EAF process optimization through a modular automation system and an adaptive control strategy

M. Piazza, F. Bianco, D. Patrizio, M. Ometto

The complexity and variability of the Electric Arc Furnace process call for advanced monitoring and control solutions, in order to improve process performances, environmental compatibility and operator safety. The innovative Danieli Q-MELT Automatic EAF system addresses these aspects implementing a centralized control system which interacts with multiple technological packages. Each of these cutting-edge technologies focuses on one aspect of the EAF cycle, increasing machine availability and resource efficiency, by means of electrode regulation and foamy slag control, charging optimization, off-gas analysis and closed loop injectors control, on-line temperature measurement, automatic tapping and robotics. Moreover, these modules provide the process supervisor application (Melt Model) with important information regarding the process status, thus allowing the adoption of a unified control strategy. The supervisor implements a robust statistical approach to identify process deviations in real time. By means of advanced data collecting and data mining techniques, the available process data are clustered and filtered, and the expected trends of the key process variables are thus extracted. Melt Model applies this data-driven adaptive strategy to the oxygen injection management during the refining phase, optimizing the decarburization process and increasing the furnace performances. With such a modular and adaptive approach, Q-MELT aims to the "Zero Operator on Melting Floor" practice and allows multiple levels of process optimization, from a single process aspect to the entire EAF cycle.

KEYWORDS: COMPUTER APPLICATIONS - SYSTEM MODULARITY - ADAPTIVE CONTROL - PROCESS OPTIMIZATION - AUTOMATION - EAF

INTRODUCTION

Nowadays, scrap-based steel production accounts for about 30% of the world steel production [1] and is based on the Electric Arc Furnace route. Given the high recyclability of steel and the foreseen increase of steel recovery from waste [1], the EAF sector is a key area for a sustainable steel production. As a matter of fact, if we consider the expected growth in global steel demand (2-4% per annum during the next decade), and the high raw materials costs (quadrupled since 2002), it is apparent that steelmakers need to maximize resource efficiency [2] to be able to produce more and better with less.

On the field, even without considering the market demand swings, steelmakers must cope also with the variability of raw material quality and costs, which requires continuous adaptation to ensure the proper production quality and plant throughput. EAF resource efficiency has increased dramatically during the last 50 years [3]; nonetheless, if we analyze the performances of a set of reasonably similar EAFs around the world [4] [5], is easy to notice a wide variability in term of performances (Fig. 1).

M. Piazza, M. Ometto
Danieli Automation S.p.A.,
V. Stringher 4, 33042 Buttrio (UD), ITALY

F. Bianco, D. Patrizio
Danieli & C. Officine Meccaniche S.p.A.,
V. Nazionale 41, 33042 Buttrio (UD), ITALY

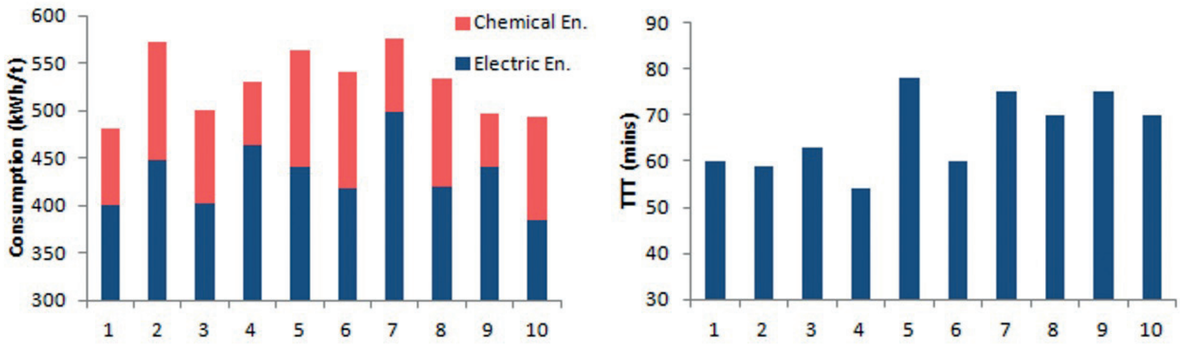

Fig. 1 - (a) Electric and chemical energy consumptions and (b) TTT of a set of 10 EAFs around the world with similar maximum rated power, charge mix and produced steel grades.

This evidence is confirmed by other surveys too [6]: charged materials and equipment availability aside, the following criticalities are still quite common:

- Lack of practices standardization.
- Lack of proper benchmarking & feedback.
- Lack of operator training.
- Misunderstanding of resources value and use.

All these facts underline that, worldwide, there is ample margin of improvement in the EAF resource efficiency field. This much needed advancements can be achieved with a high level of process optimization and automation, advanced control strategies and with the support of innovative data analysis tools.
To address all these aspects, DANIELI Q-MELT has been designed as an integrated process control supervisor. It automatically recognizes deviations from the expected behavior and re-tunes the melting program, acting on the electric power planning, on the chemical package, on the slag and steel metallurgy. Equipment constraints are integrated into the control action through functional diagnosis.
Q-MELT Process Supervisor integrates basic automation and technological functions to enable EAF steel production in an effective and safe way, supporting each operation from the charging phase up to the tapping procedure. Thanks to a new generation of machine pulpits, which implement extensively sensor- and camera-based technologies, the control room can be installed in an arbitrary position and does not need dedicated windows to have a direct visual feedback from the process, increasing operator safety and process awareness.
A suite of supplementary stand-alone Technological Packages integrates Q-MELT to further maximize the productive time, utilization factor and safety, through remotely controlled mechatronic units.

MODULARITY: DANIELI EAF TECHNOLOGICAL PACKAGES

Danieli implements modularity as a key aspect of present and future EAF automation systems. As a matter of fact, a modular system enables multiple levels of process optimization and awareness. It also allows to properly satisfy customer demand, addressing specific issues or overall performance of existing EAFs without radical machine structural modifications. This way, the importance of efficiency over productiveness is stressed, in good accordance with our initial considerations about resources cost and overcapacity issues.
Q-MELT Automatic EAF features a centralized control system as the only coordinating center (Fig. 2). As such, it receives information from multiple Technological Packages (TPs) and coordinates their action during the whole process. This way, a single unified control strategy can be adopted and system modularity is guaranteed nonetheless. The 3Q Pulpit Technology natively supports such a system, with a centralized and intuitive control station for the whole EAF machine.

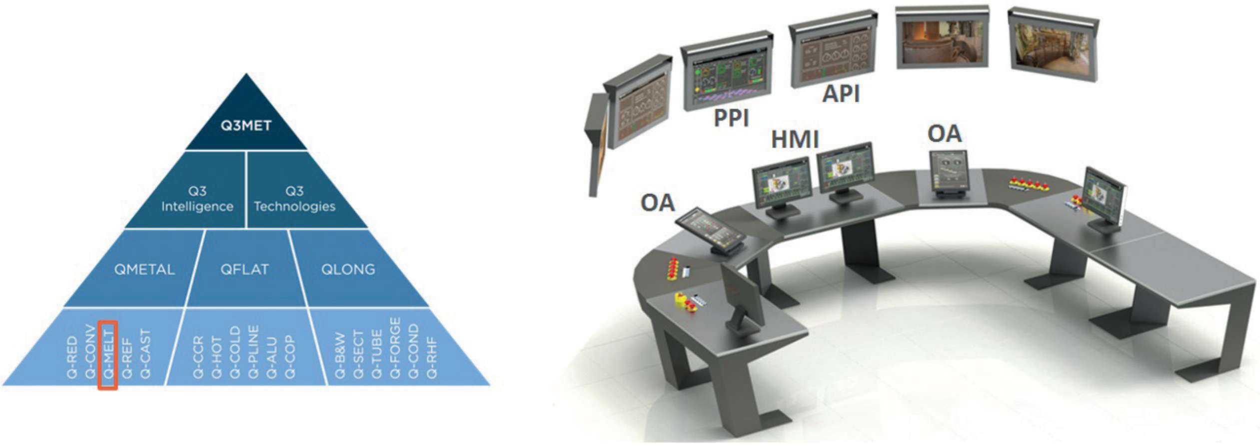

Fig. 2 - (a) 3Q Technologies pyramidal organization and (b) 3Q pulpit arrangement: Operator Assistant (OA), Human-Machine Interface (HMI), Plant Performance Indicator (PPI) and Area Performance Indicator (API).

The centralized control room coordinates the actions of all the technological packages installed. A brief summary of the most important TPs for process control and optimization will be shown hereinafter, together with their performance achievements.

LINDARC REAL TIME OFF-GAS ANALYSIS SYSTEM

LINDARC is and advanced laser-based off-gas analysis system, designed for EAF applications, which implements the Tunable Diode Laser Absorption Spectroscopy (TDLAS) technique to measure the off-gas composition (CO, CO2, O2, H2O) and temperature (Fig. 3).

Fig. 3 - (a) LINDARC installation on EAF 4th hole elbow and (b) detail of the laser beams.

The system response is very quick (less than 2 seconds compared to more than 30 seconds of traditional extractive system) and is thus well suited for a reliable on-line monitoring and control. Specifically, a Closed-Loop Control (CLC) dynamically controls the injection of post-combustion oxygen, thus optimizing the O2 consumption and maximizing the chemical power input. Moreover, H2O readings are used to monitor dynamically the water content in the off-gas and to generate a warning whenever its value, exceeding the expected trend for each process step, identifies a probable presence of a severe water leak. Recent operational results [7] show considerable improvements regarding electrical energy consumption (-3.1 kWh/t), power-on time (-0.4 min), injected carbon consumption (-1 kg/t), and process yield (+1.4 %).

Q-REG + ADVANCED ELECTRODE REGULATION SYSTEM

Q-REG+ is an advanced PAC-based (Programmable Automation Controller) electrode control system for AC and DC EAFs. The system uses high performance algorithms together with intelligent measurements technology. The control strategy is based on fast data acquisition to manage both the electrical and chemical EAF power input.

Electric arc furnace

Dynamic electric energy regulation
Controlling the position of each electrode column, the system dynamically adjusts the electrical set-points to adapt to the furnace and network conditions and to achieve the highest possible active power input.

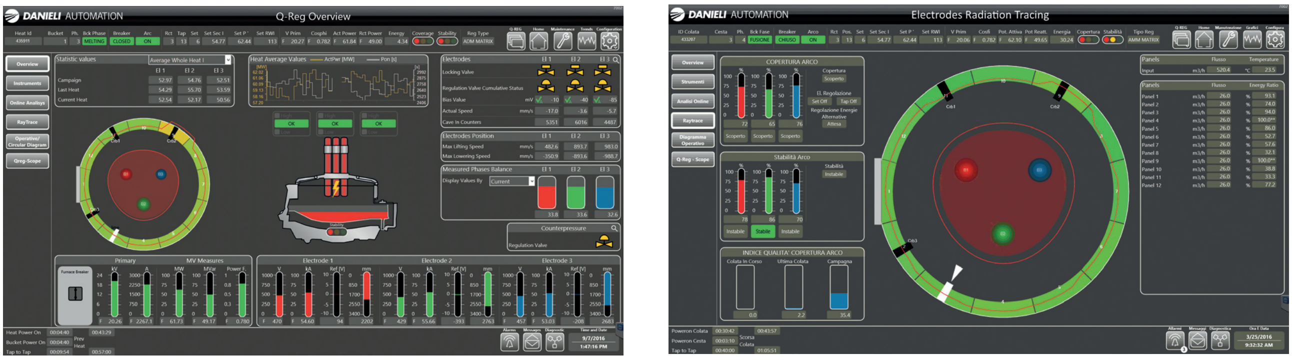

Fig. 4 - (a) Q-REG+ overview and (b) Q-RAY arc irradiance supervisor

In this field, Q-REG+ main futures are: fast response hydraulic counter pressure control and touchdown function (lower electrode breakage risk), boring-down dynamic control (auto-regulation of the electrical working point, to increase the power as soon as possible), automatic supply voltage compensation (uniform operation and power inputs without operator intervention), transformer over-current and thermal protection with secondary insulation control (safer EAF operation) and real-time irradiance supervisor (Q-RAY) for longer cooling panels and refractory lifetime (Figure 4). This innovative supervisor evaluates the total radiative heat flux on the furnace panels to modify the electrical set-points, thus balancing the thermal loads on the water-cooled panels
Fully-fledged customization tools allow interactive set-point input and visualization. As an example, the circular diagram view (Fig. 5a) was developed as an interactive visualization of the furnace working area and electrical settings, to quickly check and modify the EAF working points. Other advanced diagnostic functions enhance process and machine monitoring; dedicated statistical data analysis is performed by Q-REG Scope (Fig. 5b).

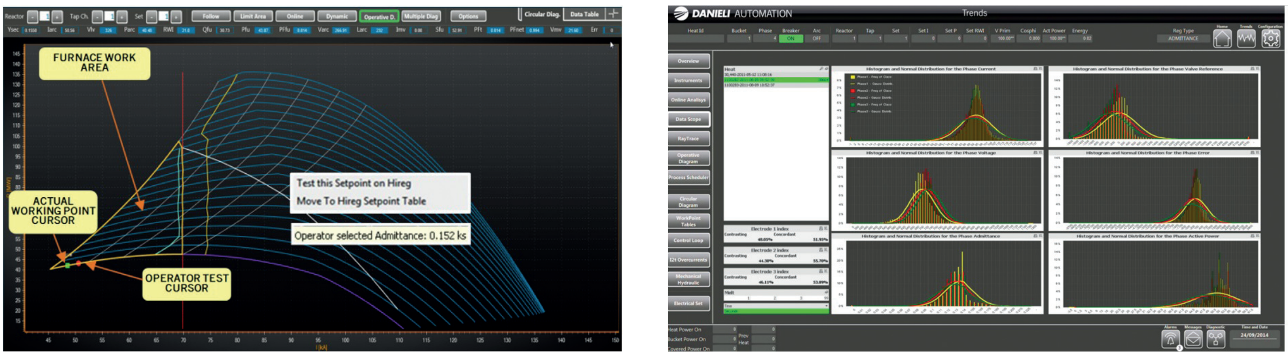

Fig. 5 - (a) interactive circular diagram view and (b) Q-REG Scope statistical analysis tool

DYNAMIC FOAMY SLAG CONTROL
During the refining phase, arc coverage by the foaming slag is the key parameters to monitor the process.
Q-REG+ continuously monitors the slag condition evaluating the Arc Coverage Index (ACI), a proprietary function based on arcs' V and I real time analysis.
When the ACI exceeds a proper threshold, optimal foaming slag conditions are detected and the system automatically reduces the static C injection flow set-points. If the arc gets uncovered, the carbon flow is increased accordingly (Fig. 6).

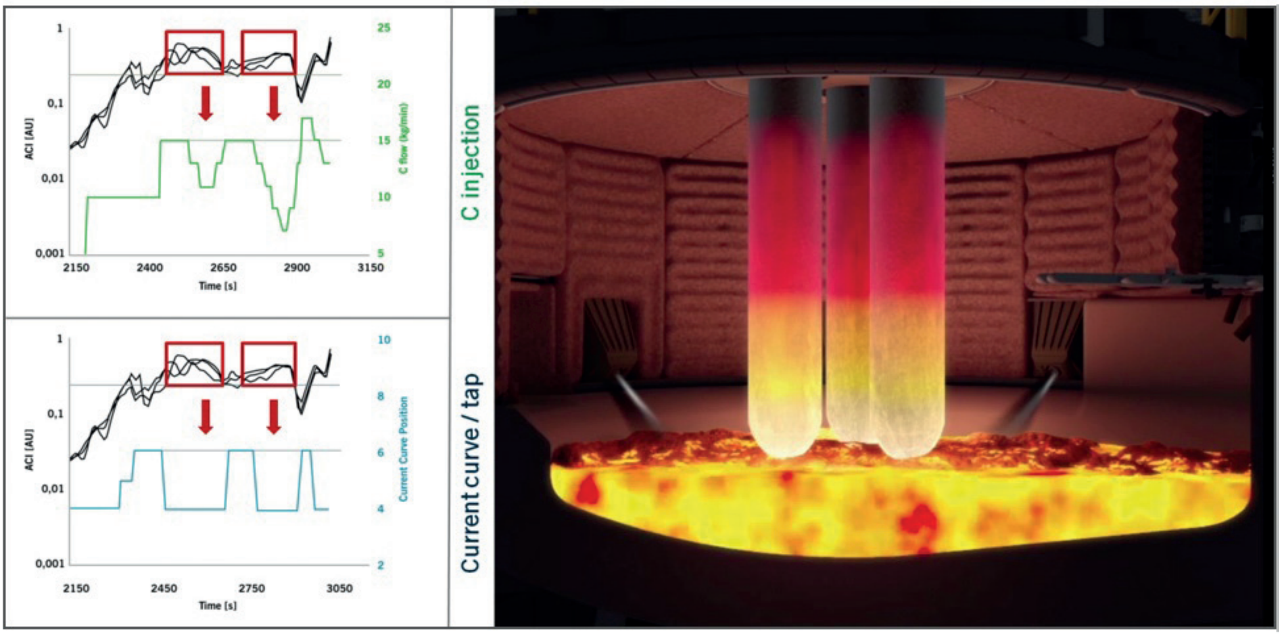

Fig. 6 - Dynamic carbon & lime injection and dynamic electric set-points management based on Arc Coverage Index (ACI).

Towards the end of the process, dynamic regulation is applied also to lime-dololime injection, to recover proper slag basicity while optimizing the slagging agents consumption.
Typical and expected results of a Q-REG+ installation are the reduction of electrode consumption (-6%) and of electrical energy consumption (-5kWh/t), as well as a higher average active power (+3%) and a reduction of flicker (-10%).

Q-CHARGE BUCKET RECIPE AND CHARGING OPERATIONS OPTIMIZATION

Q-CHARGE is a set of tools to manage the EAF charging process from the bucket recipe calculation to the basket unloading into the EAF. Charge recipe optimization and automatic crane movement imply higher plant productivity, efficiency and output quality. A least-cost charge calculation function is implemented to attain the tapping analysis targets respecting the maximum residual elements concentrations allowed. The main outputs of the algorithm are the total charge recipes, the individual bucket charge recipes and scrap purchase lists, for a faster and more reliable recipe calculation and a support to long-term production planning (Fig. 7a).

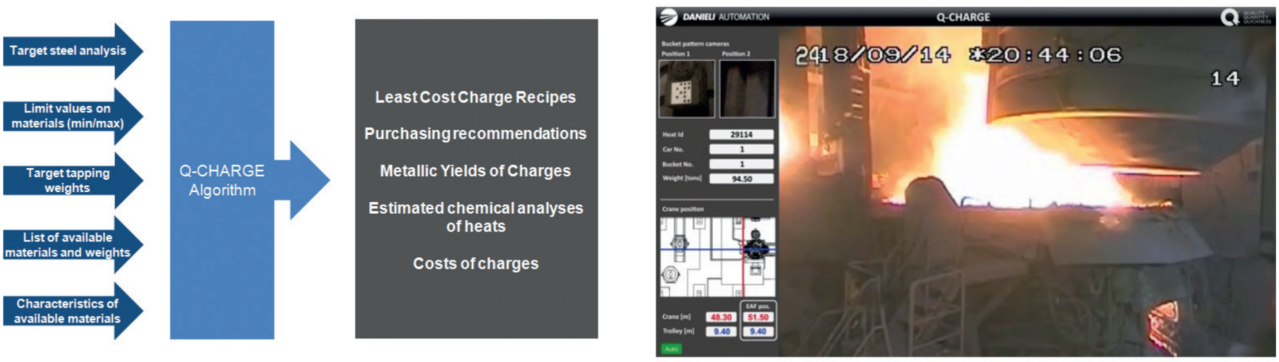

Fig. 7 - (a) Q-CHARGE least-cost charge calculation algorithm and (b) HMI for bucket movement/alignment supervision

After the operator's request from the main EAF pulpit, a laser-based crane positioning system allows assisted bucket picking, movement and positioning over the EAF. When the bucket is discharged, the system automatically closes the EAF roof and the doghouse and delivers the empty bucket to the proper bucket car/parking position. Bucket identification is carried out by a camera-based pattern recognition system (Fig. 7b). Thanks to the integration with the EAF automation system, the movements of the doghouse door, EAF roof and crane hook are highly synchronized to minimize non-productive time and energy losses.

Q-TEMP IMPULSIVE CONTACTLESS TEMPERATURE SENSOR

Q-TEMP is a pyrometer-based sensor designed to provide a continuous feedback of the bath temperature. A specially-optimized nozzle, co-axial with the pyrometer line-of-sight, directs a supersonic shot of N2 which penetrates the slag layer thus exposing the molten steel bath. The system is typically installed on the EBT panel, which eases the installation on existing furnaces avoiding substantial modifications (Fig. 8a).

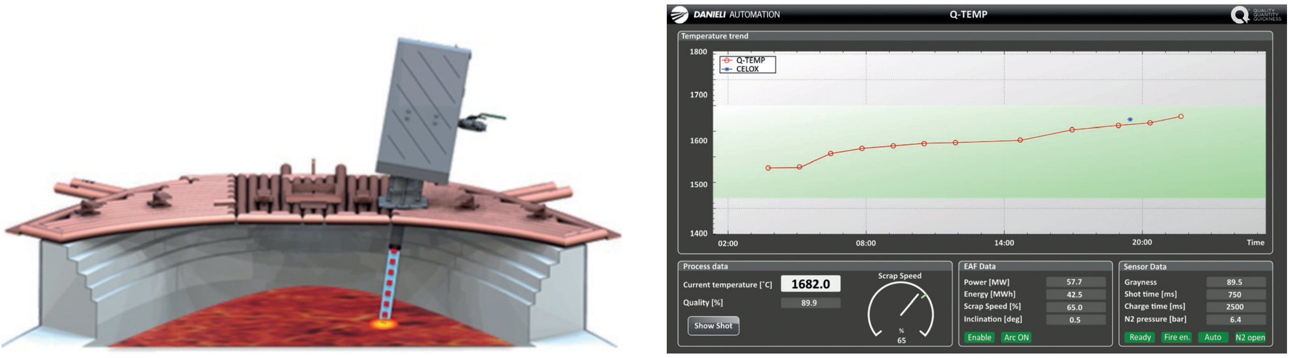

Fig. 8 - (a) Q-TEMP typical installation and (b) HMI for bath temperature monitoring

The instrument feedback, showed in real-time on a dedicated HMI (Fig. 8b), is in general very useful for the operator to monitor the melting progress, but it is particularly useful for EAFs with continuous scrap or DRI charging systems. Here, the charging rate can be optimized to meet the best melting conditions, with positive consequences on process stability and throughput uniformity. Moreover, as traditional temperature measurements are not needed, savings in power-off time and sampling cartridges are achieved. As a matter of fact, typical installation results are the reduction of cartridges expenses alone by ca. 4$ per heat.

Q-ROBOT MELT ROBOTIZED STEEL AND TEMPERATURE SAMPLING

Q-ROBOT Melt is a system composed of an anthropomorphic robot equipped with a water cooled sampling lance and a dispenser for automatic cartridge loading and unloading. The system can be used with any type of cartridges, from chemical sampling to fast oxygen/carbon content and/or temperature measurement (Fig. 9).

Fig. 9 - (a) Q-ROBOT Melt in operation and (b) automatic cartridge picking from the dedicated dispenser

The inherent movement precision of this technology ensures high sampling repeatability and full trajectory tunability. Moreover, the furnace power-off time can be reduced as the sampling procedure can be carried out with the furnace on. Also, as no manual operations are required in this very dangerous area, operator safety is significantly increased.

Q-SMARTEC ELECTRODE SAVING TOOL

It is well-known that the majority (60%) of the overall furnace electrode consumption is due to lateral oxidation. Q-SmarTEC was designed to reduce the lateral oxidation to a minimum implementing an optimized design of the cooling rings (Fig. 10a) and an automatic management of the water and air flow rates passing through them (Fig. 10b). Specifically, the water flow is adjusted to each process step (p-on and also p-off) considering the different expected oxidation rate, thus avoiding electrode over- or under-cooling. Q-SmarTEC also monitors the water conductivity and the pressure - pressure drop in the pipings in order to maintain the cooling system in the best operating conditions.

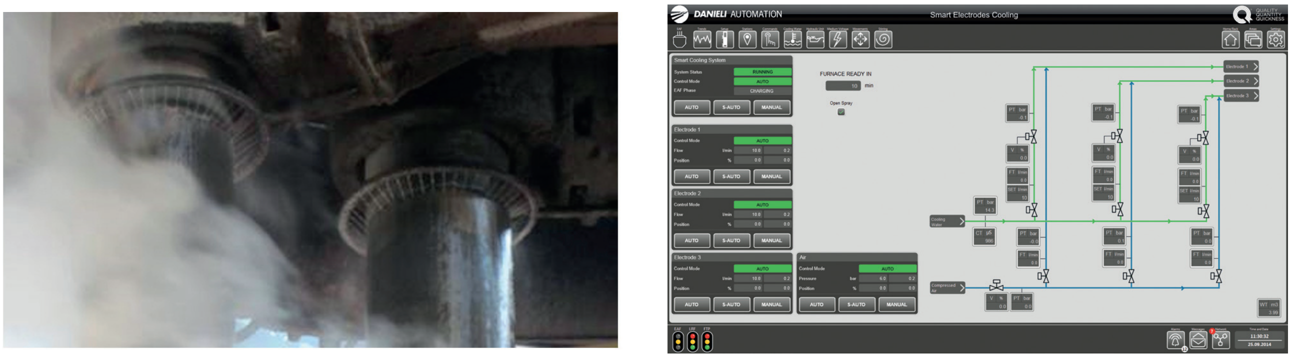

Fig. 10 - (a) Q-SmarTEC cooling rings and (b) Q-SmarTEC overview from the EAF HMI

The typical installation result of Q-SmarTEC, achieved during trial tests, is a 15% reduction of electrode consumption.

Q-ATS AUTOMATIC TAPPING SYSTEM

Q-ATS system is a suite of tools to automate and support the operator during the EAF tapping phase. Thanks to a thermal camera pointed at the steel stream, the system triggers the automatic furnace tilt-back when slag is detected in the stream or when the maximum tapping weight is reached (Fig. 11a). This reduces to a minimum the slag carryover, which would eventually demand for ladle slag raking, and improves the refractory lining lifetime at the slag line. Higher consistency in steel quality, as well as lower costs, lower ferroalloys consumption and lower ladle treatment time are also proven advantages.

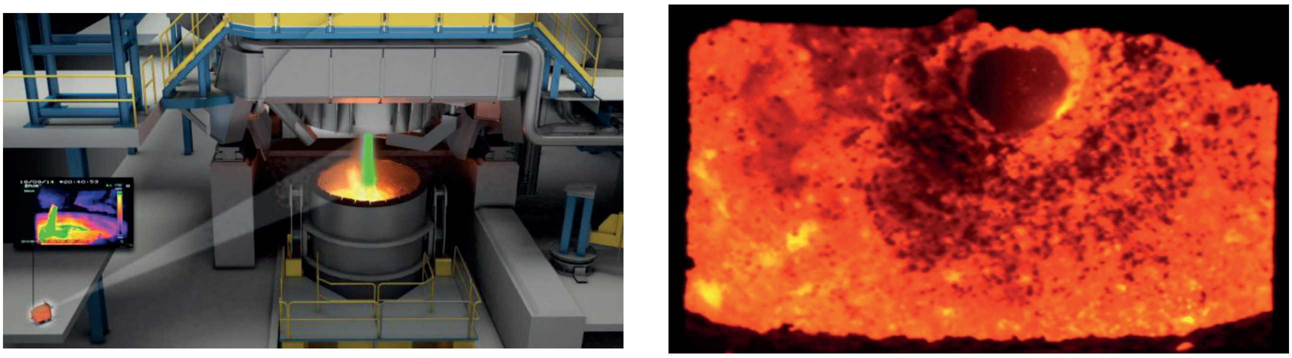

Fig. 11 - (a) Q-ATS slag detection module and (b) camera-based EBT inspection

The suite also comprises a module for remote EBT filling with olivine, controlling the sand storage bin valve. This reduces the power off time and dramatically increases the operator safety, as no manual operation is needed in this dangerous area.
The entire tapping and EBT-filling process is monitored from the main pulpit thanks to a rugged, air-cooled camera mounted above the EBT slide gate (Fig. 11b). This technology gives an immediate feedback regarding the EBT status and further increases the operator safety.

3Q TECHNOLOGY AUTOMATION

3Q Technology Automation is the basis for Danieli philosophy of coordination and full process control from a single point, which radically changes the role of the operator. 3Q Control Desk improves plant performances, reducing dependence on the skill of operators. All EAF operations are controlled and supervised from a single point control room, which can be remotely located (Fig. 12).

Fig. 12 - 3Q Technology pulpit installation at Riva Thy-Marcinelle

The knowledge-based approach consists in showing the operator only the useful information required for that precise process step. As an example, The EAF Area Performance Indicator (API, Fig 13a) is designed to summarize the current process status and the process models main outputs, while the Plant Performance Indicator (PPI, Fig. 13b) shows the synthetically the entire plant operative status.

Fig. 13 - (a) EAF Area Performance Indicator (API) and (b) Plant Performance Indicator (PPI)

One of the key points of 3Q Control Desk is the provision of a full Soft-Desk pulpit, totally based on touch-screen technology, through which the operator can both monitor the plant and operate it at the same time. Coordination between different areas is natively embedded in the integrated architecture. Traditionally the operator gives commands and instructions to start the operating cycles. With the 3Q approach, the automation is responsible to coordinate commands and instructions, with maximum overlapping and synchronization, while the responsibility of the operator is to supervise and decide upon exceptions. When an exception in the standard operating cycle occurs, a dedicated interface asks the operator for his decision, based upon a selected multiple choice based on the immediately next action required in the sequence tree.
The 3Q Technology installed at RIVA Thy-Marcinelle shows how modules coordination positively impacts plant performances. Here, the centralized control room covers and manages the entire EAF process, from the bucket alignment (via laser system and automatic crane positioning cycles) to the tapping phase. The activation of all the Autopilot System functions, together with the massive introduction of overlapping cycles, greatly reduced the total number of delays due to automation (from 20% to 2%), thus improving the machine productivity by half heat for each 12-hours shift. The results were obtained without mechanical or procedural intervention; thanks to the delay reduction, the power off time was decreased from 13 to 9 minutes [8].

ADAPTIVITY: MELT MODEL EAF PROCESS SUPERVISOR

The operational results achieved with the 3Q technology implementation at Riva Thy-Marcinelle demonstrate how the adoption of a single-point control room is the best strategy to guarantee the highest machine availability and utilization factor. From a strict process control point of view, the key consideration is the same: as the process data retrieved from the field by multiple technological packages can be very variegated (from continuous signal retrieved by the sensors to the current charge recipe and sample analysis results), occasional process deviations could very easily be hidden by the complexity of the available data. A single, robust real-time supervisor application must then be designed to efficiently cope with and contextualize the current and historical process data to identify process deviations and adapt the furnace operating conditions, optimizing the EAF process.
Melt Model EAF process supervisor is a real-time application developed to apply this robust data-driven strategy to the electric arc furnace control. It implements a statistical approach to identify process deviations in real time: by means of advanced data collecting and data mining techniques, the available process information is clustered and filtered, and the expected behavior of the desired variables is thus extracted. This procedure generates the fingerprint of the process: the average & deviation trends of the key process variables. Comparing their expected and current behavior, the system performs an adaptive process monitoring; based on this, it then acts on the EAF actuators (Fig. 14).

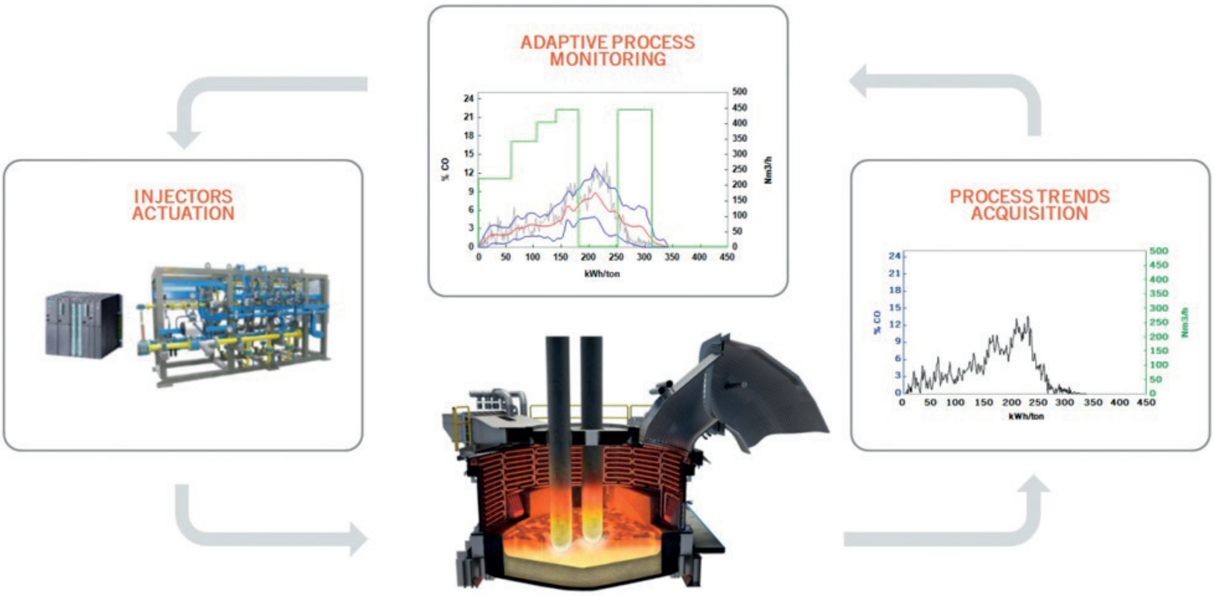

Fig. 14 - Melt Model implementation of a trend-based adaptive process control

Melt Model applies this very general approach to control the decarburization process during the refining stage. The aim is to optimize the oxygen injection to hit the %C and temperature targets in the most efficient way, adapting the O2 profile considering the current heat characteristics.
To do so, at the start of the heat the application extracts the fingerprint of the off-gas composition (%CO, %CO2, %H2O), total O2 flow and total C rate filtering the available historical data to consider the proper relevant class of charge materials, melting profile, final %C and other parameters. Comparing these expected trends with their real-time counterparts, the application detects whether the decarburization process is proceeding with the expected rate or not. It thus dynamically adapts the current O2 injection profile and generates the proper O2 set-points to achieve the target bath %C and temperature (Fig. 15).

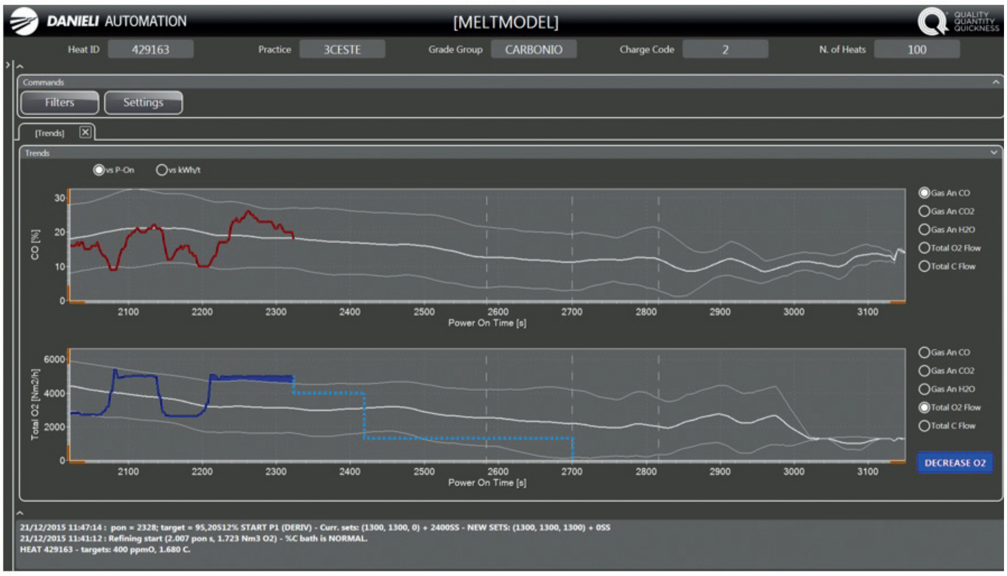

Fig. 15 - Melt Model main view showing the fingerprint - real time trends comparison and the dynamic O2 injection profile.

From the first valid Celox measurement on, the application also tracks the bath %C / Temperature / a[O] thanks to its integrated process models (Fig. 16). These models are fitted on the data stored by the system, so their output is tuned on the specific EAF considered and it adapts to slow process changes over time.

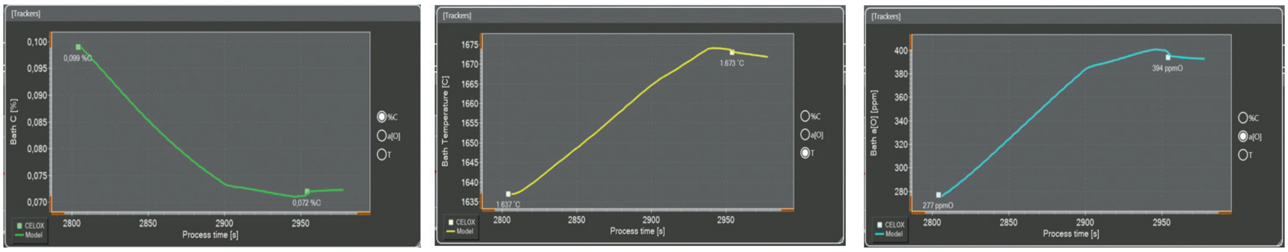

Fig. 16 - Melt Model process trackers for bath %C, temperature and a[O]

The cartridge measurements results, as well as the steel analysis, are also considered by the application to control the decarburization: when available, this information is used to further increase the accuracy of the final bath composition and temperature.

Melt Model is currently under trial and its approach showed very effective. Thanks to the O2 injection optimization, during the first trials the yield was increased by 0.3% and the final oxidation (already very satisfactory) was preserved while the standard deviation of the final oxidation was decreased by 20%. This last figure is a clear indication that the application helps to achieve the targets more reliably and that it effectively acts as a profile optimizer.

CONCLUSIONS

Given the steel market forecasts and the current over-capacity issues of this productive sector, it is apparent that steelmakers need to maximize resource efficiency to be able to produce more and better with less. A modular process control and automation system, featuring one central control system interacting with multiple technological packages, gives the best possibilities in this field. Danieli's Q-MELT Automatic Furnace concept is based on these principles and gives to the steel makers the needed flexibility to improve the EAF process, with proven results in Acciaierie Bertoli Safau, Gerdau Jacksonville and Thy Marcinelle, where the modularity concept increased the plant flexibility and productivity. The adaptivity of the system is currently being further improved with an on-line, data-driven process supervisor which can identify process deviations in real-time and therefore acts on the process profiles. The positive results of its first installation are very encouraging and are already suggesting several other EAF process areas where a similar approach can be successfully applied.

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