Application of process simulation strategies in off line prediction models and on-line Decision Support Systems with through process approach on Feralpi sites

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ABSTRACT
Feralpi Group strongly address its productions developments to improvement of production plants with adoption of new technologies and solutions Industry 4.0 for data analysis and process control. With the contribution of the R&D department, process technology production areas and research partners, predictive mathematical models have been created for production phases and whole steelmaking process. This has been done internally in order to be able to better setup the optimal operating practices for each process phases as EAF, Ladle Furnace, and Continuous Casting also as a way how to capitalize the knowledge and competences of steelmaking and metallurgy gained in process management. Based on the off line approach also on-line Dynamic Decision Support Systems have been created to gain real time process guidelines with for Feralpi Siderurgica and Acciaierie di Calvisano.

Keywords: Steelmaking, Process, Simulation, On-line control, EAF, LF Solidification

1. INTRODUCTION
In modern steel productions, the necessity of a better knowledge and control of the process became more important in order to improve production performances, to maintain repeatability on the product quality and to support the necessary process flexibility due to frequent changes in production programs. For this reason the capability to better understand the phenomena in the different process phases of the steelmaking process including scrap melting, steel treatments in ladle and solidification process in continuous casting is important to optimize operating practices. A through process view is necessary to respect the process/quality constrains aiming at improvement of performances and productivity. Based on the off line approach also the on-line installation of mathematical simulators has been realized in order to gain on-line process monitoring, and real time digital twins to be used to support online decision support systems with a through process approach for whole steelmaking area.

2. GENERAL SCHEME OF STEELMAKING PROCESS MODELLING IN FERALPI

2.1 Mathematical modelling of steelmaking processes in Feralpi

The main necessities covered by mathematical modelling approach used for steelmaking processes are:
- Off line prediction modelling to evaluate result with operating practices variations
- On-line process modelling for actual process monitoring and control
- Technological KPI’s estimation for data analysis

In particular this is done for following main steps:
- For EAF Process → to estimate scrap melting evolutions and energies/materials consumption depending by scrap charged, electrical parameters and chemical injections adoption.
- For LF Process → to evaluate the optimal steelmaking additions and steel treatments in ladle in order to optimize the steel composition and energies/materials consumptions.
- For Continuous Casting to evaluate steel solidification evolution in billets depending by cooling setting and casting speed adoption in order to maximize productivity and increase billets quality.
- Through process modelling in order to optimize through process management.

3. Modelling for off-line process prediction

2.1 Off-Line modelling for prediction of EAF process

The application of mathematical simulation of the EAF and LF process have been started with Matlab/Simulink code as following described and the main input/output for EAF are following described:

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scraps weight charged in basket</td>
<td>Steel/slags/Off Gas compositions</td>
</tr>
<tr>
<td>Dynamic electrical parameters adopted</td>
<td>Steel/Slag/Off Gas temperatures</td>
</tr>
<tr>
<td>Chemical injections O2, Gas, C, CaO</td>
<td>Electrical/material consumptions, Power On, Losses</td>
</tr>
</tbody>
</table>

![Figure 1](image1.png)

Figure 1 – Scheme of mathematical modelling as support to single process phases and through process

![Figure 2](image2.png)

Figure 2 – Terms of the operating practice evolution described as input

![Figure 3](image3.png)

Figure 3 – Simulation results in terms of electrical and main chemical consumptions
2.2 Off-Line modelling for prediction of LF treatment

Also the simulation of LF treatment following the whole history of ladle treatment from EAF tapping till tundish has been developed starting by tapping conditions from EAF having as input/output:

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ladle additions weight charged</td>
<td>Deoxidation and oxygen activity evolution</td>
</tr>
<tr>
<td>Ladle treatment: electrical energy, gas stirring, treatment time, Additions</td>
<td>Desulphurization</td>
</tr>
<tr>
<td>Steel/Slag Composition</td>
<td>Steel temperature evolution</td>
</tr>
</tbody>
</table>

**Oxygen balance**

The simulation model also includes as example the calculation of the oxygen balance. This calculation requires that at each iterations the oxygen level is updated by subtracting the oxygen reacted with the deoxidizing elements. This calculation is carried out by considering: Si, Mn and Al.

\[ O_i = O_{i-1} - \Delta O(Si) - \Delta O(Mn) - \Delta O(Al) \]

\[ \Delta O(Si) = \left(\frac{\%Si}{\%SiO_2}\right) \times (\%O) \times K_{empSi} \]

For Si, Mn, Al

The graph below shows oxygen activity in steel bath during ladle treatment, starting from tapping.

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Figure 4 – Simulation results in terms of steel temperatures and compositions evolutions during the heat

Figure 5 – Off-line oxygen activity estimation during ladle treatment since EAF tapping till tundish
3.3 Off-Line modelling for prediction of Solidification in continuous Casting

The simulation of solidification in continuous casting is a significant topic for Feralpi Group since several years in order to optimize casting conditions of billets both for conventional and special steels. In particular the off-line simulations to predict the thermal conditions during casting have been realized by external consultancies (PoliMi, Rina CSM, Primetals, Seamthesys) in order to optimize the casting conditions for different configurations of the plant and cooling parameters. Feralpi has also decided to implement its own solidification model provided by PoliMi with software development realized by Visiorobotics.

The calculation of temperatures in the steel strand is the first module implemented in Calvisano. A further simulation output is the indication of the liquid, solid and mushy state of the material. Simulation inputs, such as Liquidus and Solidus Temperatures, can be modified for different steel grades, to consider the real physical parameters (conductivity, density, ecc …) to the solidification process. Figure 6 – Temperature distribution simulated.

The post-processing information useful in the continuous casting process are:

- The whole thermal mapping of the billets in all sections
- The solidified thickness and liquid diameter along the cooling line
- The metallurgical length of the complete solidification of the caster strand.

Figure 7 – Scheme of calculation for Solidification off-line model

The activity of solidification model in CC is still under development in the project SteelPro4.0 of Acciaierie di Calvisano and next steps consist of:

- Calibration of the simulation to the different steel grades of special steels
- Representation of the effects with different spray nozzles in secondary cooling.
3 On-line simulation for process control

3.1 On-line simulation application for EAF process

For EAF Process Feralpi the on-line system EAFPro developed with Rina CSM has been implemented in both steelmaking plants of Feralpi Siderurgica and Acciaierie di Calvisano.

The EAFPro system is able to follow on-line the EAF process in order to:
- Collect all data of the EAF
- Simulate process conditions
- Give indication as support to process control
- Summarize process relevant KPI’s

Result of dynamic mass and energy balance in EAF:
- Steel and slag masses
- Evolution of %C and steel composition during the process
- Steel temperature evolution

Figure 9 – Main view on-line available for monitoring of EAF process and heat summary results

Figure 10 – Steel composition and temperature available on-line by dynamic mass and energy balance.
3.1 On-line simulation application for LF process

The on-line ladle treatment is followed ladle by ladle and represented in site views. In particular following steel temperature are estimated depending by steel treatment followed including: Treatment time, ladle position, electrical energy provided, stirring gas activation, ladle additions real temperature detection.

In this way the main functions on-line available are:
- Temperature estimation on-line for each ladle
- Auto tuning depending by real temperature samplings
- Prediction of temperature estimated at ladle arrival to further process phases
- Alerts function in case of abnormal temperature predicted

Figure 11 – Page views of temperature estimation on-line for different ladles

3.1 On-line application of solidification prediction in continuous casting

The mathematical modelling of solidification has been developed also to be applied on line in a general configuration that include several steps: On-line casting parameters acquisition, thermal mapping measurement, On-line defects detection, comparison of solidification estimation with real on-line detections, relevant parameters representation, Postprocessing and process guidelines and alerts.

For the on-line approach, the inputs are taken from the automation of continuous casting machine. including: casting speed, primary and secondary cooling water flow, water delta temperature, ecc.

Figure 13 – View of on-line application of on-line solidification model coupled with relevant detections
In parallel a system for surface defect detection has been developed by Visiorobotic using a laser scanning and signal postprocessing for surface status representation.

As off-line application the system has been used to evaluate the accuracy in detection of relevant defects. Billets with relevant defects have been used for trials, and subsequent surface Postprocessing was realized. In on-line application following steps are available (figure 14):
- Processing of the data are realized on line in real time during the process.
- Surface conditions are shown after on-line postprocessing

Figure 14 – Off line and on-line application of surface defects detections

The on-line application of solidification model has been realized and the whole configuration and coupling with the on-line detection and alert systems are under development as shown in Figure 15.

Figure 15 – Simulator interface with heat data, simulation output, measurement systems data and alerts

4. RESULTS

4.1 Application of On-Line Decision support Systems

Main results in this activity are the development of the process modelling of each process phases and the on-line availability for the main process steps as EAF, LF and continuous casting.
By this 2 steps the application of on-line application of decision support systems and alerts function have a deeper development for the EAF and LF process mainly for the steel temperature estimation, for arc covering and coal injection in EAF and for estimation of overoxidation cases as in Table 1.

<table>
<thead>
<tr>
<th>Evaluations</th>
<th>Benefits Aimed</th>
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<tbody>
<tr>
<td>Periods or arc discovered in refining</td>
<td>Reduction of energy dispersions</td>
</tr>
<tr>
<td>Evaluation necessity of Coal injection</td>
<td>Reduction of energy consumption</td>
</tr>
<tr>
<td>Comparison of practices performances in terms of a specific KPI, ACI (Arc Covering Index)</td>
<td>Reduction of thermal stress on the refractory due to arc emission</td>
</tr>
</tbody>
</table>

Table 1 – Summary of main evaluations and benefits aimed with on-line systems available in EAF and LF.

Figure 16 – Acoustic sensor to detect arc covering during process to suggest on-line Coal injection

The application of decision support system and alert functions for continuous casting is under development taking into account also on-line detection as Thermal Mapping and surface defect detection. Main alerts in this case will be related to variation in casting length, or abnormal solidified shell thickness or residual liquid diameter in relevant casting positions, These alerts will be used to provide relevant suggestions in terms of casting process management.

4.2 Application of autolearnig and autoadaptation procedures

The systems on-line take into account also relevant functions of autolearning or autoadaptations as:
- Autoadaptation of coal injection suggested by arc covering detected
- Autoadaptation of steel slag composition depending by sterile content in Charge in EAF
- Autoadaptation of temperature estimation of steel temperature in ladle.

In continuous casting main autolearning procedure foreseen include:
- Autotuning of temperature estimated for the billets by thermal mapping
- Deep learning application for laser surface detection of the billets

4 CONCLUSIONS

Feralpi Group is strongly following strategies Industry 4.0 including steps as Data analysis, realization of digital twins and process simulations, Autoadaptation of data analysis and application of on-line control rules thanks to developments of Decision Support Systems off-line and on-line as support to the production. In some cases these aspects are coupled with developments of relevant detection systems as for the case of the Off gas composition measurement in EAF, Acoustic measurements, thermal mapping and defect detection in continuous casting.
The list of developments is quite long and the necessary activities take long time and included in a strategic roadmap coupling ideas coming from production sites, Automations, Technological areas, R&D, Direction. Feralpi has obtained several results by this approach considering that when the new feasible application are ready they become available on-line as continuous improvement of production processes and knowledge. Main results obtained include: the system EAFPro coupling process monitoring and dynamic simulation of mass and energy balances for both the EAF process and ladle treatments. Furthermore the systems for estimation of ladle additions, the continuous casting monitoring and simulation, till arriving to data integration to the rolling mill are available for special steel of Arlenico in an approach called “Quality Integration”.

Thanks to these results obtained, the activities by Feralpi are on-going to complete the whole production areas with mathematical and software systems able to support the increase of process performances and product quality coupled with an environmental sustainable approach. These activities are realized also with the collaboration of technological and Research Partners as Rina Centro Sviluppo Materiali, PoliMi, UNIBS, Visionrobotics Automazioni Industriali Capitanio, Ergolines, SAP Regesta, SMS, Primetsl and others.

Furthermore several projects are prosecuted also thanks to the funding support of R&D Funding schemes as the projects WireAccuracy 4.0 (of the MISE), and for Acciaierie di Calvisano SteelPro4.0 (of Accordi per l’innovazione of Regione Lombardia) and SupportCast (RFCS of EU).

REFERENCES