Q-MELT AT KROMAN CELIK EAF: PERFORMANCE RESULTS AFTER ONE YEAR OF OPERATION *

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Abstract

The present work analyzes the results achieved in Kroman Celik EAF one year after the installation of the Q-MELT Automatic EAF system and the revamping of the furnace chemical package. The main features of the system, such as electrode regulation and foamy slag control, charging optimization, off-gas analysis and closed loop injectors control are summarized. Further improvements have been achieved with the fine tuning of the melting practices, which allowed to progressively reduce the electrical energy consumption. The effect of oxygen dedicated to post combustion is analyzed in terms of electrical energy savings. In addition, slag sampling has been increased to improve the slag builder's recipe and to reduce the variability of the main chemical compounds. The initial results achieved after the first months of installation were confirmed and improved during (year) 2018. The system showed how its adaptive characteristics changed dynamically the input process parameters according to the variability of the different parameters measured, such as charge mix, off-gas analysis, arc coverage index, etc.

Keywords: EAF, Gas Analysis, Post-Combustion, Process Control.

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1 INTRODUCTION

The present work analyzes the results achieved in Kroman Celik EAF one year after the installation of the Q-MELT Automatic EAF system and the revamping of the furnace chemical package. The main features of the system, such as electrode regulation and foamy slag control, charging optimization, off-gas analysis and closed loop injectors control are summarized. Further improvements have been achieved with the fine tuning of the melting practices, which allowed to progressively reduce the electrical energy consumption. The effect of oxygen dedicated to post combustion is analyzed in terms of electrical energy savings. In addition, slag sampling has been increased to improve the slag builder's recipe and to reduce the variability of the main chemical compounds.

2 DEVELOPMENT

2.1 Kroman Celik EAF Revamping

In July 2016 Kroman Celik, located in Gebze (Turkey), a plant producing reinforcing bars and wire rods, chose Danieli Q-MELT process control and MORE chemical package to upgrade their 150-ton EAF (Fig. 1), aiming at improving the EAF productivity and at reducing operative expenditures.

Figure 1. Kroman Celik EAF.

The main electric arc furnace design features are indicated in Table 1.

Table 1. Kroman EAF design features

Start up (year)	2010	
Power supply type	AC	
EAF Supplier	Danieli	
EAF Type	EBT	
Tapped steel weight	150	t
Hot heel weight	25	t
Productivity	175	t/h
Annual Production	1.300.000	tpy
Inner panel diameter	7200	mm
Electrode diameter	710	mm
Pitch circle diameter	1350	mm
Transformer nominal rating	140	MVA
Max secondary voltage	1350	V

Owing to the progressive deterioration of the scrap quality, it was decided to equip the meltshop with the Q-MELT Dynamic Heat Suite package, which collects all the necessary melting information to perform automatic and dynamic adjustments during melting and, specifically, to perform the metallurgical control of the electric arc furnace process.

The system includes:

> Q-REG, the latest release of the dynamic electrode regulation with foamy slag control, managing coal and lime injection to keep the arcs shielded and balanced at the highest power input, although not entailing excessive radiation losses.

> Real-time process optimization and control based on Lindarc^{TM}, an innovative fast gas analyzer performing *in-situ* laser spectrometry and allowing the closed loop control of post-combustion [1].

A chemical package revamped with the most recent MORE's technology for technological gases and solids' injection management [2]: M-ONE sidewall injectors to improve oxygen and coal efficiency and Limejets to integrate lime and dolomite injection as well in order to optimize the slag foaming practice

2.2 Adaptive Process Control: Q-MELT

The inherent high variability and low measurability of the EAF process call for a set of responsive yet very reliable control strategies. Q-MELT implements a statistical approach to identify process deviations in real time. Process data are automatically collected, clustered and filtered, and the average and standard deviation trends of the key process variables are extracted. This set of statistical figures is called "fingerprint" and it gives a picture of the normal, expected process behavior. Through a comparison between the real-time trend and the expected one, the system performs an adaptive process control and acts on specific actuators (Fig. 2).

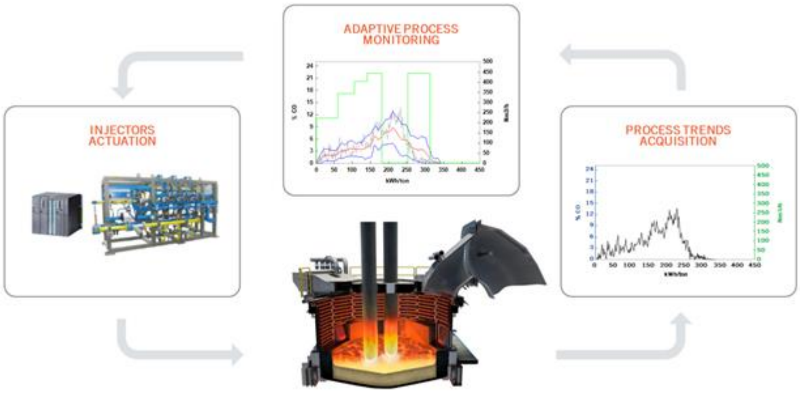

Figure 2. Melt Model implementation of a trend-based adaptive process control.

Melt Model applies this general approach to control the decarburization process. At the start of the heat, the fingerprint of the off-gas composition (%CO, %CO_2, %H_2O) and of other controlled variables (injectors' O2 flow, dispensers' C rate and others) is retrieved from the historical data base. The extraction is done considering a proper set of filtering criteria (practice, charge materials and others). The resulting fingerprint represents the expected behavior of the heat. Comparing the fingerprint and the real-time trends, the application detects whether the decarburization process is proceeding as expected or whether the profile requires some adjustments.

2.3 Q-REG Electrode Regulator

Q-REG is Danieli's latest release of the electrode regulator system for electric arc furnaces. The controller is based on the innovative PAC (Programmable Automation Controller) high-performance platform which has plenty of computational power to manage the complex electrode regulation control with very short response times.

2.3.1 Dynamic electric energy control

Q-REG main features 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 fast as possible), automatic supply voltage compensation (uniform operation and power inputs without the intervention of the operator), transformer over-current and thermal protection with secondary insulation control (safer EAF operation). A faster hydraulic system response and a stiffer mechanical design further improve the electrode positioning performances.

2.3.2 Q-RAY arc irradiance supervisor

An innovative real-time arc irradiance supervisor was added to further optimize the electrical profile.
This module evaluates the total irradiative heat flux along the furnace walls to monitor the thermal load on the water-cooled panels (Fig. 3). The system thus modifies the electrical set-points to maximize the active power until the end of the heat, avoiding severe stress to panels and refractory lining in case of operation with uncovered arc.
The main characteristics of Q-RAY control strategy in Kroman Celik are:

- Possibility to dynamically unbalance the electrode current if the temperature of the corresponding panel reaches the alarm threshold.

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> Possibility to reduce the tap position if the predicted panels' temperature rises quickly towards the trip threshold.

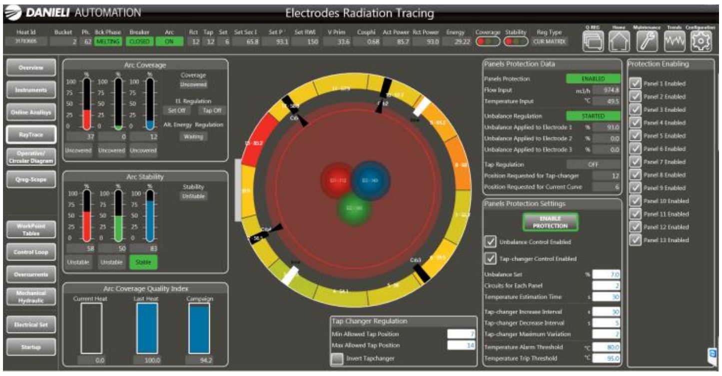

Figure 3. Q-RAY arc irradiance supervisor overview.

These features were enabled to improve the panels' protection; they also reduced the current on each electrode by 5%.

2.3.3 Dynamic foaming slag control

During the refining phase, the coverage of the arc performed by the foamy slag plays a key role. The dynamic foamy slag control constantly monitors the slag condition, evaluating the Arc Coverage Index (ACI), a proprietary function based on arc voltage and on current real-time fast signal processing.

The status and tendency of the ACI are monitored by a controller acting on the coal injection flow to increase the electrical energy transfer while keeping the arcs shielded by the foaming slag.
As arc coverage is evaluated for each electrode, coal injection is regulated by acting on each single carbon dispenser, as to concentrate the action on the injectors as much as possible during the unstable phase.
Towards the end of the heat, dynamic regulation is applied also to the lime-dolomite injection to recover proper slag basicity and viscosity and thus to decrease the bath thermal losses.

2.4 New Chemical Package

The new EAF layout is shown in Fig. 4. It is composed of:

> 4 M-ONE combined oxygen and carbon injectors (to replace supersonic oxygen injectors and carbon lances);
> 2 Post-combustors.
> 1 Oxygen jet at the sump.
> 2 LIMEJET injectors for pneumatic conveying of lime and dolomite.
> 3 MOLI lime dispensers to dose and inject lime and dolomite into the EAF.

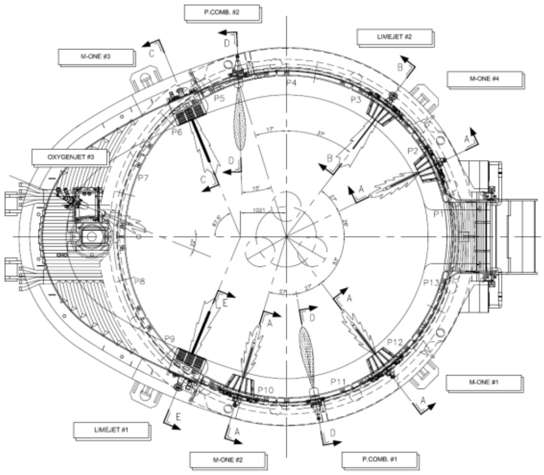

Figure 4. New EAF layout

Post-combustors are installed in the cold spots as well. They are designed to cooperate with M-ONE units, which can be considered as carbon monoxide generators. Post-combustors are designed to blow soft oxygen in order to perform the carbon monoxide combustion inside the furnace close to the bath and inside the scrap during melting based on the real-time off-gas analysis from Lindarc^{TM} that provides feedback for the Closed Loop Control (CLC).

The control is based on the evaluation of the Post Combustion Degree (PCD), defined as follows:

$$PCD = \frac{CO_2}{CO_2 + CO} \qquad (1)$$

The formula assesses the oxidation level at the furnace freeboard. The lower the PCD, the more extra-oxygen will be injected by post-combustor units. The higher the PCD, the lower the burners oxygen-natural gas ratio will be, with the lowest limit defined by the oxygen-natural gas ratio set in the burner profile.

2.5 Operational Results

The EAF commissioning in Kroman Celik was completed in 9 days only and the first heat was performed on March 9, 2017.

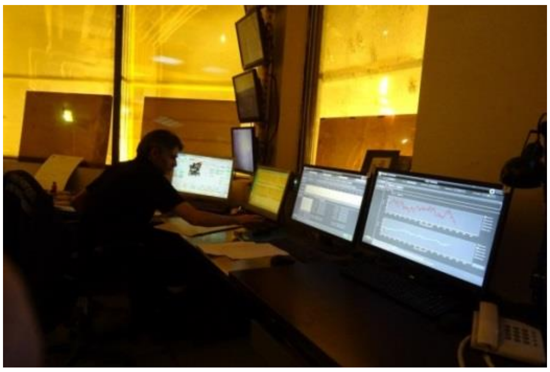

Figure 5. Control room with Q-MELT in operation.

The learning curve was very fast with a rapid ramp up of the productivity. The differences between the average EAF performances three months after starting up (1602 heats) and 6 months before the startup (2867 heats) are indicated in Table 2.

Table 2. Results achieved after 3 months from startup

		Δ
Power-on	min	-2.9
Tap-to-Tap	min	-2.7
Electric Energy	kWh/t	-20
Oxygen	Nm³/t	+2.6
Natural gas	Nm³/t	+0.7
Coal	kg/t	-1.0
Pig iron	%	-5
Lime	kg/t	-3.6
Dolomite	kg/t	-1.8
Electrode	kg/t	-0.30

The process fine-tuning continued during the following months of production and it allowed a more consolidated comparison in 2018. Table 3 shows the comparison between the results achieved in 2018 and 2016.

Table 3. Results achieved in 2018 compared to 2016

		Δ
Power-on	min	-2.6
Tap-to-Tap	min	-2.6
Electric Energy	kWh/t	-36
Oxygen	Nm³/t	+0.9
Natural gas	Nm³/t	+0.9
Coal injected	kg/t	-2.0
Pig iron	%	-0.4
Lime	kg/t	-1.1
Dolomite	kg/t	+3.6
Electrode	kg/t	-0.12
HMS 1	%	+3.9
HMS2	%	-7.7
SHREDDED	%	-1.1
DOMESTIC	%	+4.8
EAF slag generation	Kg/t	-3.2

Analyzing the results, it should be considered that changes in the scrap mix were minor: the increase of HMS 1 by 3.9% was compensated by an increase of domestic scrap by 4.8% that has historically been the lowest quality of scrap in Kroman Celik scrap mix, affecting negatively the EAF performances.

The electrode datum must be observed considering that over the months the electrode quality changed from prime to lower quality electrodes: the initial benefit of 0.3 kg/tls achieved during the first months was reduced to 0.12 kg/tls.

Coal consumption was decreased by 2 kg/tls, with a substantially unchanged content of pig iron in the charge.
Excluding the oxygen used during burner phase in stoichiometric ratios with fuel, the oxygen/carbon ratio increased from 1.51 Nm^3/kg to 1.66 Nm^3/kg; the steel oxidation was not affected owing to the following reasons:

- The extra oxygen was given mainly in the post-combustion phase during the bucket melting, with an average input of approx. 2 Nm^3/t.
- The carbon was reduced thanks to the more effective side-wall injectors and to the injection reduction in covered-arc conditions.
- The oxygen dynamic control during flat bath operation allowed to control the level of oxidation within the established limits.

The most remarkable result after 1 year of operation is the electrical energy reduction of 36 kWh/t. Owing to the many changes simultaneously applied to the process, it is difficult to attribute to each technological package the benefit/advantage achieved during the EAF revamping. Followingly, the main factors that contributed to improve the EAF performances are listed based on a qualitative point of view:

- Avoidance of bucket over-melting thanks to the arc coverage index that helped the operators understand the proper timing for the next bucket charging;
- Reduced overtemperature of the panels thanks to Q-ray trace: less energy losses on water-cooled panels.
- Improved arc stability due to Q-REG dynamic control of slag foaming;
- Different oxygen repartition: the oxygen used for burner and post-combustion phase was increased by 4 Nm^3/tls, decreasing by 3 Nm3/tls the oxygen used in lance phase;
- Decreased variability in slag chemistry both for FeO and slag basicity, as described below;
- Less human intervention during the refining period: the manual intervention on oxygen and carbon set points during refining (period) was eliminated;
- Increased efficiency from coal injectors due to the new chemical package employed;
- Increased efficiency of lime and dololime additions by means of side-wall injectors.

2.6 Effect Of Oxygen From Post Combustors

As mentioned above, the average input of oxygen for post-combustion is 2 Nm^3/tls.
The oxygen comes from post-combustors used during the first 50-55% of the melting of each of the 3 buckets.
It was decided to limit the maximum flow rate from each post-combustor to 750 Nm^3/h to avoid negative side effects on slag overoxidation or electrode oxidation.
The average PCD ratios recorded during the melting of the 3 buckets are the following:

Table 4. PCD ratios recorded in 3 bucket meltings

	Melting 1	**Melting 2**	**Melting 3**
	%	%	%
AVERAGE	48.9	44.9	38.9
ST.DEV.	9.0	8.9	6.8
% ST.DEV	18.4	19.9	17.4

The variability of the scrap and, consequently, of the CO generation, allowed to analyze the effect of the oxygen employed in post-combustion on electrical energy consumption. 1592 heats containing all the grades produced between August and November 2018 were analyzed.
As indicated in Figure 6, the trend shows an effect of 3.64 KWh/t of electrical saving per each 1 Nm^3 of oxygen used for post-combustion.

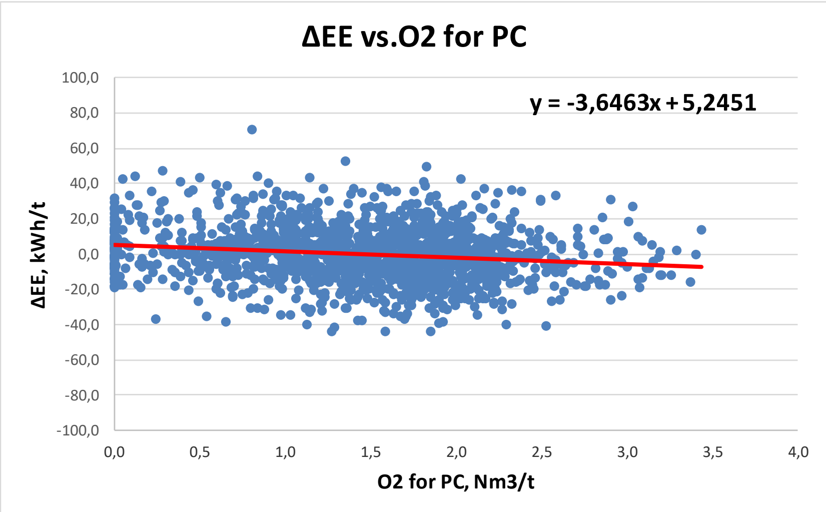

Figure 6. Effect of PC on electrical energy consumption.

In order to further investigate this aspect, the analysis focused on heats with the same steel grade (SAE 1008), and 2 series of data were compared in Table 5: the comparison among 112 heats with lower O2 inputs and 282 with higher oxygen inputs is shown.
In the first column the value differences are indicated, including the tapping conditions, coal input and, additionally,
in the second column the electrical energy savings are shown on the basis of the oxygen for lance and of the oxygen for post combustion.
Based on previous papers [3], we considered a substitution of electrical energy of 3.1 kWh/t every 1 Nm^3/t of O2 in lance phase.
Taking into consideration the extra tap to tap time, the resulting benefit of 1 Nm^3/t of oxygen for post-combustion is 4.1 kWh/t.

Table 5. SAE 1008 heats performance effects with higher chemical input.

		Δ	**Δ EE**
			kWh/t

Power-on	min	-0.5	
Power off	min	-1.3	+2.2
Electric Energy	kWh/t	-9.9	
Total Oxygen	Nm^3/t	+2.2	
Oxygen for lancing	Nm^3/t	**+1.2**	+3.6
Oxygen for post combustion	Nm^3/t	**+1.0**	**+4.1**
Injected/charged coal	Kg/t	=	
Tapping temp.	°C	+3	
O2 ppm	ppm	-27	

The analysis demonstrates how the energetic contribution of post-combustion can range between 3.6 and 4.1 kWh/Nm^3, but it highlights also that heats with more oxygen for post-combustion are those with higher oxygen utilization in lancing phase, indicating a more favorable charge quality in terms of C content and CO generation. This trend can be observed in Figure 7 as well: for every 1 Nm^3/t of oxygen for post-combustion, the overall oxygen utilization increases by 1.55 Nm^3/t.

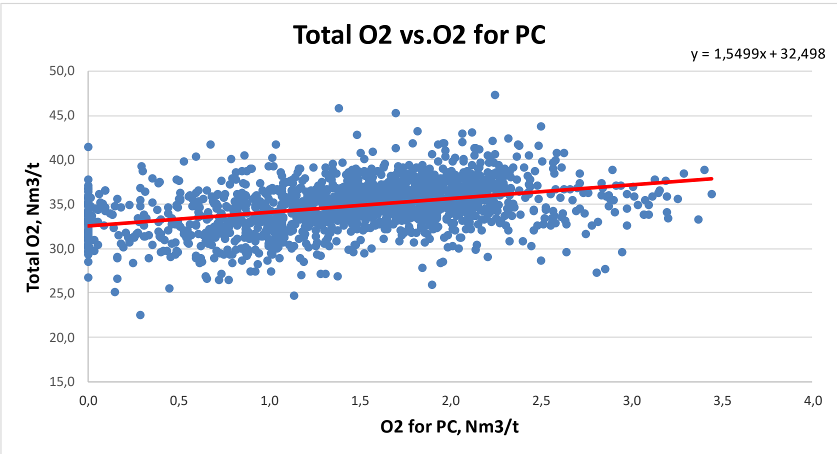

Figure 7. Effect of oxygen for PC on total oxygen consumption

2.7 Slag

Over the months that followed the startup, a major effort was made in order to further improve the slag chemistry, reducing its variability from heat to heat and controlling its chemistry.
Slag composition was analyzed comparing the percentage standard deviation of Fe_2O_3, MgO, CaO and IB_2 during 3 different periods:

> 2 months before Q-MELT
> 2 months after Q-MELT
> 1 year after Q-MELT

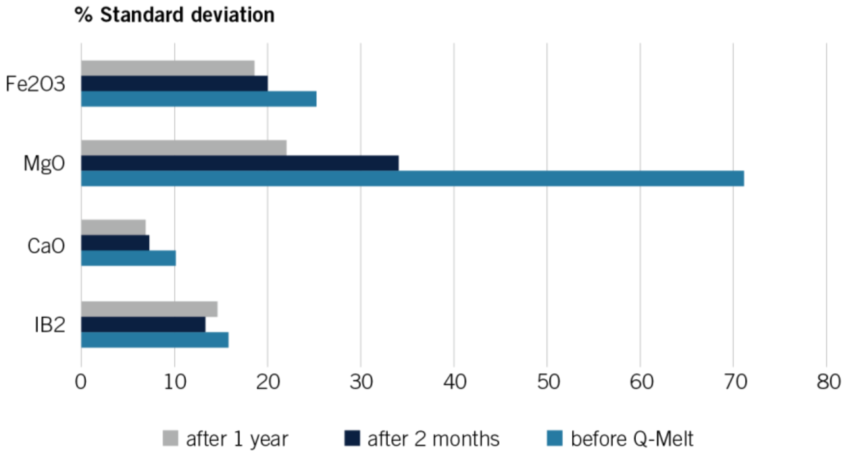

Figure 8. Percentage standard deviation during different periods of production.

The results are shown in Figure 8, where it can be observed that the percentage standard deviation of Fe_2O_3 was reduced by 26%, that of MgO by 69%, CaO by 32% and IB_2 by 7%.

The capacity of controlling oxidation during the refining period is due to the soft-landing logic: it dynamically adjusts the oxygen injection to reach the final carbon content and temperature without over-oxidizing the heat (Figure 9).

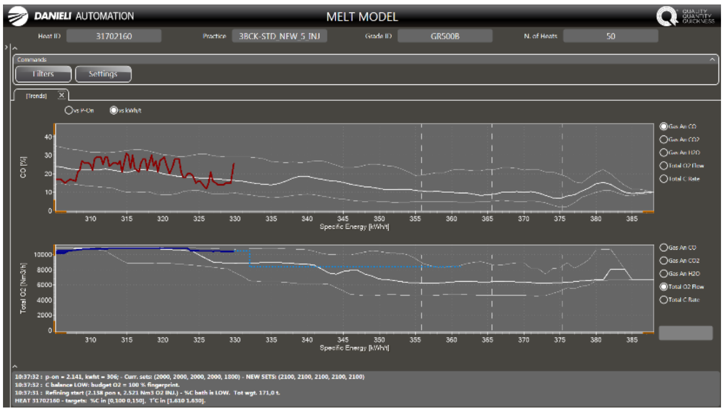

Figure 9. Soft landing control in action optimizing the decarburization profile in real time.

Tests were made with a double slag sample in order to verify not only the bath oxidation but also the evolution of the slag oxidation during the refining, as shown in Figure 10.

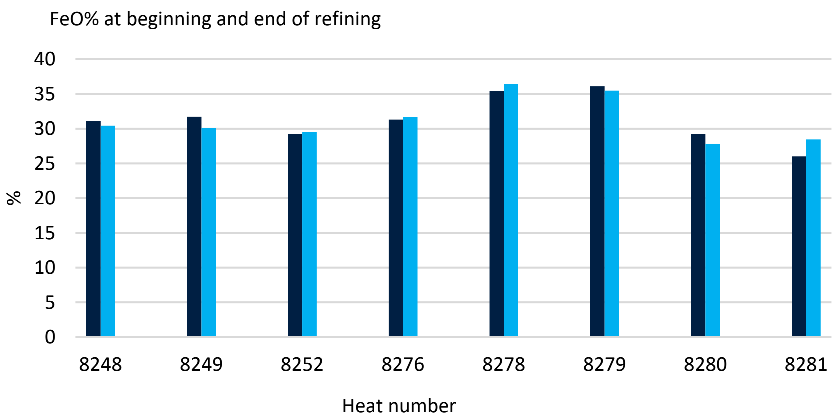

Figure 10. FeO content between the 1st and 2nd sample.

The samples were taken in a time frame that can vary from 6 to 7 minutes. The average result is a reduction of FeO by 0.05% even though both FeO increases and decreases were observed: most of the reductions are related to high opening FeO (32%), while the biggest increment is related to an opening FeO content of 26%.

In addition, from the analysis of the main melt shop parameters, as indicated in Table 3, the slag generation was reduced by 3.2 kg/tls. This datum in conjunction with the slag builder increase of 2.5 kg/tls with unchanged basicity index indicates that, as an overall result, the iron losses were reduced. A comparison between the period before and after Q-MELT demonstrate that the average FeO content in the slag does not show a clear improvement, but it is also shows that the chemistry indicated in this paper is usually measured at tapping condition and does not reflect the real average slag condition that, in the end, generates the iron losses.

The higher consistency and repeatability of the slag conditions benefited the refractory life. The shell campaign duration was extended by 17% with respect to the previous campaigns. This result was achieved in the first 3 months of operations after Q-MELT was further consolidated thanks to the improved control of the oxidation (steel and slag) during the refining stage and thanks to the reduced variability in the slag basicity. Eventually, after 1 year of operation, the refractory consumption was reduced by 26%.

2.8 Future Developments

In addition to soft landing logic, Kroman Celik and Danieli jointly decided to increase the frequency of slag sampling by means of X-Ray Fluorescence analyzer installed in the EAF pulpit.
The goals are the following:

> Analysis of the EAF Slag that can be carried out quickly in order to produce changes for the subsequent heat.
> Integration of the slag analysis in the Q-MELT to create the necessary database that will permit to reconstruct a “Fingerprint” of the slag characteristics.
> A new fingerprint that takes into account the slag composition (related with the type of steel / Charge mix) and that can improve the way the lime and dolo are

injected in the furnace, making the lime/dolo injection profiles dynamic or eventually making dynamic the amount of lime/dololime charged from the roof.
> In the end, the aim is to have an improved slag chemistry, with correct and improved basicity and viscosity.

A logic was developed and some initial trials are ongoing. The first results related to 38 heats gave positive feedbacks: owing to the modifyication of the lime added from the roof it was possible to improve the control of the IB_3 slag index.
After comparing the analyses carried out on heats before and after slag control, the result is that the standard deviation of IB_3 decreased by 26%.

3 CONCLUSIONS

Q-melt system fully demonstrated its capabilities to improve the performances of Kroman Celik EAF. The initial results achieved after the first months of installation were confirmed and improved during (year) 2018. The system showed how its adaptive characteristics changed dynamically the input process parameters according to the variability of the different parameters measured, such as charge mix, off-gas analysis, arc coverage index, etc.
The future improvement is identified in the management of a routine slag analysis that will allow to complete the information received from the sensors described in the present work.

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