dynamic EAF process model developed by Logar et al. and further adjusted by Meier and Hay is able to estimate these process parameters.

In the scope of the RFCS funded project “DevH2forEAF” the substitution of natural gas by hydrogen in the auxiliary burners of the EAF is investigated. The effects of the hydrogen combustion on the EAF operation are simulated using the EAF process model with the addition of the hydrogen combustion to the process model. For further investigation of the effects of hydrogen combustion on the EAF process, a pilot scale burner is operated in a pilot scale EAF. Especially the effect on the melt and slag composition are analyzed. These findings will help with the adjustment and validation of the hydrogen combustion in the EAF process model.

Feasibility of direct carbon fuel cells as a synergistic energy source in the scrap recycling route

Gianluca Dall’Osto, Davide Mombelli, Andrea Pittalis, Carlo Mapelli, Politecnico di Milano

Although CO_2 emissions from steel production have remained relatively constant in recent years, the industry emissions reduction is now more than necessary. As a result, increased steel production by EAF appears to be the most promising option as a replacement for the currently more widespread integrated cycle due to the lower associated emissions. However, two main issues for further EAF emission mitigation are still open: the high energy demand is responsible for large amounts of indirect emissions (especially in countries that still rely on coal-fired plants), and the replacement of fossil carbon with biogenic carbon or polymers is not yet fully mature. For these reasons, there is a need to explore new low-emission energy sources such as fuel cells, which due to their efficiency and scalability could be a possible solution for EAF indirect emissions mitigation. In particular, since most carbon-containing

materials from the scrap recycling cycle are characterized by high purity, they appear to be perfect candidates for electrochemical power generation within a direct carbon fuel cell (DCFC). This preliminary study aims to evaluate the electrical performance of four EAF-related carbonaceous materials (electrographite, coke, torrefied biochar, and hydrochar) as fuels for a DCFC, with emphasis on the influence of fuel morphology (bulk/pellet or powder) and their chemical composition. In addition, the feasibility of a scaled DCFC power plant to cover part of the EAF annual electricity demand was evaluated, considering the current availability of biomass and steel production in Italy. The results showed improved performance once the fuels were used in powder form due to the higher specific area, with coke powder having the highest peak power density value. Electrographite provided acceptable results only as powder, because of the inhibitory effect of pitch and the high smoothness of the bulk morphology. In contrast, the melting of the organic binder, used in both pelletized biomasses, during the cell tests allowed the morphological alteration (from bulk to powder) of the fuels and decreased the efficiency penalty of the bulk morphology to almost negligible. This offers the advantage of avoiding the grinding process and the related production of fine particulate matter from an industrial point of view. Finally, the current availability of Italian biomass seems capable of easily covering more than 10% of domestic steel production.

Session on Fossil-free raw materials in the EAF

Session chairs: Isnaldi R. Souza Filho and Petri Sulasalmi

Investigations in Hydrogen Ironmaking

Joe Govro, Missouri University of Science and Technology

As the need for greener steel solutions grow, hydrogen reduced iron is becoming a viable alternative to traditional ironmaking processes. This presentation highlights the work being done at Missouri University of Science and Technology to investigate the nuances of producing steel with hydrogen. Laboratory and commercial scale (electric arc furnace) melting experiments have been conducted. The melting rate of hydrogen produced DRI and traditional carbonaceous DRI have been investigated in a laboratory melting apparatus and compared to finite element analysis model. The impact of varied carbon content in HBI has also been investigated on both the commercial and laboratory scales. In addition to melting characterization studies, hydrogen-plasma direct reduction experiments have been carried out in a laboratory scale reactor.

Fundamentals of the hydrogen plasma reduction of iron ores

Isnaldi R. Souza Filho, Dierk Raabe, Hauke Springer, Max-Planck-Institut für Eisenforschung GmbH

Although steel is a key enabler of sustainability, especially via its high recyclability rates and/or when it is employed in devices for sustainable energy generation, the primary production of iron is a heavy CO_2 emitter, accounting for 8% of all CO_2 emissions on the planet. To fight global warming, the most global polluting sources must be tackled, including steel manufacturing sector. This means that alternative green solutions must be urgently investigated and implemented already in the coming decades.

Hydrogen, serving as a reducing agent to transform iron ores into iron, is a promising candidate to replace the carbon-based substances currently utilized in the conventional technologies in the ironmaking sector.

In this context, the fully electrified hydrogen plasma reduction route (HyPR) offers a sustainable alternative to reduce iron ores with water as the direct by-product. In this process, a hydrogen-containing electric arc is ignited between the electrode of an electric arc furnace (EAF), slightly modified to support small concentrations of gaseous hydrogen in its atmosphere (e.g. a gas mixture of Ar-10%H_2) and the feedstock ore to be processed. HyPR permits to simultaneously melt and reduce the ore in one single process step, a fact that can help shorten the number of process chains in steelmaking with energy savings.

This lecture will explore the fundamental aspects of the hydrogen plasma reduction of iron ores (HyPR), focusing on the underlying mechanisms that drive the chemical changes and phase transformations from the feedstock hematite into product iron. A brief consideration of the important chemical aspects of hydrogen plasma arcs will be presented as well.

Development of a New Laboratory-scale Reduction Facility For the H_2 Plasma Smelting Reduction of Iron Ores Based on a Multi-electrode Arc Furnace Concept

Felix Hoffelner, Johannes Schenk, Michael Zarl, Montanuniversitaet Leoben

Steel production accounts for a significant share of industrial CO_2 emissions. H_2 plasma smelting reduction is a possible alternative to reduce these emissions massively, if not completely negate them. In principle, Fe ore is reduced at high temperatures in the plasma of a direct current electric arc. H_2 reacts with the oxidic melt at the gas-liquid interface. Yet, further investigations on process stability and kinetics are necessary. Various concepts for the H_2 plasma reduction of iron ore have already been investigated, but the process technology has not yet surpassed the demonstration scale. Experimental setups for charge masses from a few grams to a few hundred kilograms have been realized. These problems are to be addressed by an improved furnace concept.

The starting point for designing and constructing the new plasma furnace is an existing laboratory facility. There are several problems with this experimental setup. The dimensions of the reactor and limitations of the power supply restrict the length of the arc. This leads to problems with excessive wear of crucibles made from refractory material. Strong cooling when using Fe crucibles and the unstable nature of the arc complicate the process control. A promising concept to deal with the problem of arc stability is the use of multiple electrodes in a direct current arc furnace. With an optimized furnace geometry, new potentials for further investigations can be opened up. Investigations on thermodynamically more stable oxides such as SiO_2 or Cr_2O_3 have shown, that these also can be reduced via H_2 plasma. The use of a multi-cathode furnace is also promising to further explore possible applications for ferroalloy production.

An electric arc furnace was designed based on the requirements for the planned plasma reduction facility. The energy requirement was based on assumptions for heat transfer from the arc to the melt, walls, and lid as well as continuous transfer through the individual furnace parts. Considerations of power supply, hearth dimensions, refractory design, controlled gas atmosphere, and the implementation of auxiliary equipment were central to creating an ideal basis for a variety of experimental setups.

The 5th European Academic Symposium on EAF Steelmaking is organized by

University of Oulu
Process Metallurgy Research Unit
Pentti Kaiteran katu 1
90014Oulu, Finland

and

RWTH Aachen University
Department for Industrial Furnaces and Heat Engineering
Kopernikusstr. 10
52074 Aachen, Germany

For questions and additional information contact:
Ville-Valteri Visuri
Phone: +358 50 412 5642
mail: ville-valtteri.visuri@oulu.fi

or

Thomas Echterhof
Phone: +49 241 80-25958
mail: seminar@iob.rwth-aachen.de

Booklet published June 2nd 2023