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New techniques for improvement of the monitoring and conditioning of slag in EAF steelmaking for the optimization of steel treatment and slag recovery

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In EAF steel production, the development is moving toward the direction to improve both the process management and the potential reuse of the residual materials, to reduce the environmental impact in terms of CO_2 emissions and residual wastes to be treated.

Both necessities pass also through the management and monitoring of the slags coming from EAF process or from secondary metallurgical treatments considering slag is strictly connected with metallurgical processes occurring between steel and slags and is also the main quantity of materials to be recovered. Acciaierie di Calvisano (AdC), included in the line of special steels production of Feralpi Group, is improving slag management as way to improve the metallurgical treatments through application of sensors for slags and process monitoring, a process modelling approach and new control systems.

For this reason, it has been developed the project "iSlag" with a Consortium of other EU companies, co-funded by Research Fund for Coal and Steel. The main goal of this project is not only to improve capability of process monitoring, but also to develop the necessary Decision Support Tool, in order to manage the slags in a proper way as based on the previous concept of process management, including in particular new sensors and also process modelling.

KEYWORDS: STEEL TREATMENT, EAF, SLAG, MODELLING, STEELMAKING, PROCESS CONTROL, LF, SIMULATION;

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INTRODUCTION

In modern steel production it is important to have an integrated view of the production processes and plants, including performances optimization, maintenance conditions, and reduction of environmental impacts through reduction of residual wastes and CO_2 emissions from the production.

In particular to consider the slags generated by the processed production of EAF and LF is a relevant point, including both evaluations regarding the process treatments optimization and the conditions of residual slags from production, as necessary to increase capability of slags recovery.

In fact, the proper slags conditions both in EAF and in LF are crucial to increase the efficiency of the metallurgical processes as dephosphorization, desulphurisation, decarburization, deoxidation, slag foaming and avoidance of refractories erosion.

For this reason, knowing the present status of the slags

during the process and defining the proper target as slag conditions to be adopted during the treatments is a relevant point, in order to manage and to improve the production processes to make more efficient the metallurgical processes.
It is also fundamental to know the necessary target of the slags to be adopted for subsequent landfill or for the slags reuse and recovery.
The slag conditioning and the process management to obtain the proper slag conditions is a point affecting both the circularity of the sector and the processes performances.

METHODOLOGY

For these scopes, a global approach has been adopted coupling in a single strategy/architecture new slag monitoring sensor, a new modelling approach and a control system to realize a Decision Support Tool-DST.

Architecture of the Global Approach

A general view of the global approach architecture is reported following with overall purposes as:

- supporting the process monitoring;
- correlating the slag conditions with the practices adopted and technological phenomena occurring during the process;
- supporting process management suggesting evidences or actions to be promoted.

These actions have to be adopted for the whole steelmaking area meaning both EAF and LF processes of liquid steel production and considering the time-dependent evolution of the process in different steps.
The architecture of the DST system is flexible, aiming to provide operators with the following main features:

- on-line time trends of relevant process parameters which describe relevant technological aspects;
- a summary overview highlighting measurements or aspects of the process, which are relevant to the slags conditions coming from EAF and LF;
- flexibility and user-friendliness for the needs of the operators and process technologists.

For these reasons, the architecture depicted in figure 1 has been designed as basis of the project, which is composed of five main modules corresponding to the functionalities that can be used in different periods.

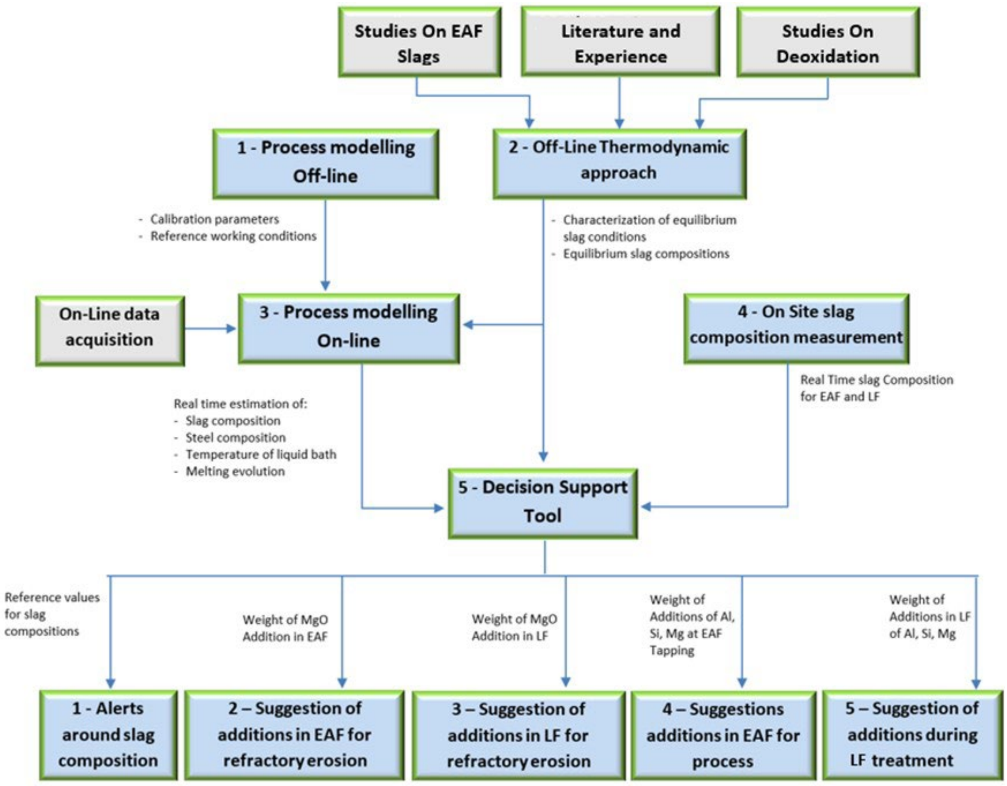

Fig.1 - Overview of the architecture of the decision support concept implemented at AdC.

1. ***Off-line process modelling:*** it predicts the process results depending on the adopted operating practices.
2. ***Off-line thermodynamic approach:*** it provides a deeper knowledge of slag conditions that are not available by simple on-line process modelling.
3. ***On-line process modelling***: it makes available in real time a whole continuous representation of the processes and the associated technological parameters that are not measured.
4. ***On-site slag composition measurement:*** it provides the slag composition in real time during the process, with a measurement time that is low enough to enable process control or management.
5. ***Decision Support Tool:*** it provides indications for process adjustments.

These modules are working together in a flexible way with a modular architecture, being the data exchange between the modules flexible and managed depending on the specific application to be realized.

Module 1: off-line process modelling for EAF and LF

The off-line process modelling of the EAF process estimates the effects on the main process parameters when modifying of some variation of operating practices. The final target is to improve the settings of new operating practices and to assess the reference values of slag compositions aimed at the EAF. In particular, the system allows the operator to visualise and monitor the time trend of a series of relevant EAF power supply parameters, weights, temperature and contents of the main chemical components of the EAF steel and slag composition. The off-line simulator of EAF process estimates the reference conditions in terms of process results and aimed slag compositions to be used as reference for subsequent evaluation of thermodynamic equilibrium and for the on-line system and the DST.

On the other hand, the off-line process modelling of steel treatment in LF predicts process results by variation of practices to improve the settings of new operating practices and to assess the reference values of slag compositions aimed in the secondary steel treatment. The system allows to visualize the time trend of relevant variables such as steel temperature after tapping from the EAF and LF slag composition.

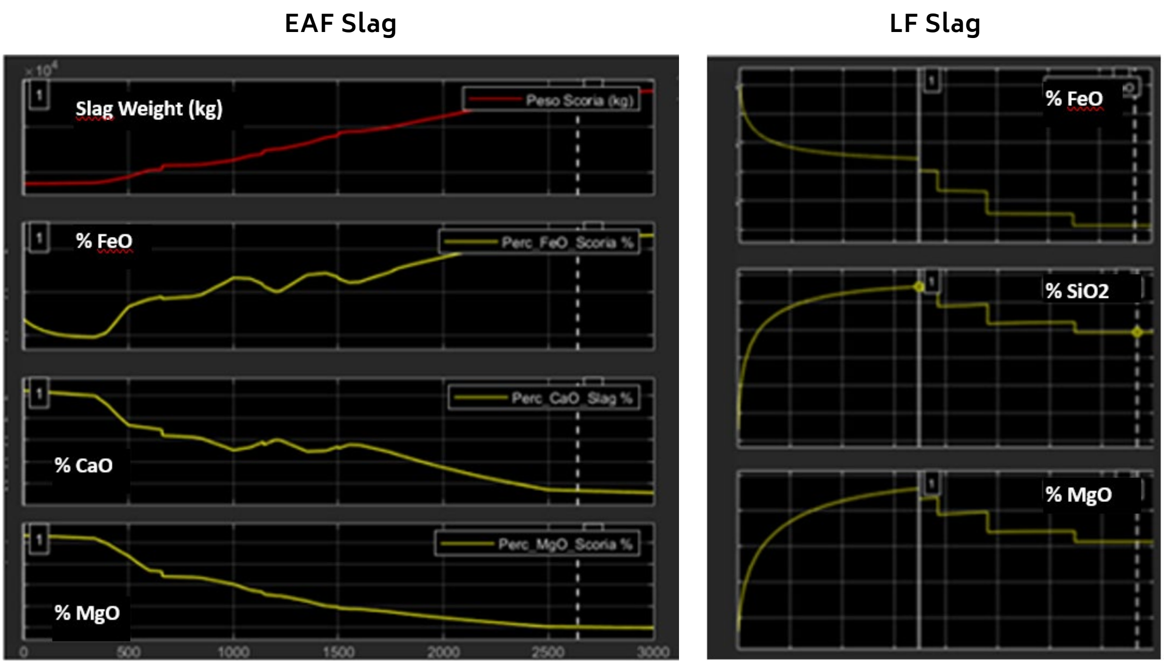

Fig.2 - Visualization of the estimated EAF and LF slag composition provided by the off-line model.

Module 2: off-line thermodynamic approach

Thermodynamic equilibrium calculations have been realized by Rina-CSM by using the tool ThemoCalc. In particular, considering the reference conditions of masses and reference slag composition measured, the equilibrium conditions that would be obtained in terms of slag composition and precipitate formations have been realised in different theoretical conditions.

In particular, the main investigations that have been carried out included:

- evaluation of saturation in terms of % MgO in slag;
- evaluation of precipitates formation (%).

Based on the results provided by the above-described investigations, mathematical rules were derived to describe the %MgO saturation in slag in different conditions and these rules were implemented in the subsequent module of on-line real-time process description and for providing the operators with suggestions on additions to be made during treatment. The knowledge of %MgO of saturation can be a reference condition for DSS to know the actions to be adopted to reach the MgO saturation in slag.

<u>Module 3: on-line process modelling</u>

The EAF process model was applied on-line to AdC EAF, preliminary, as separated system with data exchange with onsite automation and, subsequently, as tool integrated into the on-line database available on-site. In this way the difficulties and time necessary for data exchange are strongly reduced, improving system maintenance and for data availability.

The on-line system includes:

- data acquisition;
- parameters calculation;
- results visualization in reference pages.

The models implemented within such system includes following estimations:

- mass and energy balance;
- dynamic energy balance with available input/output energy values;
- representation of chemical reactions between steel and slag;
- steel conditions: mass, temperature, composition[A1.1][A1.2];
- slag conditions as: mass, temperature, composition (CaO, FeO, SiO_2, MgO, MnO, Cr_2O_3, Al_2O_3);
- evaluation of MgO saturation in slag;
- evaluation of the arc covering by foaming slag (with acoustic measurement principle);
- alert raising in case of too low MgO content in slag with respect to the saturation degree;
- alert raising in case foaming agents injections (coal, polymers) are needed due to arc uncovering.

Figure 3 provides an exemplary overview of the window shown on-line simulations available in real time.

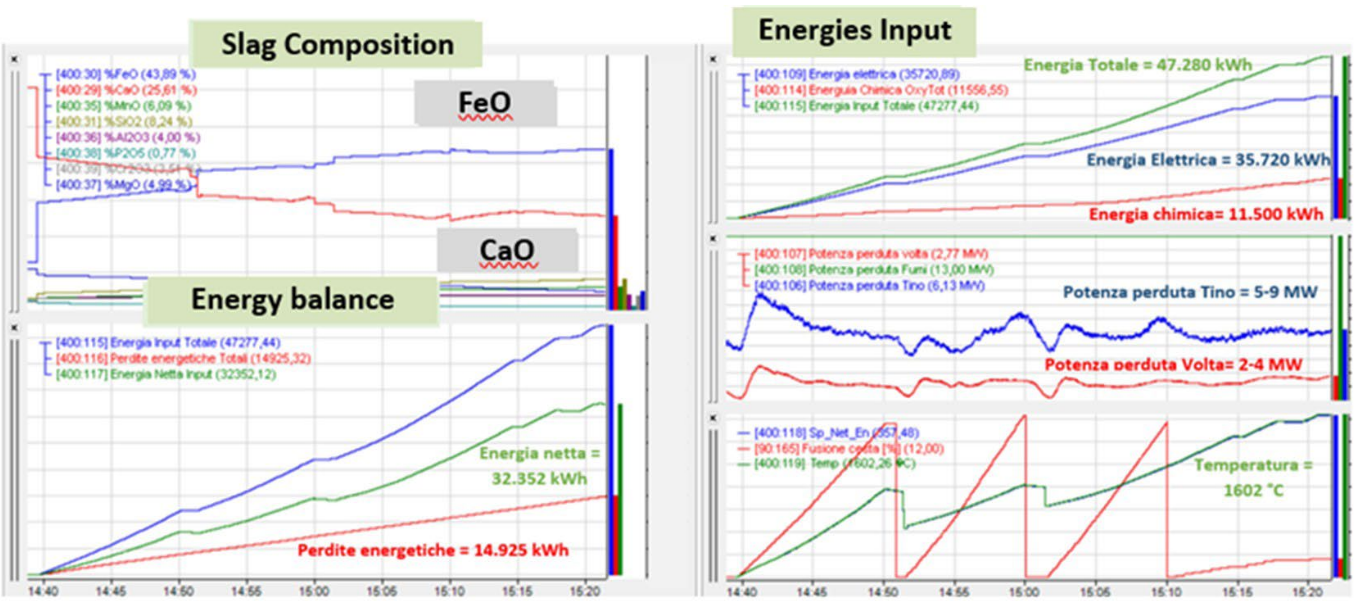

Fig.3 - Window showing on-line simulations including energy balance and slag composition.

Module 4: On site slag composition measurement

A system for EAF and LF slag composition detection (Fast Slag Analysis system) has been implemented, which exploits the QLX9 analyser based on laser Optical Emission Spectroscopy (OES) produced by Quantolux Innovation GmbH. The introduction of this device was needed to measure the composition of the EAF and LF slag after 3/5 minutes from the liquid slag sampling. In this way the knowledge on the slag composition is a real-time information included in subsequent steps of calculation.

The procedure for application of this approach includes: 1. Sampling, 2. Granulation, 3. Charging of the sensor with obtained sample, 4. Laser measurement, 5. Slag composition evidence, 6. Application of management action on LF treatment based on slag composition detected.

The activity is included in the frame of the project Multisens EAF supported by EU funding scheme RFCS (Research Fund for Coal and Steel).

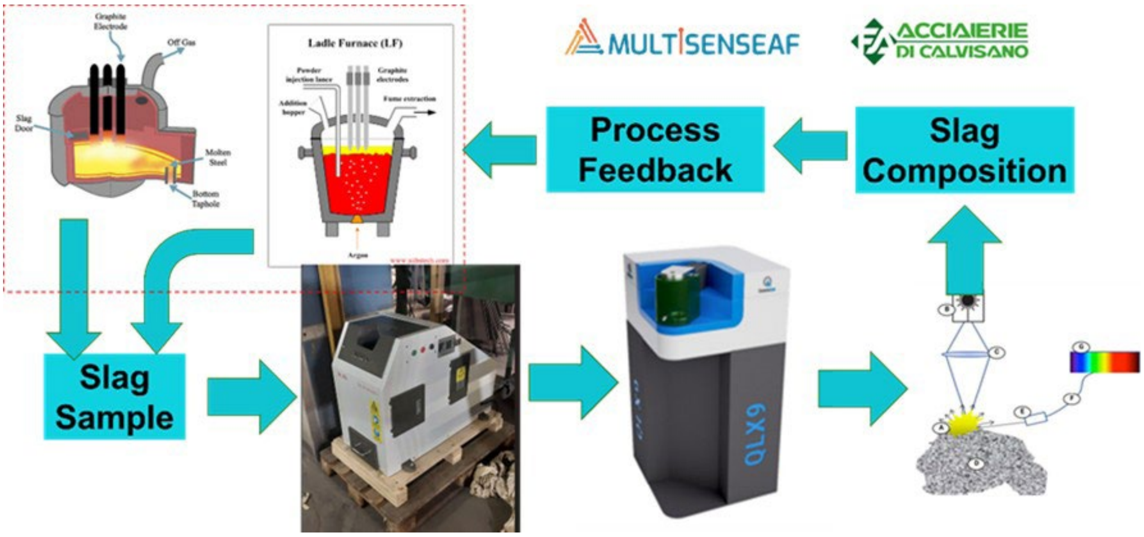

Fig.4 - Control loop of application of fast slag analysis system on the EAF/LF process management.

Module 5: Decision Support Tool for EAF and LF

The DST includes the following functionalities related to the EAF process:

- detection of poor slag foaming/arc uncovering → indication of foaming agents injection;
- determination of low %MgO respect the saturation level → indication addition with MgO in EAF;
- determination of necessary deoxidation, desulfurization, steel composition corrections and indication of correct materials additions (For LF Process).

Detection of poor slag foaming/arc uncovering → Indication of foaming agents injection

The detection of arc uncovering in refining phase is realized thanks to acoustic detection. It occurs if the Arc Foaming index, which is dynamically represented during the refining phase, overcomes the acceptable level in terms of arc uncovering, as this is considered a reliable indicator of arc uncovering and poor slag foaming. In this case the indication to increase the foaming agents injection is shown, to optimize the process.

Determination of low %MgO respect the saturation level → Indication to Add MgO addition at EAF and LF

To achieve this goal, the following steps are carried out:

1. evaluation of the current slag composition/status (by using the Fast Slag Analysis System);
2. evaluation of the level of %Saturation in terms of MgO, indicated following as $\%MgO_{Sat}$;
3. calculation of difference (indicated in the following as $GAP\_\%MgO_{Sat\_EAF}$ for EAF slag and $GAP\_\%MgO_{Sat\_LF}$ for LF slag) between the saturation level and the current %MgO content in slag ($\%MgO_{Slag\_EAF}$ and $\%MgO_{Slag\_LF}$, respectively) namely:
   $$GAP\_\%MgO_{Sat\_EAF} = \%MgO_{Sat} - \%MgO_{Slag\_EAF}$$
   $$GAP\_\%MgO_{Sat\_LF} = \%MgO_{Sat} - \%MgO_{Slag\_LF}$$
4. showing an indication of the addition of MgO in slag is needed in case the value of the difference computed

at the previous step is higher than a fixed threshold. Figure 5 shows an example related to EAF slag samples. In this figure the three possible ranges for the values of $GAP\_\%MgO_{Sat\_EAF}$ can be distinguished: the "admissible" range is highlighted in green, and here a MgO addition is not required; the "intermediate" range is highlighted in yellow, and here adding a small amount of MgO is beneficial but not strictly needed; the "warning" range is highlighted in red, and here adding MgO is strictly needed.

The DST raises an alert in case the value of $GAP\_\%MgO_{Sat\_EAF}$ for EAF slag or $GAP\_\%MgO_{Sat\_LF}$ for LF slag is out of the admissibility range and suggests how much MgO needs to be added.

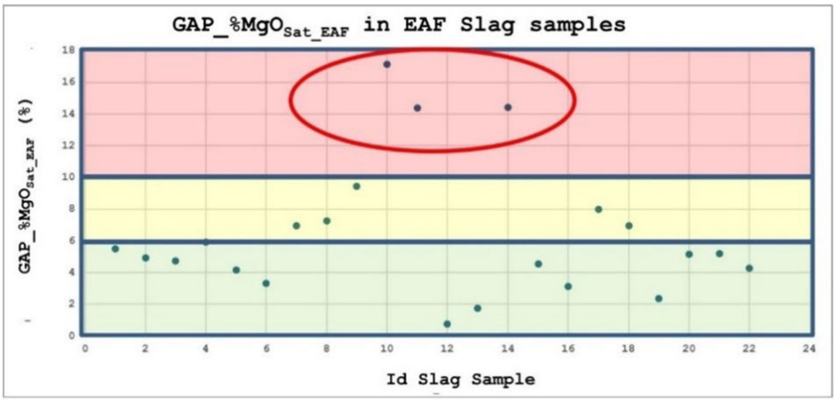

Fig.5 - Exemplar values of $GAP\_\%MgO_{Sat\_EAF}$ for some EAF slag samples collected during the trials.

The use of the Isosolubility Diagram approach (ISD) is a further method followed using the slag composition measurement for the EAF and in particular to evaluate the proper slag conditions for the slag foaming and arc covering.
In this way the area of the slag liquid or solid due to precipitates formation are shown, and the distance of the actual slag composition detected in relation to these areas are represented.
This approach takes into account composition and temperatures of the slags to determine when the slag in EAF is too much liquid or solid, which are conditions not proper for a slag foaming. Differently it can be seen when a good portion of precipitate formation is present to fit with an optimal composition for slag foaming.

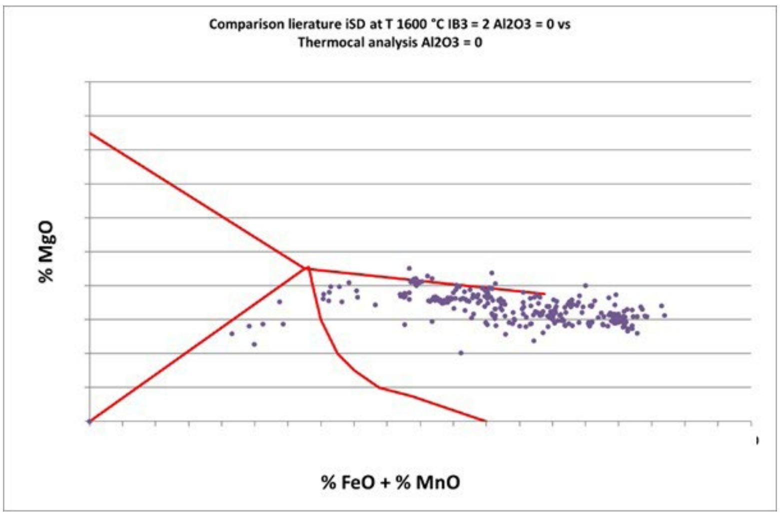

Fig.6 - Application of ISD approach to evaluate optimal slag conditions for foaming.

Determination of necessary deoxidation, desulfurization, steel composition corrections → indication of correct material additions at the LF

A tool has been developed as preliminary approach to estimate ladle additions at tapping and in LF and tested to evaluate the feasibility of this approach for additions suggestions at different conditions of steel and slags also using the LF slag analysis provided by the Fast Slag Analyser Quantolux QLX9. In particular, two functions developed:

a) **assessment of possible weight of compounds to be added and associated results on steel and slag to estimate the best additions depending on the targeted results;** → The Oxygen ac-tivity at arrival in LF is estimated as a function of different additions of materials for deoxidation (Si, Al, Mn) at tapping. The DST estimates the suitable additions of materials in the LF for deoxidation;

b) **suggestion of additions (in weight) provided by the DST based on the targeted Oxygen activ-ity and steel and slag conditions in arrival from EAF or after sampling in LF**. The system runs to realize several iterations of the simulation with different additions combination until it reaches the aimed conditions. Figure 7 shows an example of the results estimated for the iteration of different combinations of deoxidants additions in terms of oxygen activity at arrival of steel in LF.

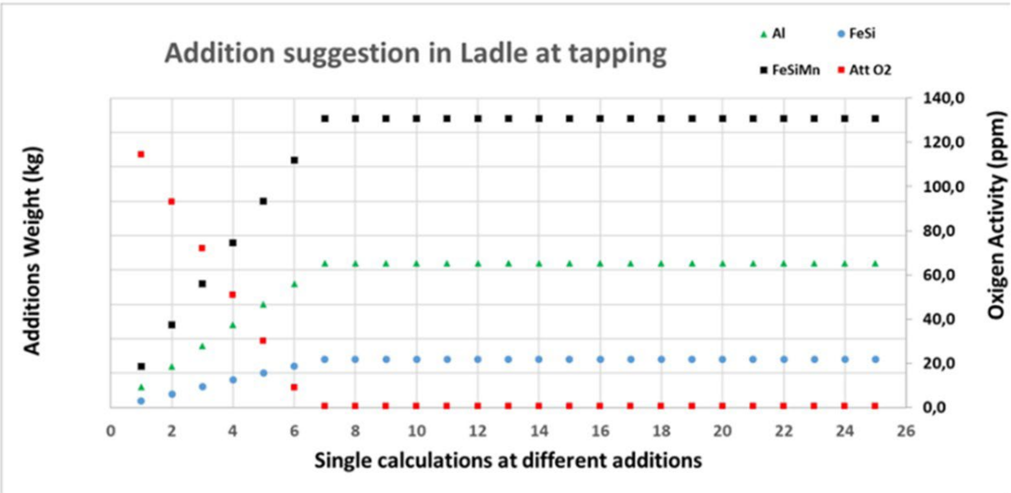

Fig.7 - Results of iteration of different combinations of additions in LF at tapping in terms of O_2 activity.

Figure 8 shows an estimation of different additions at tapping into the ladle depending on different levels of oxygen activities in EAF. At higher levels of oxygen activity in EAF higher amounts of additions are needed.

While figure 9 shows estimations of different additions in ladle for different targets of oxygen activities at the entrance to LF. At higher levels of oxygen activity target in LF higher amounts of additions are needed.

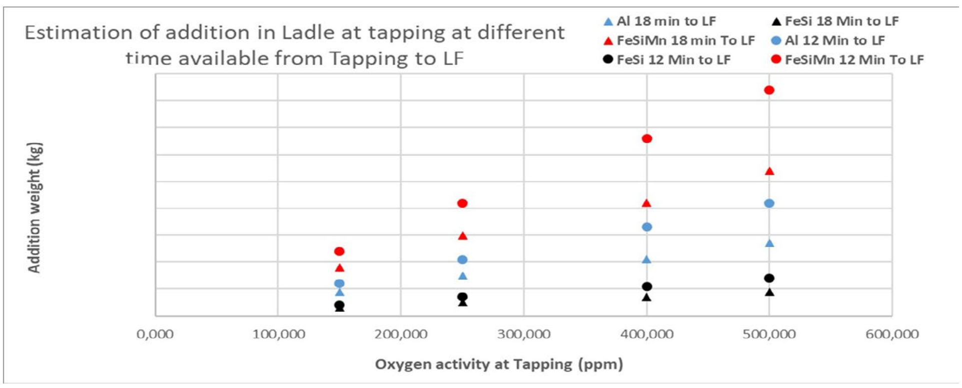

Fig.8 - Estimation of different additions in LF suggested at different oxygen activity at tapping for different values of the time available from EAF to LF steps (12 min vs 18 min).

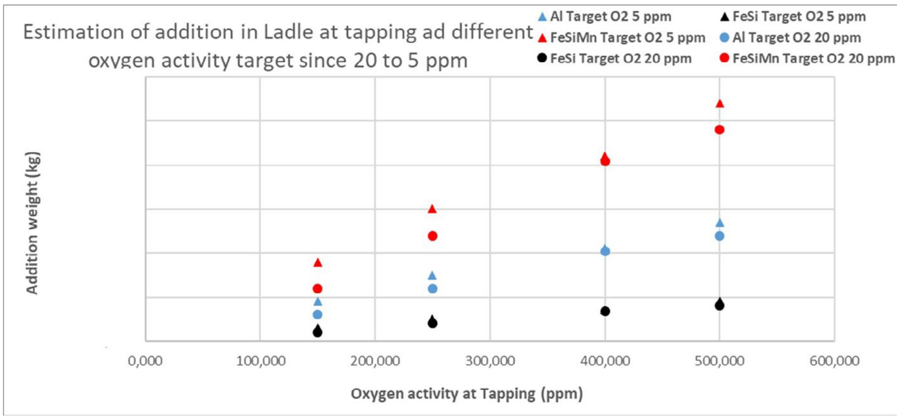

Fig.9 - Estimation of different additions in LF suggested at different oxygen activity at tapping for different aims in terms of oxygen activity at LF inlet (5 ppm vs 20 ppm).

Industrial tests of the Decision Support Tool

At AdC different trials have been realized for the project during the period 2023-2024 by exploiting the Fast Slag Analyser for different purposes and Application Cases (AppC):

AppC1- evaluation of status of steel oxidation at arrival to the LF and of slag carryover from EAF tap-ping;
AppC2- detection of low MgO content in EAF and LF slag that can lead to high refractory erosion;
AppC3- determination of necessary additions for deoxidation, desulfurization, steel composition cor-rections to be performed in Ladle at EAF Tapping.

In **AppC1** previous simulations enabled the identification of the ranges of acceptability of the slag composition, which allows identification of abnormal values (see figure 10 which refer to assessment of oxidation status).

The following situations can therefore be identified:

- slag carryover from tapping at regular deoxidation of steel;
- high oxidation status of the steel in arrival in LF to act with soon deoxidation.
- Figure 10 exemplifies the detection of excessive steel oxidation through the analysis of the slag at the end of the EAF process.

In case an excessive oxidation status is detected, the following decisions can be taken:

- lowering the use of O2 injection in EAF in subsequent heat;
- increasing the use of deoxidant in ladle at tapping or at entrance to the LF treatment on-going.

In case of slag carryover from EAF tapping, unnecessary additions for deoxidation can be avoided.

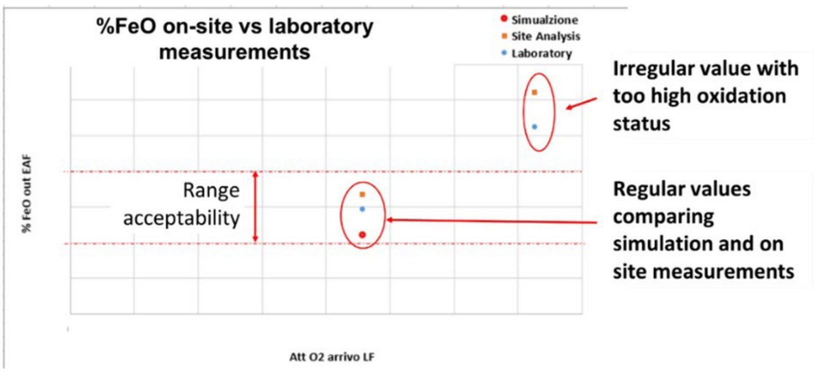

Fig.10 - Admissible ranges of FeO content in slag at the arrival to LF.

In **AppC2** trials were conducted on both EAF/LF slags and the procedure elaborated and based on comparison of $GAP\_\%MgO_{Sat\_EAF}$ and $GAP\_\%MgO_{Sat\_LF}$ with previously computed admissibility ranges is applied. If MgO content in slag is low, the additions of MgO must be performed to reduce refractory erosion.

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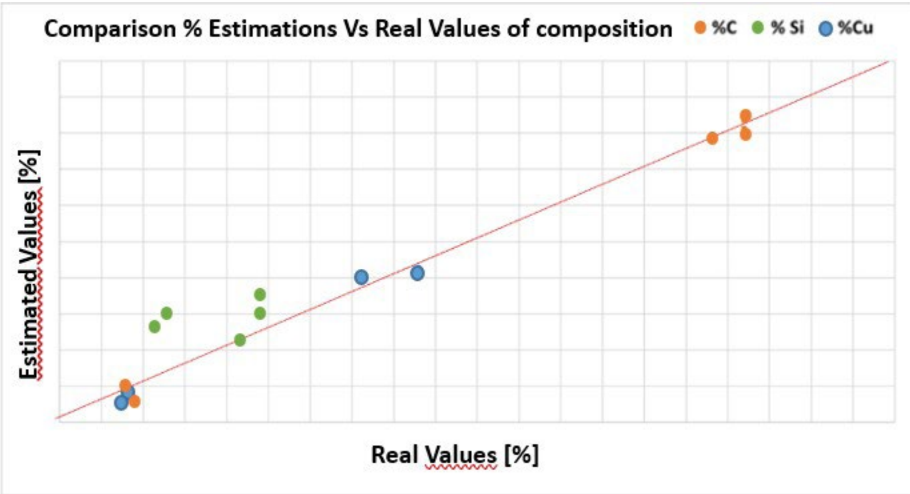

Fig.11 - Computed vs real value of the contents of C, Cu and Si in steel.

In **AppC3** the trial campaign for tuning and calibration of the system proved that the DST achieves a good accuracy in the determination C and Cu contents in steel, while a lower level of accuracy was obtained for Si, such as exemplarily shown in figure 11.

As already explained, two functions were developed based on the same modelling approach and comparison of additional suggestions reported in figure 12. In particular, different cases of calculation of suggested additions (in weight) are shown based on the targeted oxygen activity, steel and slag conditions in arrival from EAF or after sampling in LF: Case a) oxygen activity at tapping = 150 ppm, calculated weight additions as reference; Case b) oxygen activity at tapping = 300 ppm, calculated weight additions +94% in relation to reference; Case c) oxygen activity at tapping = 600 ppm, calculated weight additions +247 %; Case d) oxygen activity at tapping = 600 ppm and increase of time available for treatment in LF since 18 min till 30 min; calculated weight additions +136%.

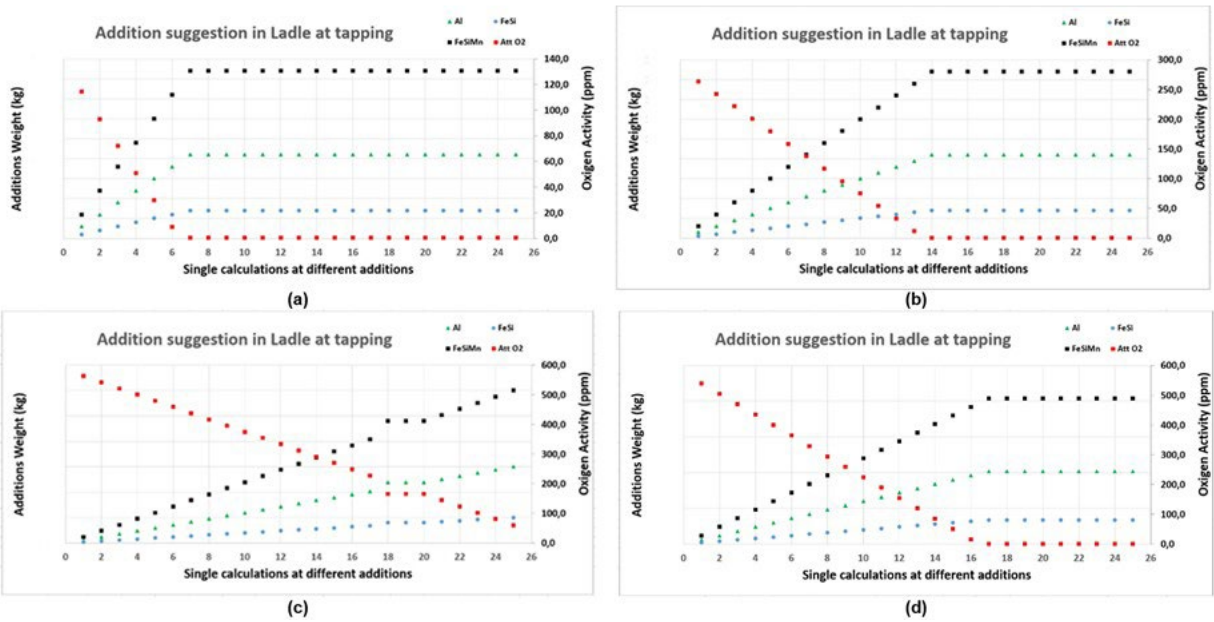

Fig.12 - Examples of calculation of suggested additions (in weight).

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