

Sensor and digital twin solutions developed in DiGreeS project for improvement of scrap-based EAF steelmaking

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On the path toward low-carbon steelmaking and increased circularity, the Electric Arc Furnace (EAF) is pivotal for European steelmakers. Within the EU-funded Horizon project "Demonstration of Digital twins for a Green Steel value chain (DiGreeS)" an integrated digitalisation approach is developed across the steel value chain, to leverage process data, Artificial intelligence (AI) techniques and human experience for seamless industrial integration. This paper presents sensor-based and digital twin solutions being developed in DiGreeS for two key challenges in scrap-based EAF steelmaking: (i) automated verification of scrap feedstock quality and (ii) real-time assessment and control of foamy slag conditions. The approach combines novel sensing technologies, including multi-modal scrap characterisation and EAF process monitoring, with machine learning models embedded in a digital twin framework. First project results demonstrate the potential of the proposed methods to improve scrap quality assessment and enhance process efficiency in EAF operation.

KEYWORDS: EAF PROCESS; DIGITALISATION; SENSORS; SCRAP; SLAG FOAMING CONTROL.

INTRODUCTION: EAF STEELMAKING USE CASES IN DIGReeS

The transition towards low-carbon steel production, as outlined in the EU Green Deal and Circular Economy Action Plan [1], requires a substantial increase in low-quality scrap utilisation in Electric Arc Furnace (EAF) steelmaking. However, decreasing quality of scrap input and the complexity of the EAF process introduce significant challenges for both feedstock quality control and energy-efficient furnace operation. In particular, unnoticed variations in scrap compositions and in process conditions directly affect steel quality, energy efficiency, and productivity.

In current industrial practice, scrap purchasing and classification remain largely based on established supplier relationships and manual inspection. As a result, the bulk chemical composition of heterogeneous scrap types such as Heavy Melting Scrap (HMS) remains highly uncertain at the time of charging. To mitigate this, techniques such as Laser-Induced Breakdown Spectroscopy

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(LIBS) [2] enable fast, contactless elemental analysis and are increasingly explored in research projects and industrial environments. However, their application to large, bulk scrap flows is still limited, particularly with respect to representative, truck-scale composition assessment under realistic plant conditions.

In parallel, EAF process monitoring relies on established measurement systems such as off-gas analysis and arc signals, which provide indirect information on process conditions. While these signals are routinely used, their integration into real-time predictive and control-oriented frameworks remains limited, and key process phenomena—such as foamy slag formation—are still strongly influenced by operator experience. Additional sensing approaches, including structure-borne and airborne vibration measurements, offer further insight into process dynamics but are not yet systematically combined with existing data sources for real-time control.

To address these challenges, the Horizon Europe project "*Demonstration of Digital Twins for a Green Steel value chain (DiGreeS)*" develops integrated sensor and ultimately digital twin solutions for improved monitoring and control along the steel production chain. Within this framework, this paper presents two complementary developments targeting scrap-based EAF steelmaking.

First, a multi-sensor system for automated characterisation of HMS is introduced, combining RGB-camera-based imaging for geometric analysis with LIBS-based surface composition measurements. Through machine learning-based data fusion, the approach enables the estimation of bulk chemical composition at truck scale, overcoming the limitations of conventional sampling-based methods.

Second, a sensor-integrated digital twin approach for EAF operation is presented, combining off-gas analysis, EAF power signals, and vibration measurements within a hybrid modelling framework. This approach allows the on-line prediction of foamy slag conditions based on physics-based and data-driven modelling and provides a basis for a digital twin enabling improved control of carbon and oxygen injection.

The paper is structured accordingly: the first part focuses on sensor-based scrap characterisation and data fusion, while the second part addresses the digital twin-based monitoring and control of EAF process conditions, with particular emphasis on foamy slag behaviour.

CHARACTERISATION OF HEAVY MELTING SCRAP (HMS)

The characterisation of heavy melting scrap with large scrap pieces of high inhomogeneity is today based on manual and thus highly empirical visual inspection. In some plants also random samples are analysed with hand-held XRF sensors. However, such measurements are time consuming when making them representative for the full scrap load and are therefore typically only taken occasionally. Consequently, the bulk chemical composition of HMS remains uncertain.

To address this limitation, DiGreeS develops an automated, AI-driven dual-sensor fusion system for in-situ elemental analysis of a full truck load which will be set up at the premises of Tata Steel in The Netherlands. The system is designed to estimate the bulk chemical composition of HMS, with an initial focus on the critical tramp element copper, which significantly affects downstream steelmaking processes and final product quality. To achieve an in-line characterisation, the system uses a combination of images generated by two RGB cameras for geometrical information with the surface analysis from a Laser Induced Breakdown Spectroscopy (LIBS) system. The sensor set-up will be installed on a gantry system for scanning a truck upon delivery, enabling to estimate the average copper concentration as a bulk value for the whole scrap load. This approach aims to minimise unexpected impurity levels in scrap feedstock and thus to improve the crude steel quality. The overall concept is sketched in figure 1 together with a sketch showing the envisaged dimensions and the distance between sensors and scrap load. The single components will be described hereafter.

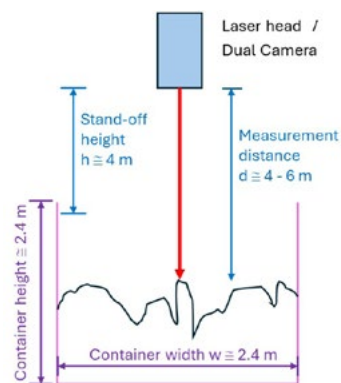
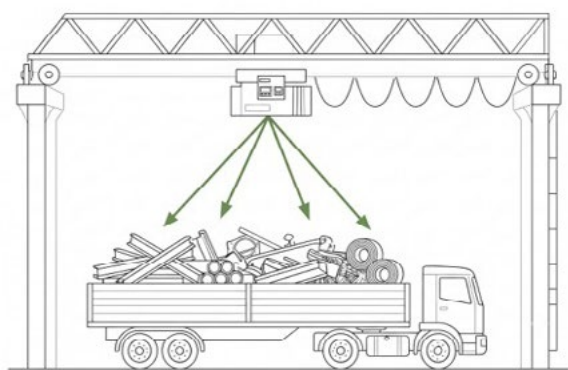


Fig.1 - Concept and dimensions of sensor system for characterisation of heavy melting scrap.

Dual RGB camera system

The dual RGB camera system is used to capture geometric information of the scrap load, including the size and shape of the scrap pieces as well as of the height of scrap pile. Several images are acquired and stitched to generate a full picture of the scrap load surface regarding distribution of size and shape of the different scrap pieces. Furthermore,

the image analysis of the stereo camera system allows to calculate the filling degree of the truck and the scrap pile height, see figure 2. This image data provides the basis for segmentation of individual scrap objects and spatial referencing of compositional measurements performed by the LIBS system.

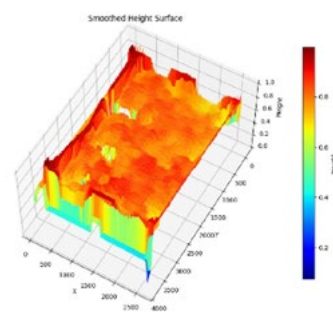
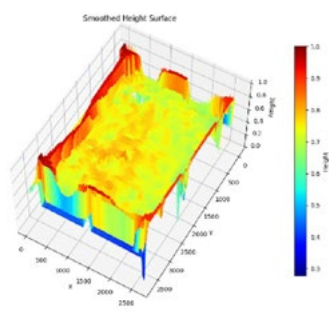


Fig.2 - Stereo camera image for scrap pile height detection: Half full (right) and full (left) scrap box.

LIBS system

The LIBS sensor will be used for remote, contactless surface analysis of the scrap pieces including the separation of coatings from base material [3, 4]. LIBS is a laser-based spectroscopy method that allows for non-contact testing of the components [3]. Each individual LIBS measurement reveals the elemental composition of the HMS under investigation. The LIBS data will be timestamped and localized on the sample surface based on external position measurements of the system. The laser installed in the LIBS system is a Q-switched laser which operates at 1645 nm and a 1000 Hz pulse frequency. To create a plasma on the sample surface the energy density must exceed roughly 1 GW/cm² [5]. To reach this power threshold, the laser light needs to be focussed by means of optics. The

focused laser beam creates a small region around the optimal focus, in which the power density still surpasses the required one to create a plasma, called the plasma depth. For this system, it is spread on 10 mm. Furthermore, the HMS is very heterogeneous in shape and size, which means the laser focus must be moved at high speed due to topographic variations. To focus the laser light and collect the resulting plasma, the optical configuration is therefore of vital importance. The autofocus system ensures that the material is always in focus for optimal measurement conditions. The long-range LIBS sensor is a telescope-based optical configuration to optimize light collection from the laser-induced plasma and to relay the focus rapidly over, relatively, large distances (see figure 3).

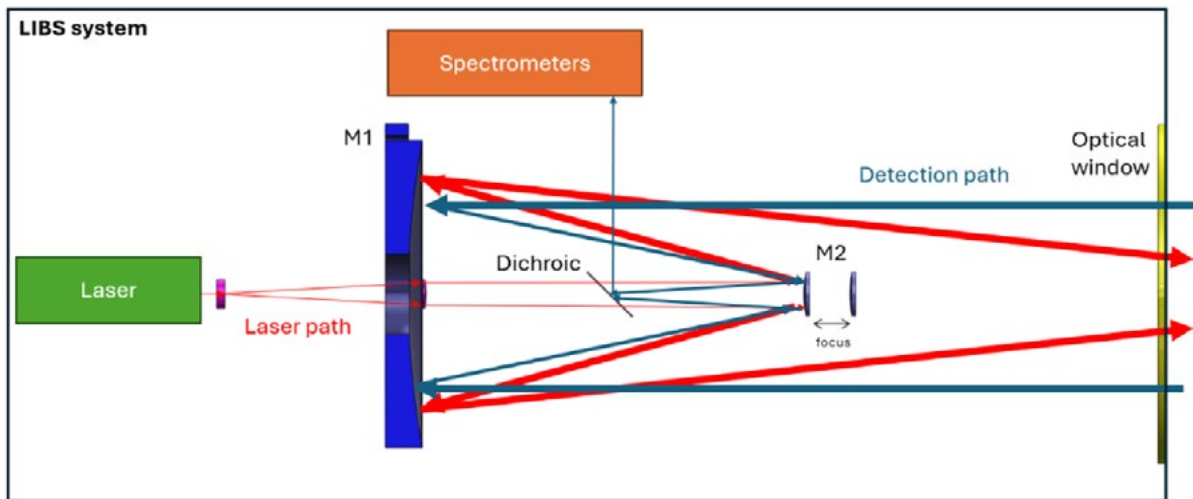


Fig.3 - Optical configuration of LIBS system.

This optical setup plays a central role in enhancing signal quality, especially under challenging industrial conditions. The reflective telescope configuration utilizes two mirrors: 1) a large mirror (M1) that focuses the laser light on a sample and collects the broadband emission from the plasma plume generated on the sample surface; 2) a secondary mirror (M2), positioned along the optical axis that creates a divergent bundle of the laser light towards M1 and reflects and focuses the collected plasma light, directing it towards an off-axis optical path where the spectrometers reside. M2 is mounted on a moving stage that enables it to reposition itself rapidly causing a change in focal distance from the sensor to the sample. A distance sensor in the LIBS sensor provides the required position data for the movable stage. This design allows the system to achieve high collection efficiency, critical for detecting

low-concentration elements.

The LIBS system is equipped with an analysis computer to directly analyse the captured spectra and convert these to quantitative elemental concentrations based on an analysis model. The analysis model is created after a calibration campaign with certified reference material (CRM) that cover the spread of expected elemental concentration in the HMS (see figure 4), illustrating a strong correlation between the ground truth data and the estimation based on the LIBS signal intensity. The calibration campaign addressed the following key needs: model training, correction of matrix effects and validation of quantification accuracy. Besides the calibration of the LIBS system using CRMs, trials in laboratory have been performed to determine the impact of moisture and of surface coating.

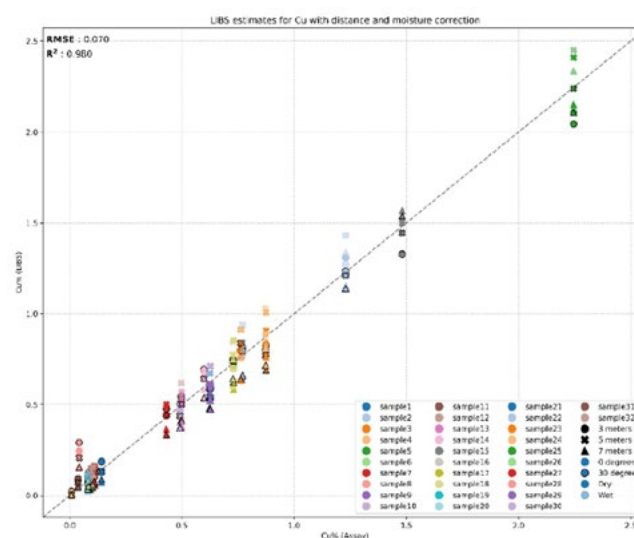


Fig.4 - Calibration curve obtained on Cu using reference materials, at different laser shot distances and in different moisture conditions.

To ensure operator safety, a laser safety zone must be defined. The focal distance of the system is 3 to 8 m (physically limited by optics and autofocus stage stroke). However, due to the nature of steel, which can be highly reflective, the eye safety should be based on the distance from the expected plasma generation site to account for a possible specular reflection. Thus, the LIBS system has been independently classified as safe 8 m away from the possible specular reflection, due to an energy density in the reflected laser beam too low to cause eye damage after that distance. The Nominal Ocular Hazard Distance

(NOHD) of 8 m is relatively low for this optical power [5], which is achieved through a combination of the laser wavelength used and the optical design.

After calibration and pre-trials, the LIBS sensor has been mounted together with the stereo camera system on a gantry for simultaneous shape detection and surface analysis of the scrap pieces. Figure 5 shows the system in a laboratory set-up which has been used for first analysis trials.



Fig.5 - LIBS analyser mounted on a gantry: Top view (left) and bottom view with stereo camera (right).

Edge processing of multi-modal sensor information

As LIBS measurements are inherently limited to the surface of the material, the resulting data require interpretation in a spatial and statistical context to enable a representative bulk composition estimation. This is particularly relevant for HMS which is rather inhomogeneous in terms of size and shape of the different scrap pieces. Thus, the data, which provide the surface analysis of single scrap pieces, and the image information for shape and size analysis of the different scrap pieces is processed by a machine learning (ML) algorithm to classify the different HMS pieces. First, the different images of the RGB cameras taken during scanning of the truck are stitched to provide

an image of the whole truck load. Then a segmentation algorithm identifies individual scrap pieces from the RGB images. Subsequently, LIBS measurements are spatially assigned to the corresponding objects by merging the segmented mask with the LIBS measurement points. This procedure with the different steps is schematically shown in figure 6.

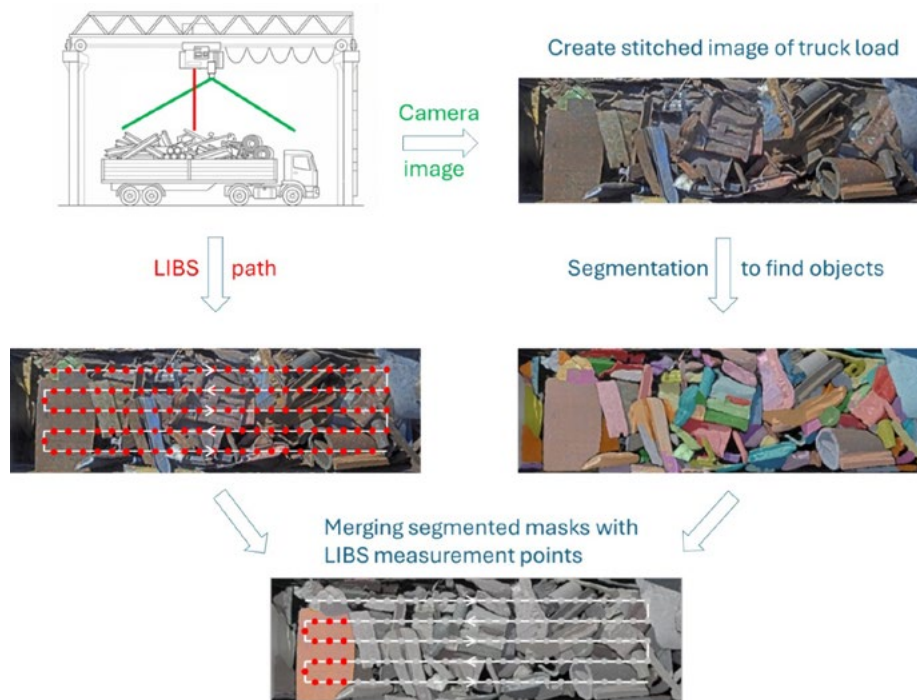


Fig.6 - Scheme for alignment of sensor information for assessment of surface scrap composition.

The dual camera system will finally provide information on the height of the scrap load in the truck. Based on the above-described mapping with piece-wise extrapolation of the surface analysis, geometrical and compositional information are combined to derive an estimate of the bulk chemical composition of the entire scrap load (see figure

7). The primary output of the system is the estimated mean elemental concentration of the scrap batch, with a first application for the Cu content. Therefore, the combination of sensor information and their ML-based analysis represent the digital twin for the bulk analysis of the scrap load.

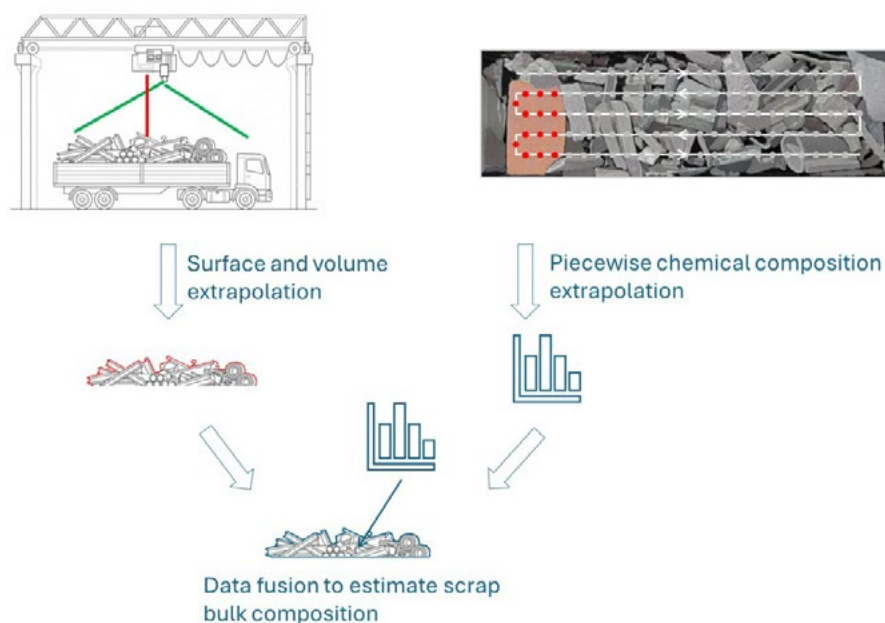


Fig.7 - Principle of extrapolation to assign the LIBS analysis to the bulk material.

Given the heterogeneous nature of HMS, the representativity of surface measurements is a key aspect. The approach leverages the relatively low fill volume of HMS scrap deliveries, which results in a high accessible surface-to-volume ratio, allowing a substantial portion of the material to be characterised during scanning.

Validation approach

To evaluate the performance of the system, a campaign with a demonstrator set-up is planned in which several truck loads are analysed using the developed sensor system. The estimated bulk compositions will be compared against reference values obtained from handheld XRF measurements on selected scrap samples and from subsequent meltdown analyses. This combined validation approach enables assessment of both local measurement accuracy and the reliability of bulk composition estimation under industrial conditions.

ASSESSMENT AND CONTROL OF FOAMY SLAG QUALITY IN ELECTRIC ARC FURNACES

To provide a high electrical power input in the EAF it is necessary to avoid any radiation losses of the electric arcs. In high power furnaces these arcs can reach open length up to 500 mm. It is a well-established technique to cover the arcs by the metallurgical necessary slag. To improve the shielding, the slag can be foamed, which increases its height significantly and guarantees an effective arc shielding. Metallurgical slags in the EAF process mainly consist of CaO and MgO provided by slag formers and the oxidation reaction products SiO₂, Al₂O₃ and FeO, which are the result of the reaction of Fe and other elements in the liquid pool with the hypersonic injected oxygen. The foamy slag is generated by the reduction of FeO in the slag by injecting coal, which leads to the formation of CO-bubbles in the slag (figure 8).

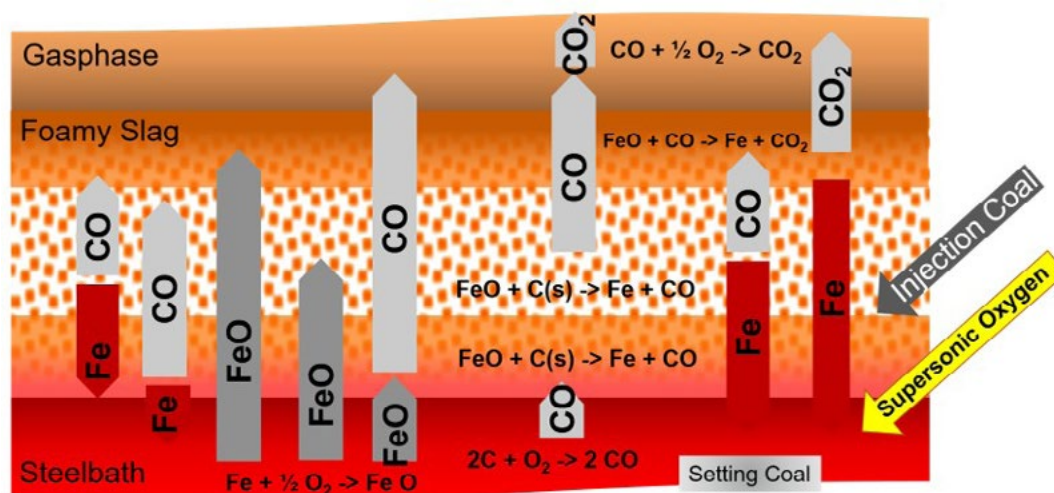


Fig.8 -Reactions to generate foamy slag.

Adequate control of the foaming process and the stability of the foamy slag is essential for an effective electrical energy input in the EAF and therefore an important task for EAF process control. As foaming is controlled by the reactions between Fe, O₂ and C, it is necessary to control the injection of coal and oxygen in a proper way to ensure a good foamy slag quality. Today, mainly fixed operating patterns are used, and the quality of the foaming process quite often depends on the individual operator skills rather than real-time measured information of the process status. So far, only isolated sensors like acoustic sensors,

the analysis of the arc harmonics or structure-borne vibration sensors [6-9] have been applied to assess the foamy slag quality. In DiGreeS, a hybrid dynamic process model driven by continuous multi-modal online sensing will be applied to foamy slag control. The sensors and process models for assessment of the foamy slag quality during the refining phase of the EAF process will be installed at the AC EAF of Saerstahl Ascoval. The overall concept is sketched in figure 9, and the single components will be described hereafter.

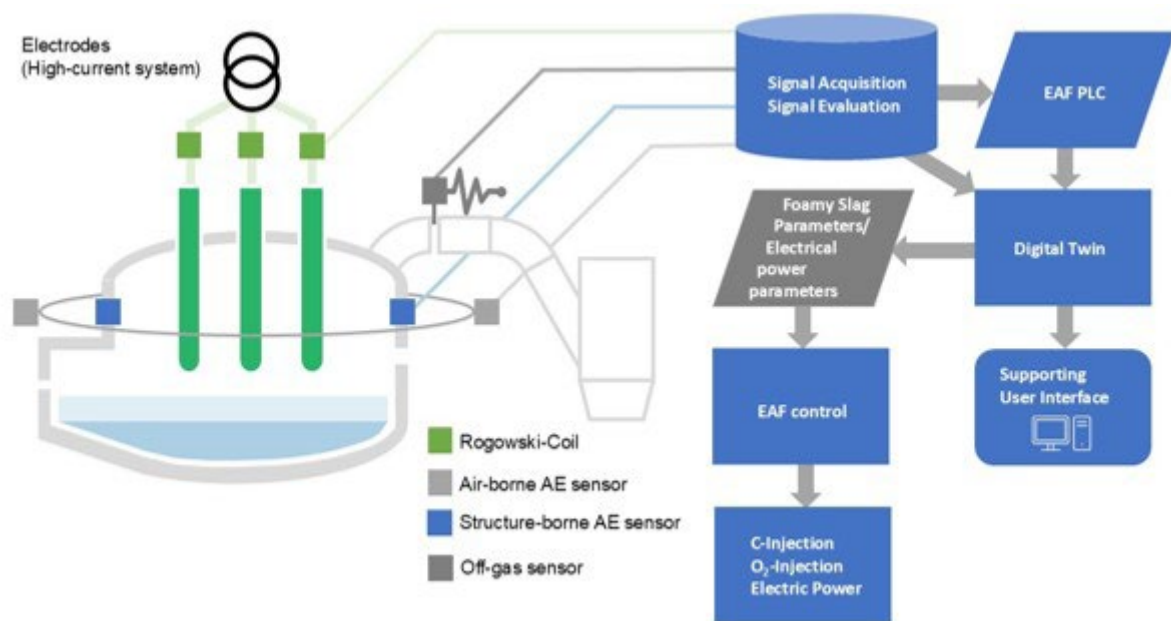


Fig.9 -Concept for foamy slag control.

Multi-modal sensor system for assessment of the foamy slag quality

The multi-modal sensor system for assessment of the foamy slag quality consists of four components (see figure 10): (i) Rogowski coils, which measure the arc currents across a very wide frequency band, are already installed at each phase of the high current system. The signals will be analysed by Fourier transformation or Wavelet analysis to detect the arc current harmonics and short-term fluctuations of the current. This measurement data provides insights into the stability of the electric arc and the formation of gas bubbles, thus providing information about the melting process and the formation (height and stability) of the foamy slag.

Two types of acoustic emission (AE) sensors will also be installed. (ii) An air-borne (AB) AE sensor, realised by a dust-proof microphone will be installed several meters away from the EAF. The temperature at this location will be max. 50 °C. This AB-AE sensor will allow to detect the characteristic noise evolution during the melting and refining phase, i.e. acoustic noise originating from the EAF and emitted into the environment, superimposed on the ambient noise. This mimics the acoustic quality analysis of the foamy slag by the ear of an experienced operator, although the cutoff frequency (> 20 kHz) and sensitivity are significantly extended compared to human hearing. (iii) In addition, three structure-borne AE sensors will be mounted on the upper part of the water-cooled panels with permanently fixed

adapters and protective housings to collect the vibrations of the furnace in the immediate vicinity of the three electrodes. Each of the two interchangeable EAF vessels will be equipped with 3 permanently attached sensors. These SB-AE sensors are temperature stable up to 100 °C, with a frequency range up to 5-10 kHz and possible amplitudes of up to 10 g. The SB-AE sensors will detect the acoustic signature of the electric arc, which is damped by the slag in the vessel and will provide information about the foamy slag height and the melting behaviour. In detail, the SB-AE sensor signals are related to the EAF process stability in different stages of the process and to the foamy slag height in the refining phase of the furnace operation. This information will be correlated with the input from the evaluated information from the high-current system to improve the quality and liability of the already used measurement technique. (iv) Finally, an already installed laser-based optical off-gas measurement system [10] allows the in-situ online analysis of CO and CO₂ with an accuracy of +/- 2% of the absolute value with a time delay of less than one second. This sensor subsystem is positioned in the off-gas duct of the EAF, as shown in figure 7, allowing a real-time analysis of the off-gas stream. It covers a large part of the cross-section of the EAF duct with no direct contact to the hot and dust-loaded off-gas, therefore there is no distortion of the measurement process. The system allows to monitor the evolution of the decarburisation process by the level of CO and CO₂ formation from the steel bath, which induces the

foaming of the slag. The provided measurement information is also crucial for real-time process monitoring and control of supersonic oxygen and coal injection processes. In addition, off-gas temperature and velocity are measured

to provide information on the energy losses via the off-gas. This will deliver valuable input for the process model to improve step by step the quality of the calculated results.



Fig.10 - Components of the multimodal sensor system: Rogowski coils, microphones, vibration sensors and off-gas analysis.

Dynamic EAF process model

An existing dynamic EAF process model [11], which is based on a dynamic energy and mass balance calculation in combination with thermodynamic calculations for metallurgical reactions like decarburisation and dephosphorisation, has been adapted to the operation practice and process data which are available at the EAF of Saarstahl Ascoval. The model uses cyclically acquired and event-driven process data to monitor on-line the evolution of the most important process state values like melt temperature as well as steel and slag amount and composition.

The model was validated with process data of around 300 heats and already provides accurate results for the evolution of the melt temperature as well as for carbon and oxygen content. It will be extended with a hybrid model part for determination of the properties of the foamy slag with focus on the foamy slag height, which will in turn affect the efficiency of the electrical energy input and the energy losses. The structure of the extended EAF process model with input and output data is shown in figure 11.

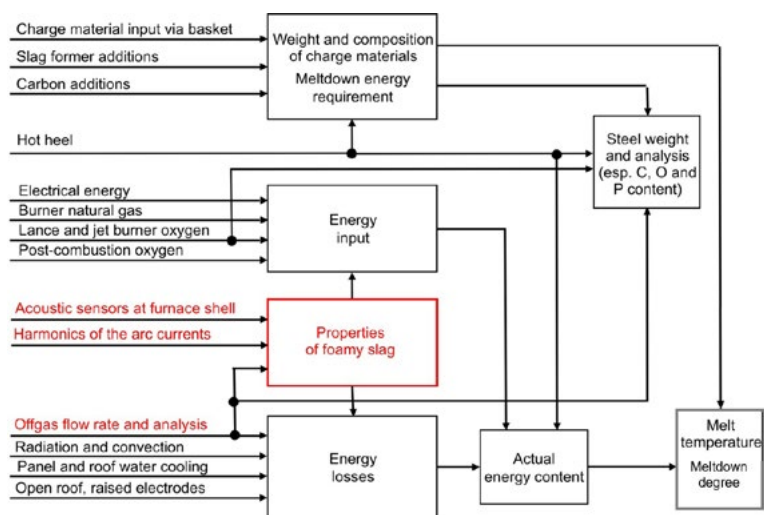


Fig.11 - Structure of the extended dynamic EAF process model.

Figure 12 shows the simulation results for steel temperature, meltdown degree as well as carbon and oxygen con-

tent for an example heat of the Saarstahl Ascoval furnace.

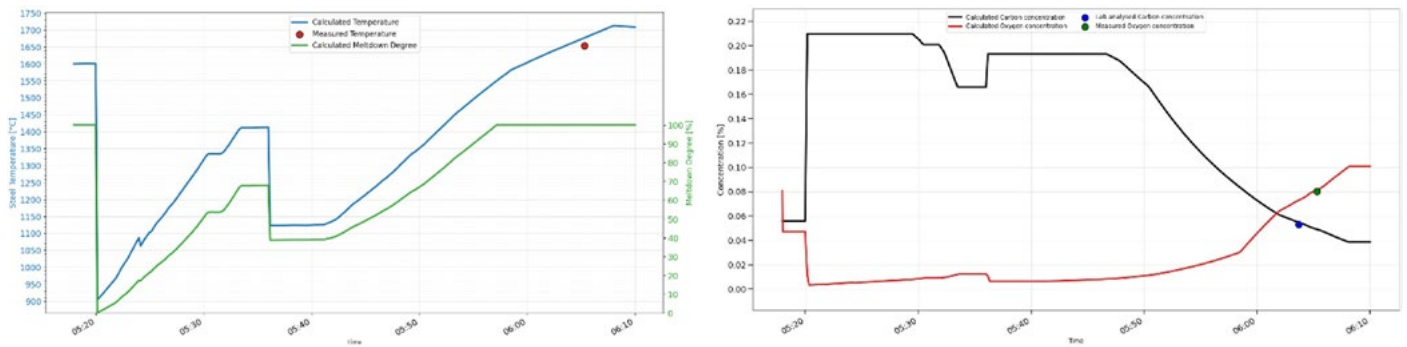


Fig.12 - Simulation results for melt temperature and meltdown degree (right) and carbon and oxygen content (left) for a Saarstahl Ascoval example heat.

For the determination of the properties of the foamy slag a hybrid process model will be developed. The already existing, physics-based EAF model includes a dynamic slag balance calculation, which provides the evolution of slag amount and composition. The model part for the decarburisation process allows to calculate the intensity of CO bubbles generation. This enables a first rough estimation of the foamy slag properties. In addition, the data of the

multi-modal sensor system will feed an AI model for dynamic foamy slag quality assessment. The estimation of the foamy slag quality from the physics-based model will be enhanced by a correction term provided from the AI-based model for a comprehensive hybrid model for the foamy slag height which allows an enhanced on-line process monitoring via a digital twin. The principle of this hybrid model is shown in figure 13.

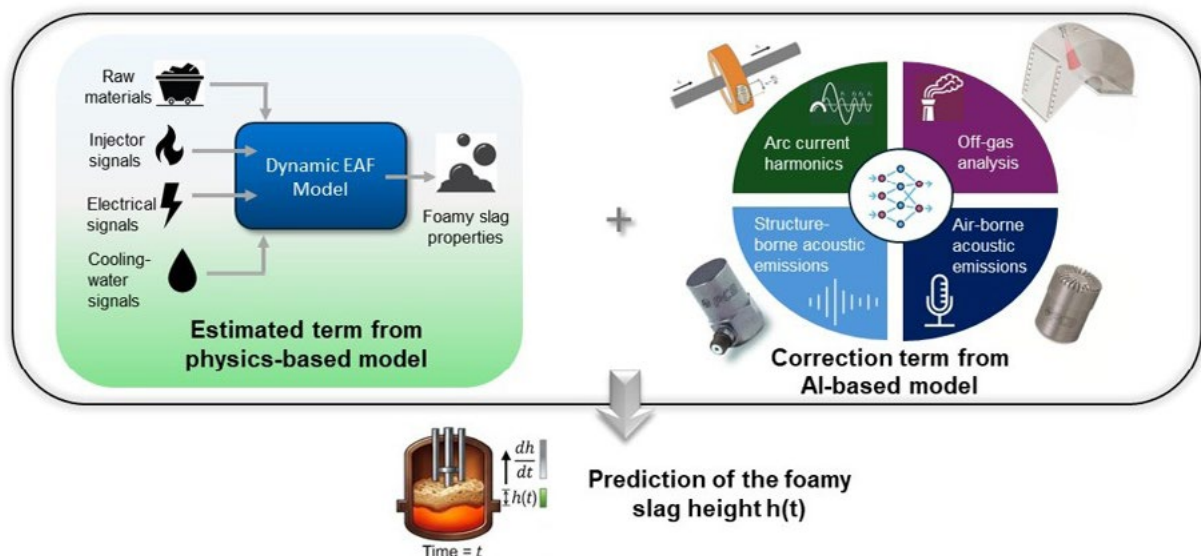


Fig.13 - Hybrid model for prediction of the foamy slag height.

Built on this real-time information of the foamy slag performance, a dynamic control and optimisation of carbon and oxygen injection as well as electrical power parameters will be developed to increase the efficiency of the electrical energy input.

Validation approach

After implementation of the multimodal sensor system at the EAF of Saarstahl Ascoval, sensor and process data will

be collected and analysed. AI-methods will be used to determine characteristic patterns of the measured signals for the different EAF process steps like melting and refining. These patterns will be correlated with already used parameters from the EAF control system.

Additionally, for training of the hybrid model for assessment of the foamy slag performance, the furnace operators will provide for a larger amount of heats their judgement on the foamy slag height by a classification system. The pre-

trained hybrid model will then be integrated in the overall dynamic EAF process model, which will be implemented for on-line process monitoring and further fine-tuning at the Saarstahl Ascoval plant.

CURRENT PROJECT STATE AND NEXT STEPS

To date, the sensors for scrap characterisation have been selected, adapted and calibrated, and a first version of the analysis software has been developed. The whole system has already been tested in a laboratory set-up and will be transferred to a demonstrator set-up for scanning complete trucks later in the project.

Regarding slag foaming control, the existing dynamic process model has been adapted to the Saarstahl Ascoval EAF. The novel sensors have been selected and are currently installed at the furnace. After commissioning and the development of sensor data preprocessing algorithms, the training phase of the hybrid process model will start. A Human Machine Interface will be developed to support the operators by providing information on the process evolution including the status of the foamy slag to keep the process in optimal conditions. By comparison of the saved patterns, the control parameters and the human interaction with the control system, the system shall achieve valuable information about the quality of the running process and shall

provide input for control of power input and the injection parameters for coal and oxygen.

CONCLUSIONS AND EXPECTED INDUSTRIAL IMPACT

The already performed preparation work for integration of novel sensors, process models and AI/ML algorithms in DiGreeS demonstrates a highly promising pathway to sustainable EAF steelmaking. By transferring these components into a unified digital twin architecture, the project is advancing to TRL7 demonstrators in operational environments. Ultimately, these AI-driven solutions for digitalization of the EAF steelmaking process are expected to facilitate a higher percentage of HMS use without affecting quality, and a significantly improved foamy slag performance to decrease energy consumption and thus the CO₂ footprint of EAF steelmaking.

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