BOF PROCESS OPTIMIZATION AND TECHNOLOGY IMPROVEMENTS – THE 5 MTPY PROJECT FOR TERNIUM BRAZIL*

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Abstract

Intensive process and technology improvements related to the BOF converter — the key process to increase steel plant productivity and stability — have been performed at Ternium Brazil. This paper details the road map for process developments and investments in equipment technology, as well as the results achieved. The main topics of this development are the process control and optimization systems, slag forming model, oxygen blowing pattern, end-of-blow point control and slag carryover control. The outcomes of this development are improvements in the reblow rate, end-of-blow oxidation, direct tapping, slag carryover, slopping ratio, metallic yield and lining life.

Keywords: BOF, LD Converter, steel plant, melt shop, dephosphorization, process optimization, slag dissolution, reblow rate, slag making, direct tapping, slag carry over, blowing pattern, addition pattern.

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1 INTRODUCTION

Ternium Brazil (BR) 5-mtpy steelmaking complex started up in 2010 from a Greenfield at Rio de Janeiro, Brazil. The Steel Making Plant (SMP), Figure 1, with an average heat size of 340 tons, is composed of two Hot Metal Desulfurization (HMD) plants, two Basic Oxygen Furnace (BOF-TBM) converter, two Ladle Treatment Stirring (LTS) stations, one Aluminum Heating Facility (AHF), two RH vacuum degassers and two Continuous Casting Machines (CCMs) with two strands of 14 segments each.

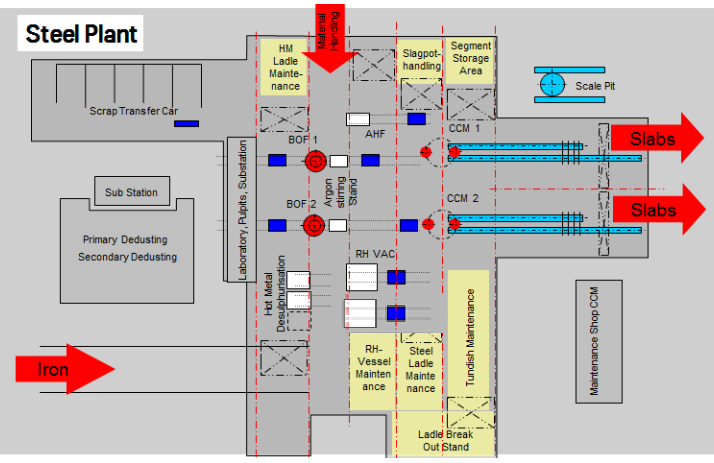


Figure 1 - Ternium Brazil Steel Plant layout.

Facing a significant challenge to accomplish the nominal capacity of production, a "5 mtpy project" has started in 2015 to define the short, medium and long-term strategy for the Steel Making Plant. A dynamic logistics simulation model (ARENA software) had been developed, evaluation of current plant status and sensitivity analysis was performed. Bottlenecks could be identified, new operational targets were unfolded looking for the short and medium term, and the board of the company defined capital investments for the long run.

This paper describes the road map to debottleneck the BOF process through a comprehensive technical understanding, considering the individual melt shop characteristics, resulting in improved process quality, control, and stability.

2 STEEL MAKING PROCESS BOTTLENECKS

Steel production process, in essence, involves the making, the shaping, and the moving of steel. When crane interference conditions are coupled with typical day-to-day disruptions caused by process variations, random equipment failures, and upstream and downstream disturbances, system robustness may not be sufficient for meeting plant expectations. Simulation is a powerful tool for ensuring that plant designs, upgrades and changes are capable of achieving targeted capacities and efficiencies. Unlike spreadsheet models or linear programs, a dynamic simulation model quantifies lost production capacity due to process upsets, logistical interferences, cycle time variations, random equipment failures, buffer constraints, asynchronous production, queuing, etc. The dynamic and constraint-based nature of the simulation analysis enables a realistic assessment of the type of production performance that can be expected, allowing the best operating strategies and plant configurations to be developed prior to actual operation or before changes to existing systems are implemented, and consequently improving global optimization of the production system [1].

The outcome of this simulation for the BOF process was a necessity to increase the availability through improvements in the BOF Charge-To-Tap (CTT) times in 8.0% and increase BOF lining performance by 33%, aiming to reduce one relining for both BOF a year.

After the definition to reduce the Charge-To-Tap (CTT) time by 8.0%, evaluation through all BOF process steps was necessary, according to Figure 2, the main topics to be evaluated was regarding to oxygen blowing phase and the time between the End-Of-Blow (EOB) and Tapping Start (TS). Reduction of tapping time by increasing the tapping hole diameter was not an option due to quality issues and the compromise between service times and frequency.

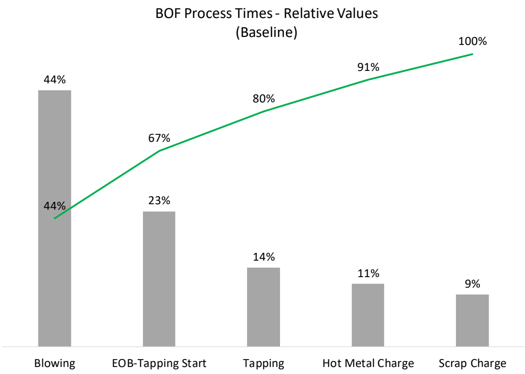
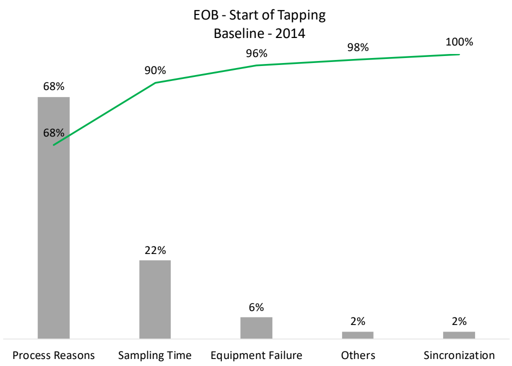


Figure 2 - BOF Process total times, relative values in percentage (%) of total CTT time.

Reduce the unexpected blowing interruption was an important aspect to improve the oxygen blowing average time, 7% of the heats were being interrupted due maintenance and operational reasons. An intensive investigation regarding blowing and material addition patterns was made necessary [(2)].

EOB-TS time delays were mainly related to process reasons, 68% of total delay times according to Figure 3.a. Looking inside the process delays, Figure 3.b, 76% were related to problems to achieve the target EOB phosphorus (P), 19% temperature (T) and 2% carbon (C). The focus for the first stage was to improvement the Dephosphorization (DeP) capacity to reduce the EOB-TS time, improve blowing end point was necessary to improve T and C problems. Nevertheless, an accurate end-point definition has also high connection to DeP. Reduction of 9.5% was the new target for the EOB-TS time.



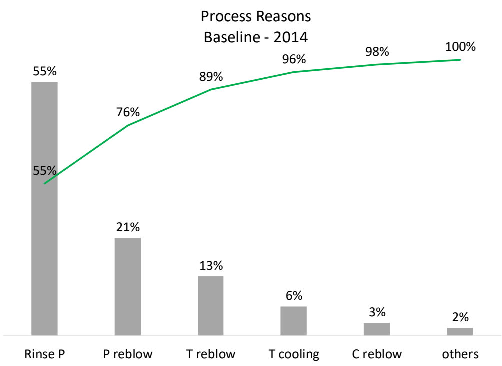


Figure 3 - a) Delays at EOB- Tapping Start (right side). **B)** Process Reasons only (left side).

Challenges for P removal from steel is coming from both sides at Ternium BR. According to Figure 4, phosphorus content in the hot metal supplied to the Steel Making Plant was increased by 10%. On the other hand, at the same time, steel products with higher

Phosphorus restrictions have been continuously required, which results in a more challenging operational condition.

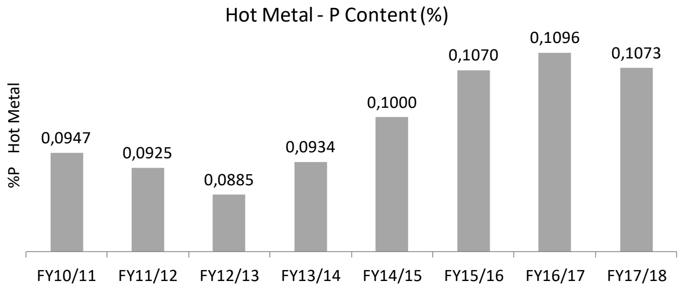


Figure 4 - Evolution of Hot Metal Phosphorus (%) at Ternium BR.

Another critical consideration is regarding the EOB aim temperature at Ternium BR. The plant is not equipped with Ladle Furnace, which means high BOF end-of-blow (EOB) temperature. The average EOB temperature is around 1685 ºC, many high-alloyed grades with P lower than 0.010% are tapped up to 1720°C, which brings a more difficulty DeP process for the BOF. According to Cappel, et al., 2015 (3), it is understandable that operations equipped with ladle furnaces have a competitive advantage compared to other plants.

3 DEPHOSPHORIZATION DEVELOPMENT

Dephosphorization reactions in BOF is a combination of dephosphorization capacity of slag defined as P-partition, slag volume, kinetics during oxygen blowing phase and post-stirring just after the end-of-blow phase.

P-partition (L_P), is the capacity to retain phosphorus in form of P_2O_5 stable in the slag phase in contact with the molten steel, see equation 1.

$$L_P = \frac{(\%P)}{[\%P]} \quad (1)$$

Phosphorus removal efficiency (%DeP), equation 2, is a multivariable problem involving the P-partition, slag mass and dephosphorization kinetics in BOF. This work in based on theoretical and empirical approach to achieve the maximum %DeP removal efficiency. The theoretical part involves the study of slag dissolution, slag saturation, blowing pattern optimization and the empirical approach involves the application of state of the art “machine learning” techniques for definition of optimal condition based on “learning from historical data” approach.

$$\%DeP = \left(\frac{[\%P_{initial}] - [\%P_{end\ blow}]}{[\%P_{initial}]}\right) \times 100 \quad (2)$$

3.1 Learning De-P From Historical Data

The target dephosphorization in the BOF process is defined by the difference of input phosphorus, coming from Hot Metal, and aim phosphorus output according to each steel grade quality. To achieve the maximum phosphorus removal %DeP efficiency, obtain a higher P-partition is necessary. Nevertheless, according to Figure 5-a, for a similar P-partition level it is possible to achieve different %DeP efficiency.

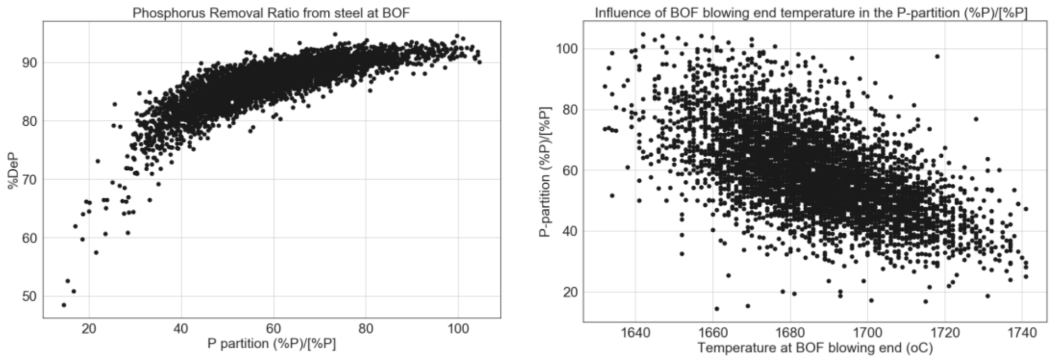


Figure 5 – a) De-P efficiency for different P-partition; **b)** Influence of Temperature in P-partition

According to Figure 5-b, P-partition is reduced approximately four times when the temperature rises from 1640 °C to 1740 °C.

Recent developments in machine learning are making its use for process engineering more feasible. Tree-based estimators and forest of trees can be used to compute feature importance. The relative rank of a feature (variable) used as a decision node in a tree can be used to assess the relative importance of that feature concerning the predictability of the target variable. Figure 6 exhibits the evaluation of feature importance through an extreme three regression model to estimate P-partition as a function of operational variables [4].

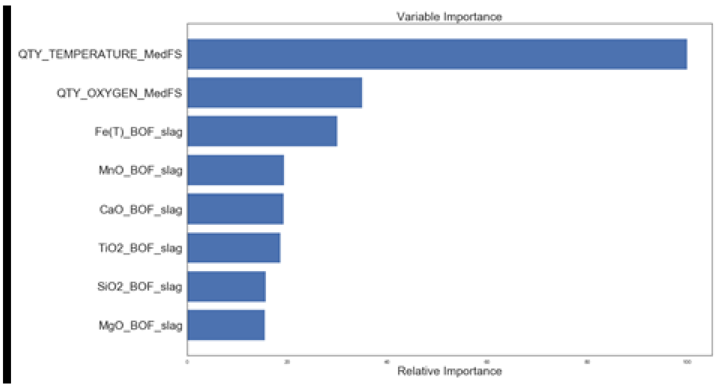


Figure 6 – Feature importance for P-partition based on an extreme three regression model.

Blowing end temperature is by far the most important feature regarding the P-partition, followed by the oxidation degree represented by $\%Fe_T$ in the slag and the electrochemical measurement of oxygen activity in the molten steel, in accordance with the various previous P-partition literature [5] [6] [7] [8] [9] [10] presented by Kumar & Chattopadhyay, 2014 [11]. CaO rate is also an important feature as expected in the theoretical approach. The present work focusses on the three main features in order to maximize the BOF dephosphorization process.

Maximize the efficiency of dephosphorization in a scenario of high end-of-blow temperature is certainly the main challenge in the BOF operations at Ternium Brazil, since the end of blow temperature is a process restriction calculated from the temperature losses in the teeming ladle from tapping to casting. The heating up at Ternium Brazil is performed by aluminothermy that must be minimized due the impact in the quality, cost and productivity of the Steel Making Plant (SMP). Phosphorus removal efficiency %DeP higher than 91.6% is required to produce steel grades with 0.010% of P at the end-of-blow if we consider as input a hot metal with 0.120 %P. To fulfill this challenge without reblow, in a single blowing operation, a precise BOF process engineering is necessary to optimize all variables involving slag chemical composition, slag mass, blowing pattern (top and bottom), addition pattern, precise blowing end definition, etc. Achieve phosphorus removal efficiency %DeP higher than 90% for temperatures above 1700 °C in a single blowing process is a considerable challenge according to historical data. (Figure 7-a).

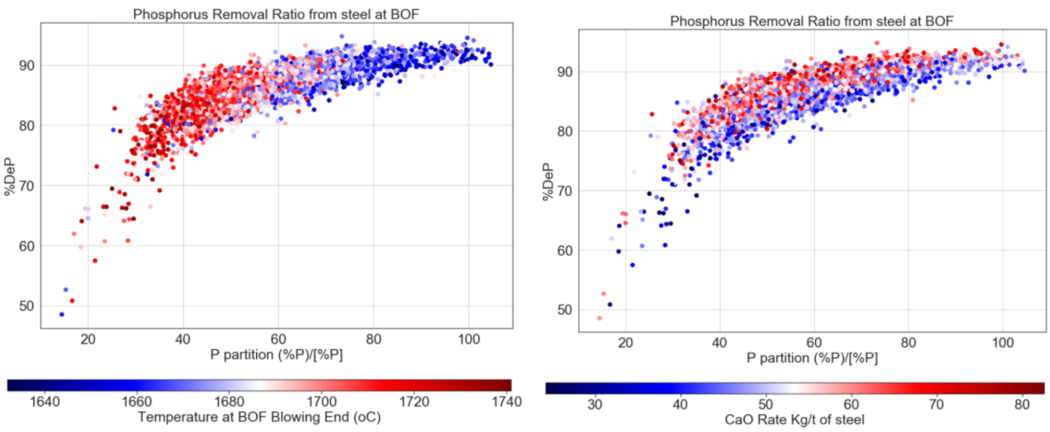


Figure 7 – De-P efficiency for different P-partition according to the influence of **a)** EOB temperature and **b)** CaO rate

Improved %DeP efficiency is achieved with higher CaO rate for slags with similar P-partition (Figure 7-b). To increase the CaO rate is necessary to consider the CaO saturation in the slag. Otherwise, slag viscosity becomes higher resulting in lower dephosphorization kinetics. Iron oxide (Fe_T) in slags works as a fluidizing substance allowing higher CaO dissolution rate and also increasing the dephosphorization efficiency due to higher oxygen activity in the slag phase.

Greater dephosphorization efficiency was achieved for higher iron oxide (Fe_T) contents in the slags (Figure 8-a). Nevertheless, higher oxidized slags have a negative impact on lining life and must be optimized in a range to keep the slag liquid at blowing end to maximize the dephosphorization efficiency. The control of iron oxide (Fe_T) content in the slag is a combination of blowing end definition, blowing pattern and bottom stirring efficiency. In the present work, the blowing end is controlled by off-gas analysis providing a good accuracy to control the iron oxide (Fe_T) in the slag for a specific blowing condition.

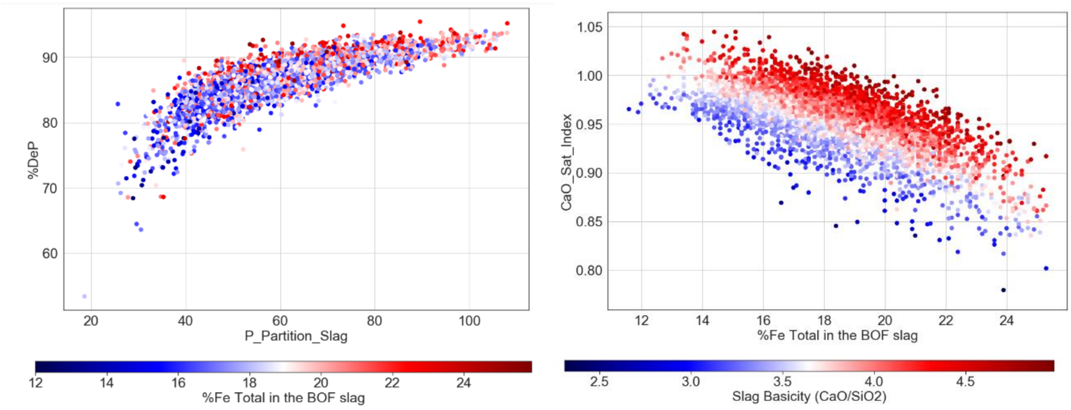


Figure 8 – a) Influence of iron oxide (Fe_T) content in %DeP efficiency for different P-partition and
b) Influence of iron oxide (Fe_T) content in the slag CaO saturation.

Since the Fe_T content in the slag must be limited in a restricted range to provide its dephosphorization benefits without damaging the refractory and reducing the BOF campaign, another key element is the adjustment of slag volume when the hot metal %Si content is low. Since the iron oxide (Fe_T) content in the slag is limited, CaO rate have also a limit related with the CaO saturation in the slag. The way the algorithm solves this problem is adding additional source of silicon to make possible to increase the CaO rate keeping the target slag closer to lime saturation. In other words, for a defined iron oxide (Fe_T) content in the slag there is a maximum slag basicity allowed to keep the slag below the saturation index at blowing end, see Figure 8-b. If basicity reaches the saturation index equals one, and the target %DeP efficiency was still not achieved, the addition of an external source of silicon is made necessary to compensate further addition of CaO to keep the saturation in its maximum value. The blowing end temperature is also considered in the slag forming model to adjust the saturation index proposed by Schürmann, et al, 1985 [12].

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According to Figure 9-a, at higher levels of MgO rate, the reactivity of the slag and DeP efficiency are reduced due to the precipitation of solid MgO, when it starts, viscosity increases with a negative impact on DeP efficiency due to reaction surface reduction between the metal and slag phase. Slags enhanced with MgO helps to increase slag viscosity and to improve their sticking and melting properties. At Ternium BR, BOF refractory wear control is performed through slags enriched with MgO by the addition of dolomitic lime over the main oxygen blow or raw-dolomitic lime for slag splashing correction.

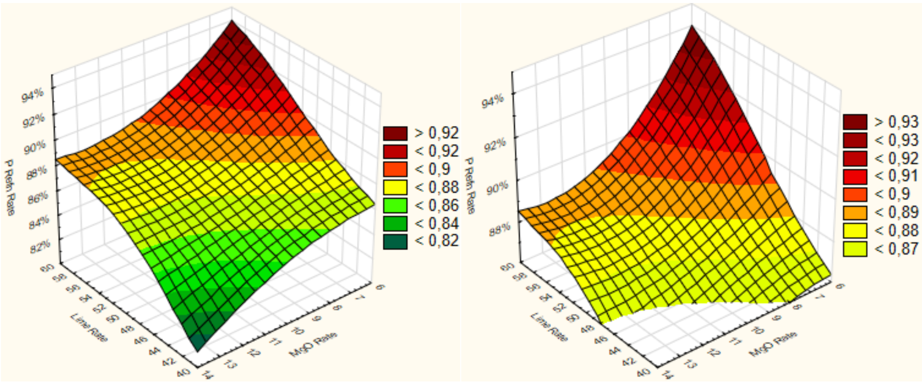

Figure 9 – De-P removal efficiency according to Lime and MgO rate.
a) De-P full range and **b)** De-P for higher removal efficiency.

Looking for the best compromise between refractory wear control and De-P efficiency, MgO content slightly higher than saturation needs to be the target. A dynamic MgO calculation based in a complex MgO saturation index proposed by Schürmann & Kolm, et al, 1986 [13], is also considered.

According to Cappel, et al., 2015 [3], the P_2O_5, is not stable at steelmaking temperatures and its activity must be reduced by liquid CaO. They also proposed to increase slag volume by the addition of lime and silica flux in cases that required dephosphorization slag volume is higher than the maximum slag volume at lime saturation. Other essential conclusions of this work were regarding the dephosphorization slag reaction control based in a kinetic phenomenon rather than a chemical one. They also mentioned that industrial processes are far away from the thermodynamic equilibrium and the individual BOF process characteristics is always an integral element of dephosphorization slag modeling.

Aiming a reliable understanding of these individual BOF characteristics, development of BOF additives dissolution model was done, and cold simulations have been developed to understand the mixing and blowing conditions better.

3.2 Additives Dissolution Model Development

A cyclic model for additives dissolution in the BOF process was developed at Ternium BR. Important mechanisms to describe additives dissolution were developed such as: oxidation mechanism for hot metal components, slag viscosity, and density calculation, turbulent mass transfer coefficient for solid particles in the BOF process connecting mixing energy input and diffusivity (an indirect way to check the lime reactivity). A complete mathematical description of CaO and MgO saturation in complex steelmaking slags dependent on slag temperature and composition (FeO-Fe_2O_3-CaO-SiO_2-P_2O_5-MgO-MnO-Al_2O_5) had been established as well [14].

Aiming to support a better BOF process control and assist an operational decision before changing some parameters, perform sensitivity analysis was possible to provide valuable information about dissolution evolution over the BOF oxygen blowing period that affects the refining reactions and also the slag physical properties. Critical operational parameters could be simulated to check their effects on slag formation; charged particle size, lime reactivity, blowing pattern strategy (top and bottom blowing stirring) as well as addition patterns philosophies. A typical curve of metal and slag chemical content evolutions over the main blow period are shown in Figure 10. These curves are the results of the simulation in each time step [14].

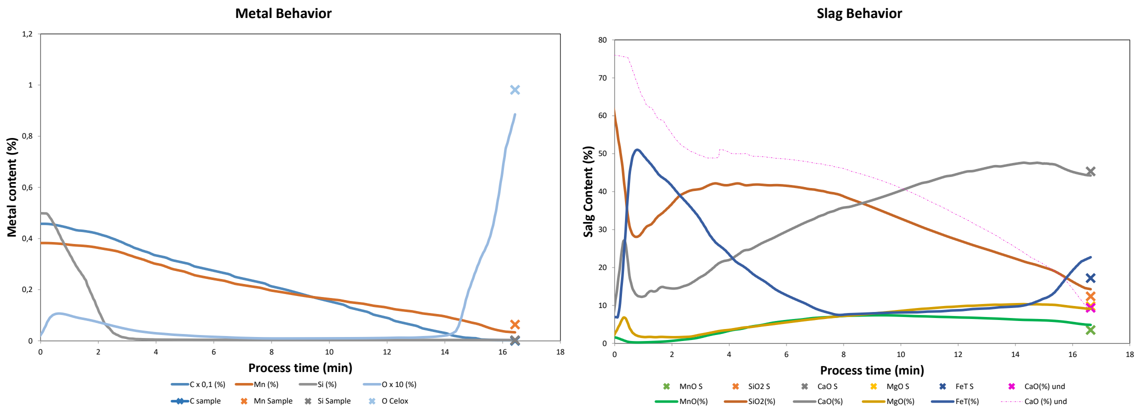

Figure 10 – a) Typical Metal and **b)** Slag behavior over BOF main blow process.

As shown in Figure 11-a, the increase in bottom gas flow rate gives a higher mass transfer rate over the main oxygen blowing process, resulting in lower undissolved additive quantities at the end of the process. Even at the beginning of the blow, high dissolved additives is already evident. Fast slag formation is necessary for a stable BOF process. Otherwise, the process becomes very unstable and costly, e.g., converter lining close to finishing the campaign and operating with low bottom stirring efficiency.

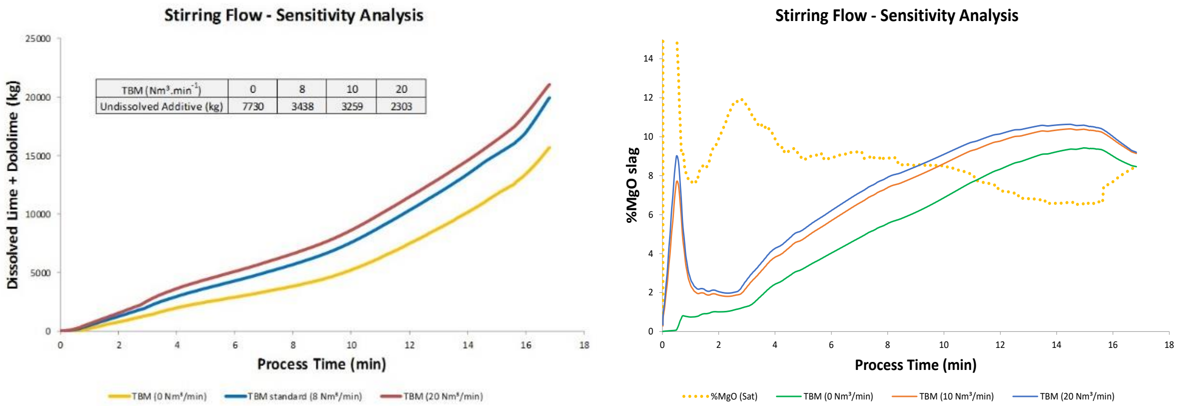

Figure 11 – a) Dissolved additives and **b)** calculated MgO sensitivity analysis over the BOF process by changing Bottom Blowing parameters.

At the beginning of the blow, even in the main decarburization period, MgO saturation is quite higher than actual MgO content calculated. At the end of the blow, when the bath temperature is rising very fast, diluted MgO of the slag must be higher than the MgO saturation level (Figure 11-b). An important point to observe is the MgO content more elevated than the calculated MgO saturation level, probably due to the precipitation of solid MgO.

This effect can be explained by the dolomitic lime dissolution mechanism proposed by Umakoshi, et al., 1984 [15], for lower FeO content (<20%) dissolution rate of dolomitic lime is controlled by dissolution of CaO through a boundary layer. On the other hand, MgO is the rate limiting when FeO content in the slag is higher than 20%. They also observed that $2CaO{\cdot}SiO_2$ film layer disappears under forced convection conditions and the formation of magnesiowustite is hardly affected by the intensity of stirring, which can be proven by Figure 11-b.

Development of blowing and addition patterns in the BOF process is a complex task for metallurgists. All operational issues, mechanical limitations as well metallurgical results should be evaluated to find a suitable result for the whole process. In order to support this decision, four different addition patterns were simulated according to Table 1.

Table 1 – Additives addition patterns proposal at the BOF process.

Addition Pattern Proposal	Trigger %O2 - Blowed	Lime % wt	Dolomitic Lime % wt
P0	1	90	90
	20	10	10
	-	-	-
P1	1	88	60
	12	12	25
	25	-	15
P2	1	60	60
	30	35	35
	85	5	5
P3	1	40	40
	30	30	30
	50	30	30

As a result of this simulation, additives dissolution in the slag is faster for earlier additions of lime and dolomitic lime over the main blowing period Figure 12-a. As shown, the BOF converter process has heterogeneous mixing characteristics. In the beginning, solid particles exist in a transient regime with regard to their particle sizes and velocities. As the particle size decreases, dissolution becomes faster in the turbulent regime.

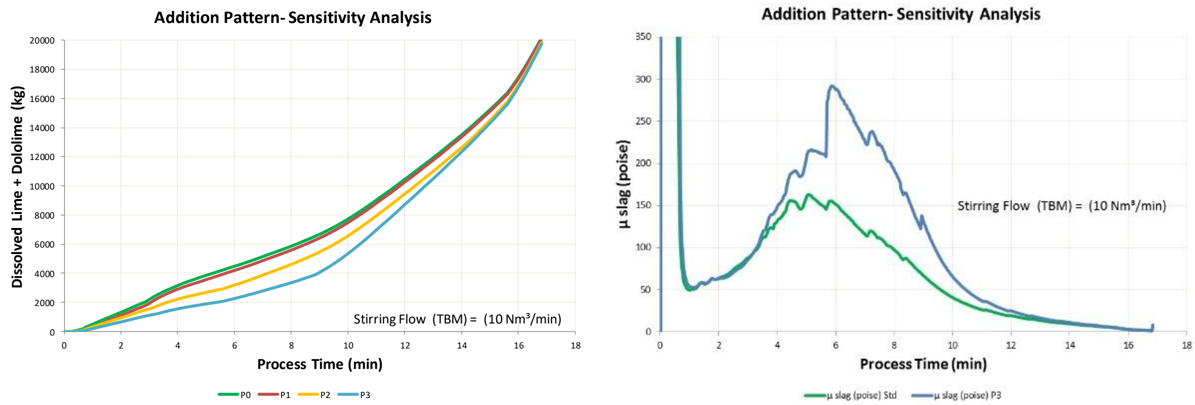

Figure 12 – a) Dissolved Lime and Dolomitic lime and **b)** undissolved CaO content through the process by changing particles diameter.

When the addition of additives occurs in the latter stages of the blowing process, the characteristics of slag fluidity changes (Figure 12-b) and impair the fast slag formation as well there is a low dolomitic lime dissolution rate (Figure 12-a). This later addition would contribute to an unsuitable slag for BOF process and may contribute to slag attack on refractory lining and an inappropriate De-P process.

Based in these simulations, raw materials specification was improved, new blowing strategies were defined looking for each step of the oxygen blowing phase, special attention in the slag forming phase (early stage of the blow), which iron (Fe_T) and silica (SiO_2) contents of the slag are quite high (Figure 10-b), resulting in a very fast dissolution.

The raw material handling system for each BOF contains ten daily silos for blowing additions, material batches are loaded in six weighing bunkers, material prepared in a weighing bunker is then charged via vibrating feeder directly into the BOF. Vibrating feeders have their adjustable feeding rate controlled by a programmable logic controller (16). The existing raw materials handling system was optimized, management of available raw materials for every ten daily silos was necessary, charging of additive materials through weighing bunkers were prioritized to accomplish an enhanced additives addition just after the blowing start.

4 OTHER DEVELOPMENTS

4.1 Blowing Pattern Development

In order to evaluate the bath homogenization and mass transfer coefficients, a cold physical model in similarity with Ternium Brasil's 340-ton converter was developed at LaSiP in the frames of technical cooperation project between UFMG University and Ternium BR [17].

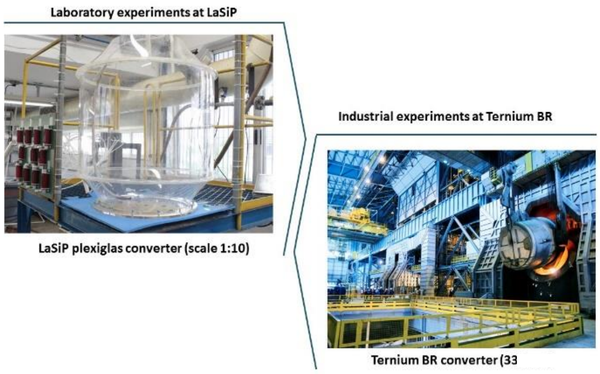

Figure 13 – Cold physical model in similarity with Ternium Brasil's 340 t developed at LaSiP.

Significant results could be transposed to industrial practices. Lance flowrate is predominant in determining the bath homogenization compared to the other parameters. For a higher lance flowrate, jet reaches a longer range along the acrylic, which allows a clash between the jet and the bubble lance from the external radius, causing a reduction in the size of the decarburization area and penetration. Superior lance flowrates are responsible for a higher mass movement, which favors the kinetics of the reactions. Larger values of the mass transfer coefficients correspond to the experiments with the largest decarburization area, which validates the theory that larger impacted areas allow the higher occurrence of chemical reactions [18].

It was also possible to check different bottom blowing patterns and configurations, this simulations indicates good metallurgical results using minimum flow rate for specific periods [19], which may reduce the operational costs through inert gas consumption savings and consequently, the lining wear.

A concept of oxygen lance "stepless" was developed looking to optimize the slag forming phase, regular lance height steps used for slag phase were changed by a sloping, inclination is defined according to the content of Si in Hot Metal, resulting in a very smoothly lance movement and slag formation as well [16].

Plenty of the blowing interruption due to operational reasons was related to strong slopping and uncontrolled high pressure on the primary dedusting system was related to high rate of iron ore pellet additions (up to 10% of total metallic charge). A concept of single blowing pattern for the main decarburization period was defined looking for the control stability, constant oxygen flowrate of 90% comparing to former blowing pattern design was defined, this set point of oxygen flow is not changed even while the iron ore pellets is added. Iron ore additions is done constant until 70% of the oxygen blow, despite the low/high quantity of iron ore. The average blowing time did not change considerable even with the oxygen flowrate reduction through the lance. Actually, the global input of oxygen increased if compared to former lance flow rate [(2)].

4.2 Blowing Endpoint Improvements

An accurate blowing end detection is a key factor for controlling the bath oxidation level and the blowing end temperature. Ternium Brazil is equipped with automatic blowing end based on off-gas online analysis. The improvements at blowing end detection was performed in four aspects:

1. Improve the accuracy of off-gas analysis system by increasing the frequency of filter maintenance, calibration and inspection;
2. Simplification of blowing end carbon by focusing on bath oxidation for a predefined slag to achieve the target DeP efficiency;
3. Increasing the data acquisition ratio by improvements of network design;
4. Simplification of blowing pattern and off-gas system after main decarburization period;
5. Improvements regarding Hot Metal ladle thermal losses (20).

4.3 Direct Tapping Model:

Industrial process data were used to train three artificial neural network regression models for phosphorus predication at BOF blowing end. Data from two complete lining campaigns were used to capture the short and long-term influences related to DeP process. The three ANN (Artificial Neural Networks) models have been trained using the available operational data at different moments after blowing end. The first ANN is trained with heat data available just after the blowing end event, the second uses additionally the oxygen activity measured by the electrochemical cell, and the third uses the inblow chemical analysis result. The decision-making algorithm is designed to maximize the direct tapping practice taking into consideration the associated risks. Normally the tapping is authorized when the risk of out of range is smaller than 1% [(21)] .

4.4 Steelmaking plant process integration, maintenance improvements and investments.

Other significant development to support the phosphorus issue was regarding to reduce slag carry over on BOF tapping phase. Investment in a new and reliable slag detection system was made, due to the higher confidence in this new system, the existing slag stopper could start to use the signal to abort the steel tapping and tilt the BOF automatically (22). In other words, it means lower phosphorus pick-up after tapping.
Important developments regarding the lining wear was performed by the Refractory Team, main actions were focused on; brick quality adjustments for lower cone region, where there was an excess of wear below the trunnions. Brick quality improvements in the area of tapping cylinder. Adjustment of upper cone panel size. Better sealing between the bottom and lower cone. Slag splashing practice start-up and commissioning was in 2014.

Regarding oxygen blowing lance, in early 2016 an investment in a device for mechanical lance skull cleaning was made. In parallel, the development of Slagless® technology has been performed. This mechanical cleaning device has high effectiveness to clean the higher side of the oxygen lance and Slagless® technology performs better on the lower side of the oxygen lance. When both technologies were associated, the necessity to remove the oxygen lance for skull cleaning is minimum. Continuous improvements in the "Laval" calculation have been performed (23).

Significant process improvements and investments took place to debottlenecking upstream and downstream facilities. The main essential points are; the best practices to optimize set-up times at hot metal desulphurization plant, secondary facilities, and CCM. Steel plant thermal balance optimization (24), best practices in teeming ladle cycle and downstream cranes, investments to increase the hot metal buffer between Blast Furnace and Steel Plant, investment in wire feed injection on RH plant and later start-up of new RH plant (25), investment in two extra segments for CCM.

Last but not least there are significant equipment reliability engineering developments to be mentioned on the maintenance side; Improvements on the boiler and dedusting system, through application of Inconel alloys (well suited for service in extreme environments subjected to pressure and heat) over the internal system exposed to high wearing conditions, implementation of frequency inverters for the pumps system. Investment in maintenance technologies to keep high availability of liquid metal cranes and converter tilting system (bearings monitored through SPM – Schock Pulse Method) as well as the implementation of maintenance best practices.

5 MAIN ACTIONS

The road map for process developments and investments in equipment technology to achieve the operational targets is according with Figure 4.

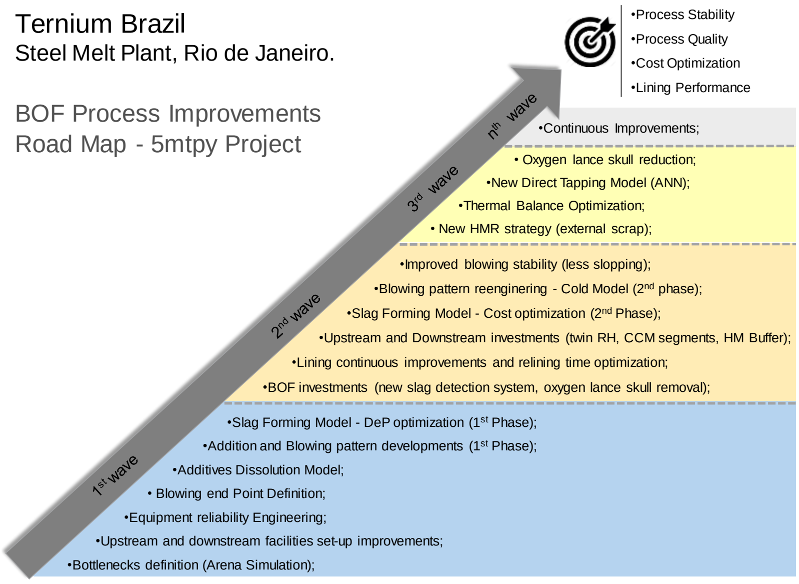

Figure 14 – Road Map: BOF Process Optimization and Technology Improvements at Ternium Brazil.

6 RESULTS

Intensive process and technology improvements related to the BOF converter have been performed over the last years at Ternium Brazil Steel Plant. Significant results related to process quality and process stability associated with costs savings and improved productivity have been successfully done.

6.1 Metallurgical Results

A new slag forming model was implemented, higher metallurgical process quality associated with significant costs savings was performed, main results was a significant 40% reduction of global reblow rate (Figure 15.a). Phosphorus reblow rate was reduced by 55% (Figure 15.b); this result was associated with intense slag forming costs savings (34%), Figure 16.

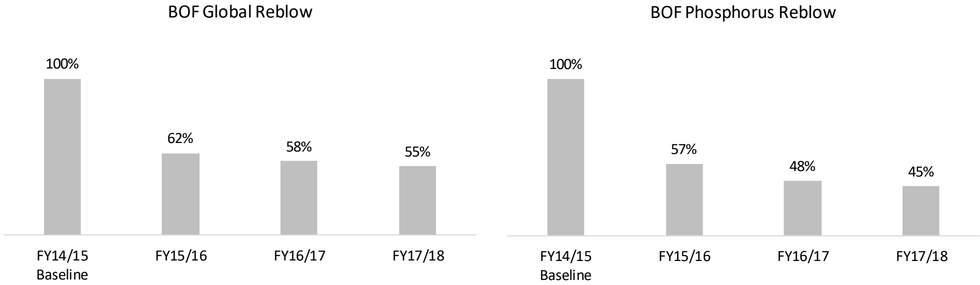

Figure 15 – a) BOF global reblow rate and **b)** BOF reblow rate due P reason (values related to baseline).

It is important to observe two different steps of phosphorus reblow rate in Figure 15-b; the first stage of improvements (FY15/16) can be associated to the implementation of new slag forming philosophy and end of blow definition point optimization. In the second stage of improvements (FY16/17), a newer version of slag forming philosophy focused on costs savings was implemented in 2016, Figure 16. Therefore, the second stage of reblow reduction may suggest a better strategy for addition and blowing patterns, which is connected with the actions to reduce the slopping ratio (Figure 19-a) as well.

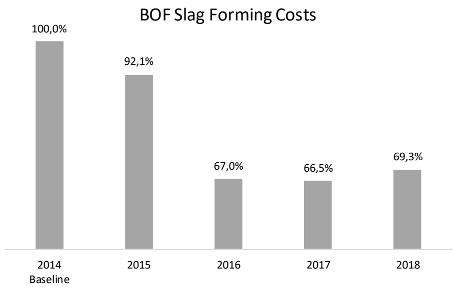

Figure 16 – BOF slag forming costs at Ternium BR (values related to baseline).

According to a novel study, regarding blowing patterns strategy and their results on dephosphorization process. A better dephosphorization degree was observed for a blowing pattern with constant oxygen flow rate (26), which is in accordance to one of the action to reduce the slopping ratio.

The new slag detection system commissioning brings more reliability to reduce the slag carry over on BOF tapping phase; best practices were also implemented. In average, the phosphorus pick-up was reduced by 30% for a specific grade, Figure 17-a. Another significant benefit to be considered is regarding the reduction in 85% of heats out of range due to slag carryover reason, Figure 17-b.

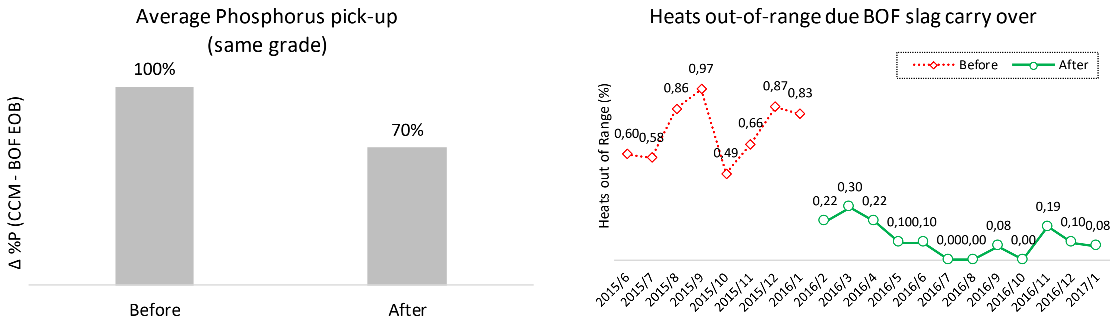

Figure 17 – a) Average P pick-up for a specific grade and **b)** Heats out of range due BOF slag carry over reasons before and after the new slag detection system *(22)*.

The reblow reduction was associated with improvements in key metallurgical parameters for the BOF process. Despite the reblow rate reduction, slag oxidation levels were also reduced. A significant reduction in slag iron oxide (Fe_T) was performed (Figure 18-a) as well as a greater Mn yield rate (Figure 18), at Ternium BR there is no practice to add Mn based materials in the BOF process.

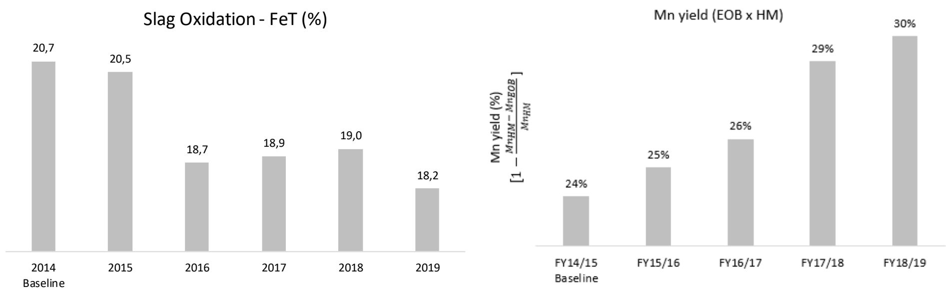

Figure 18 - a) Slag oxidation (%Fe_T) and **b)** Manganese (Mn) yield rate at the end-of-blow.

Improvements on these parameters are responsible for enhancing the steel plant metallic yield, alloying savings, and delivery better conditions for upgrading BOF lining performance. A direct benefit of slag Fe_T to be estimated is regarding the contribution to increase the production: in one year of production, this better metallic yield is responsible to delivery almost one day of extra production.

Slopping rate is a relevant indicator to verify the overall BOF process quality and stability, a reduction of 80% (Figure 19-a) was observed even for challenging additions of iron ore pellets (2).

Other important point to support a better process stability is the reduction of oxygen lance exchange for skull cleaning service (Figure 19-b), a result of a single lance running for up to 300 heats was faced. This lower necessity to change oxygen lance had a positive effect on the BOF process; changes in the blowing process are soft and indistinguishable, which brings more stability for process modeling.

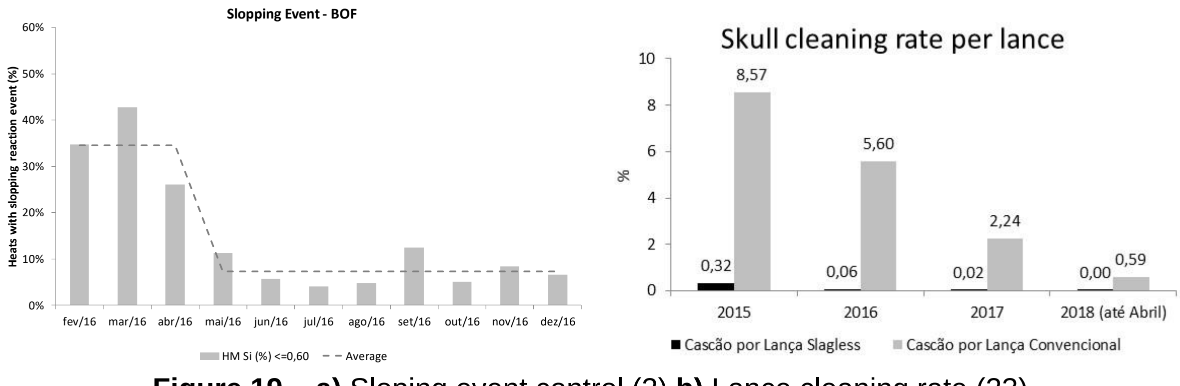

Figure 19 – a) Sloping event control (2) **b)** Lance cleaning rate (23).

6.2 Linning Results

The challenging target to improve BOF lining performance was accomplished, lining life was improved up to 50% (Figure 20-a). This result is a combination of all efforts; better metallurgical results, lower EOB-TS times, refractory engineering optimization, slag splashing technology investment in 2014 and all operational best practices.

Another significant result was the reduction of %MgO content in slag by 18%, Figure 20-b. Despite the MgO content reduction, lining performance was improved by 50%, and it is a piece of genuine evidence about the better slag balance and process stability.

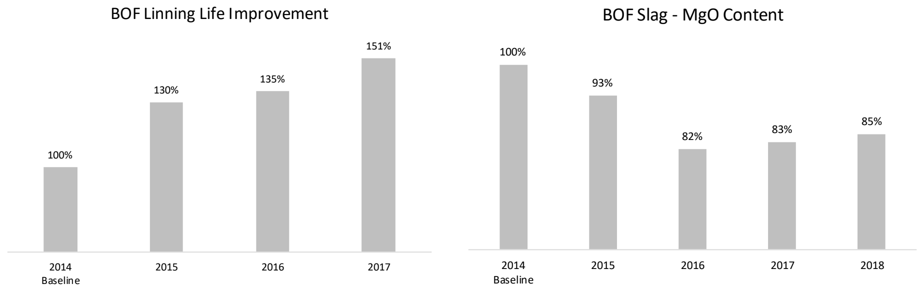

Figure 20 – a) BOF lining performance **b)** MgO content reduction (according to baseline)

It is also important to remark that MgO in excess does not help the dephosphorization process and may bring process instabilities, and this process instability contributes to worst lining performance. Therefore, the advantages of slags enriched with MgO to control lining wear is achieved when there is a good compromise between target MgO and process stability.

6.3 Productivity

As expected, improved process optimization, quality and control become the BOF process more reliable. Charge to tap times (CTT) could be reduced by 5.5% (Figure 22-a). Nevertheless, after the introduction of external scrap in 2017, new challenges have been faced to achieve the target CTT reduction (eg.: delays between scrap charge and blowing start times, tramp elements control, new challenges for stable blowing process). On the other hand, a stable reduction of 10% in the EOB/TS times have been achieved (Figure 22-b).

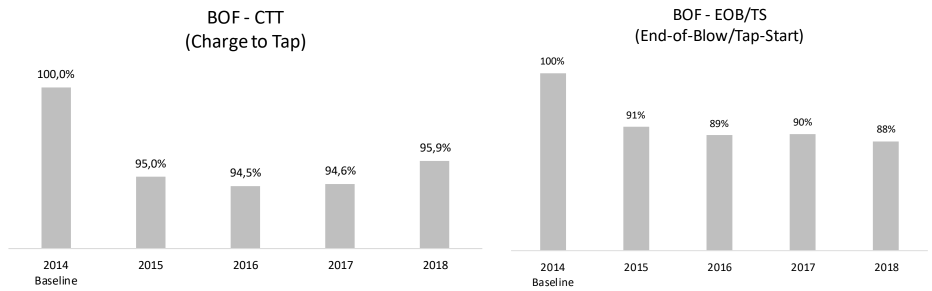

Figure 22 – a) Charge-to-tap performance and **b)** EOB/TS time improvements according to baseline.

As an outgrowth of enhanced BOF lining performance, a reduction of two relining per year was reached, Figure 23, improvement of 40% compared to baseline, and it means one relining less per BOF, in other words, approximately ten days of extra production for each BOF. Reduction of relining days by 20% due to an investment in a new relining machine is expected, commissioning planned for 2019.

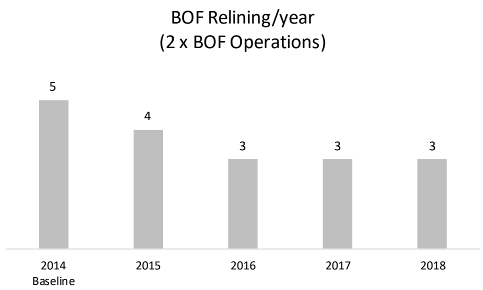

Figure 23 – BOF relining per year (according to baseline).

Higher process stability and quality have been the main drive for BOF improved productivity, maximum daily production have been increased year by year. Comparing the baseline (2014) and last year (2018), the maximum number of heats tapped in one single day was increased from 46 to 51 heats (Figure 24-a), which represents an enhancement of 11%. In a single vessel operation the maximum number of heats was increased from 39 to 43 heats (10%), Figure 24-a.

Total of 17.4 kt molten steel tapped in one single day was achieved for two-vessel operation mode. Nevertheless, for one-vessel operation mode, when upstream and downstream facilities are not a bottleneck, and lack of hot metal is not a problem, 14.6 kt molten steel tapped in one day is observed (e.g., relining and maintenance days).

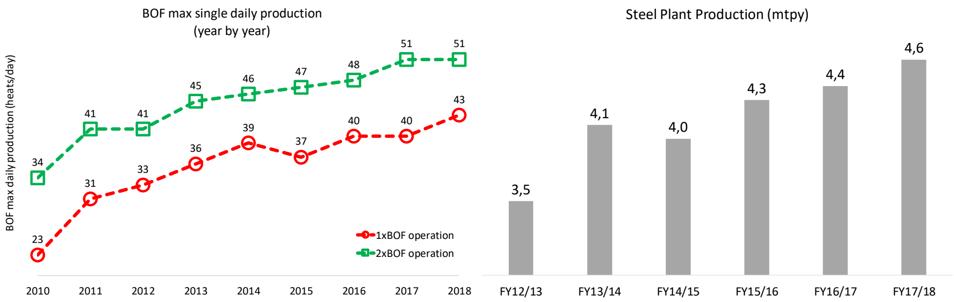

Figure 24 – a) Charge-to-tap performance, b) according to baseline.

Steel Making Plant (SMP) production has been increased year by year, comparing the baseline (FY14/15) and last fiscal year, production increased from 4.0 to 4.6 mtpy, Figure 24-b. Nominal output of 5.0 mtpy is planned to start in 2021, and investments have been made to debottleneck either SMP or other facilities over the site.

7 CONCLUSIONS

Higher process efficiency considering the individual Steel Making Plant (SMP) characteristics has been performed. BOF process complexity was reduced through a comprehensive metallurgical technical understanding and process integration; the process becomes more stable and reliable with lower deviations.

Top management promoted the innovation of process engineering philosophy through the development of "out of the box" engineering thinking involving shopping floor team in many steps, the effect was many paradigm shifts.

Definition of the short, medium, and long term targets for the plant was essential to keep the interdisciplinary and multicultural teams working integrated to develop sustainable solutions without abruptly changes in the main scope.

The challenge to tap more heats with higher added value steel associated to lower costs and production time, respecting people safety in harmony with the environment have been fulfilled, and it should be a continuous challenge to keep sustainable operations.

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REFERENCES

1. J. McGinty, C. G. (2007). Use of Dynamic Computer Simulation for Optimal Melt Shop Logistics. *AISTech Conference Proceedings* (pp. PR-351-254). Indianapolis, Ind.,: AIST.
2. Carvalho, D., Viana, M., Castro, H., Demuner, L., Formage, R., & Wojnar, P. (2018, April). BOF Blowing Process Chalenges for High Iron Ore Pellet Addition - Process Development and Results at Ternium Brazil. *Iron & Steel Technology, 15*(4), 44-49. doi:ISSN 1547-0423.
3. Cappel, J., Urban, W., & Weinberg, M. (2015, April). Dephosphorization Strategies and Modeling in Oxygen Steelmaking. *Iron & Steel Technology, 12*(4), 91-102. doi:ISSN 1547-0423.
4. Pedregosa, F. e. (2011). Scikit-learn: Machine learning in Python. *Journal of machine learning research*, 2825-2830.
5. Healy, G. W. (Jul. de 1970). A new look at phosphorus distribution. *Journal of The Iron and Steel*, pp. 664-668.
6. Bannenberg, N., & Lachmund, H. (Jul./Aug. de 1994). Metallurgical procedures for achieve very low. *La Revue de Metallurge, CIT*.
7. Suito, H., & Inoue, R. (1995). Thermodynamic assessment of hot metal and steel. *ISIJ International, 35*, pp. 258-265.
8. R. Nagabayashi, M. H.-Y. (1989). Mathematical expression of phosphorus distribution in steelmaking process by quadratic formalism. *ISIJ International, 29*(2), pp. 140-147.
9. H, S., & R, I. (2006). Phosphorous partition between 2 CaO.SiO2 particles and CaO.SiO2.FetO slags. *ISIJ International, 46*(2), p. 174-179.
10. Slag Atlas. (1995). Em M. Allibert, H. Gaye, J. Geiseler, a. et, & V. D. (VDEh) (Ed.). Düsseldorf, Germany: Verlag Stahleisen GmbH.
11. Kumar, S., & Chattopadhyay, K. (April de 2014). Application of Thermodynamic Analysis for Developing Strategies to Improve BOF Steelmaking Process Capability. *Iron & Steel Technology*, 170-179.
12. Schürmann, E., Schmöle, P., & Kolm, I. (1985). Verlauf der Kalksättigung im System FeO-Fe2O3-CaO-SiO2-P2O5-MgO-MnO beim Gleichgewicht mit einer Eisenschmelze. *Steel Research*.
13. Schürmann, E., & Kolm, I. (1986). Mathematical Description of MgO saturation in complex steelmaking slags. *Steel Research, 1*.
14. Carvalho, D. (2015). *Additives Dissolution Model in the BOF Converter Process.* Volta Redonda: Dissertation (Master Dissertation in Metallurgy) - UFF/MUL. doi:CDD 620.11.
15. Umakoshi, M., Mori, K., & Kawai, Y. (1984). *Trans. Iron Steel Inst. Jpn., 24*, p. 532.
16. Carvalho, D., Schulz, D. T., Wojnar, P., Demuner, L., Viana, M., Maia, B., & Formage, R. (June-2017). BOF blowing process development and results at TKCSA. *European Steel*

Technology and Application Days – ESTAD, *June*, pp. 1129-1137. Vienna, Austria. doi:ISBN: 978-3-200-05196-6

17. Parreiras, T., Maia, B., Carvalho, D., Reis, W., Rocha, R., Diniz, C., & Salgado, R. (Jun. de 2017). Aplication of the similarity method for cold modeling a 330t BOF converter in Laboratory. *European Steel Technology and Application Days - ESTAD*, pp. 1109-1119. doi:ISBN: 978-3-200-05196-6
18. Carvalho, D., Tavares, P., Breno, M., Diniz, C., Salgado, R., Souza, D., & Guimaraes, J. A. (April de 2018). TBM Tuyeres Arrangements and Flow – Comparison Between BOF Ternium Brasil and Cold Model. *Iron & Steel Technology*, 50-57. doi:ISSN 1547-0423
19. Carvalho, D., Tavares, P., Maia, B., Schenk, J., Salgado, R., Ribeiro, M., & Silveira, D. (2018). Evaluation of mixing and mass transfer at Ternium Brazil's BOF through cold model experiments. *IAS Steel Conference. 22nd*, pp. 1-9. Rosario, Santa Fe, Argentina: IAS.
20. Guimaraes, J. A., Viana, M., Carvalho, D., Silveira, D., Demuner, L., & Diniz, C. (2018). Thermal Losses Model At Ternium Brasil Hot Metal Ladle. *AISTech Conference Proceedings. PR-374-104*, pp. 1-9. Philadelphia, Pa., USA: AIST.
21. Viana, M., & Arruda, R. (2018). Direct Tapping Model Based on Artificial Neural Network. *AISTech Conference Proceedings* (pp. 374-313). Philadelphia, PA. USA: AIST.
22. Cerchiari, B., Klinger, L., Cruz, F., & Piller, F. (2018). Improvement in Tapping Process to avoid Slag Carry-Over. *49.* Sao Paulo, Brazil: ABM. doi:10.5151/1982-9345-31722.
23. Neves, P. R., Carvalho, D., Formage, R., Maia, B., Garajau, F., Guerra, M., & Lima, W. (October-2018). Development of lance blow performance through Slagless® technology. *ABM Week, 49*(49), pp. p. 565-576. doi:ISSN: 2594-5300 , DOI 10.5151/1982-9345-31806.
24. Junior, M., Silva, C., & Alves, I. (oct.-dec de 2018). Hybrid model associating thermodynamic calculations and artificial neural network in order to predict molten steel temperature evolution from blowing end of a BOF for secondary metallurgy. *REM - International Engineering Journal, 2*(71), pp. 587-592.
25. Gomes, H., Pezza , A., Lopes, B., & Demuner, L. (Jul de 2018). Neue RH-Anlage bei Ternium in Brasilien - ein Schritt in Richtung Industrie 4.0. *Stahl und eisen*, 1-9. doi:ISSN 0240-4803.
26. Mombelli, D., Mapelli, C., Barella, S., Gruttadauria, A., Sosio, R., Valentino, G., & Ancona, V. (2018). Model for Phosphorus Removal in LD Converter and Design of a Valuable Operative Practice. *steel research int*, pp. 1-8. doi:10.1002/srin.201700467.