Study of a New Operating Practice for Refining High Silicon Hot Metal in a BOF Converter

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1. Introduction

In the European Union, the total quantity of hot metal produced through blast furnaces amounts to 95.1 Mt.[1] Several steps characterize the production process: the hot metal is first produced in a blast furnace and then transported to the plant's steel mill using thermally insulated torpedo cars; after the hot metal is converted into steel in a Basic Oxygen Furnace (BOF), it is then treated or directly cast.

The present study is focused on a steel mill composed of a hot metal pouring station, a desulfurization station, three converters with a capacity greater than 250 t, and continuous casting machines.

New environmental requirements have spurred the development of new techniques that reduce the converter's emissions. The most significant and troublesome emissive phenomenon that may occur during the conversion of hot metal into steel is slopping, which is mainly caused by the hot metal containing a high concentration of silicon.

A high silicon concentration in the blast furnace hot metal is mostly caused by the iron ore quality: iron ore richer in silicon leads to a higher concentration of this element in the produced hot metal. Coke ashes, which are composed of more than 50% silica (SiO_2), are another source of silicon.[2]

The mechanisms used to reduce silica within a blast furnace are as follows:[3,4]

A reduction of silica in primary slag, above the tuyeres area, by the following reaction:

$$(SiO_2) + 2C_{coke} \rightarrow [Si] + 2CO$$

A reduction of silicon oxide SiO, which originates from the coke combustion at high temperatures:

$$(SiO_2)_{ash} + C_{coke} = \{SiO\} + \{CO\}$$

A reduction of slag silica due to metal–slag interactions by the reaction:

$$(SiO_2) + 2[C] \rightarrow [Si] + 2CO$$

A reduction of silica hot metal and slag covered in coke ashes.

The thermodynamics of these reactions proves that they are all favorable at high temperatures. In a blast furnace, the temperature is higher when startup of a production activity occurs after a stop event. While this only happens periodically and is usually limited to just one 1 day, it increases the silicon content in the hot metal increasing the mass concentration from about 0.38 to 1%.[5–7]

The process at the converter is influenced by this event. During the first few minutes of the oxygen blowing, all of the silicon oxidizes and the resulting silica produced from this reaction forms process slag through a combination of

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the lime added to the converter at the beginning of the conversion and the other oxidized elements present in the hot metal.

If the silicon concentration of hot metal is high (i.e., more than 0.7%), then the presence of silica in the slag will be significant, resulting in a rise in the slag viscosity due to the increased polymerization among the tetrahedral silicates as well as the formation of solid particles in the slag.

For a better understanding of the direct influence of silica on slag viscosity, we refer to the model proposed by Iida and other authors:[8–11]

$$\mu = A\mu_0 e^{\frac{E}{IB}} \tag{1.1}$$

where:
μ_0 is a viscosity reference

$$A = 1{,}745 - 1{,}962 \cdot 10^{-3}T + 7 \cdot 10^{-7}T^2$$

$$E = 11{,}11 - 3{,}65 \cdot 10^{-3}T$$

$IB = \frac{\%CaO}{\%SiO_2}$ is the slag basicity index.

If the treated hot metal contains a high silicon concentration, the basicity index of the produced slag will be low and (according to Equation 1.1) the viscosity will increase.

Viscous slag encourages the slopping occurrence in two ways, one more gradual and the other more violent.[9]

In the first case, the process gases (mainly composed of carbon monoxide CO) slowly pass through the slag due to its low permeability, which causes a slow slag foaming. The slag volume increases progressively until it can no longer be contained within the furnace and escapes, causing the slopping.

In the second case, the gases are trapped in the viscous lower layers of the slag. When the gaseous pressure exceeds the internal pressure of the slag, there is a violent escape of gases that causes the emission of smoke and dust.

If the silicon concentration of the hot metal from the blast furnaces is greater than 0.7%, the current operating practice consists of a double-deslagging operation. Double-deslagging reduces the slag amount in the converter due to the high CaO addition required to achieve the desired basicity. This procedure leads to loss of productivity in the conversion operation. In order to eliminate this negative aspect, a new procedure has been defined for the refinement of high silicon hot metal.

In this study, a new procedure with proven effectiveness that omits the double-deslagging operation has been applied in a converter with a capacity greater than 250 t.[12]

2. Current Operating Practice for High Silicon Hot Metal Refining

If the silicon concentration of a hot metal is greater than 0.7%, the molten pig iron will need to undergo a double-deslagging operation: the first slag removal takes place when 30% of the overall injected oxygen has been blown. This operation aims to remove the high viscous slag, while the second slag removal takes place at the end of the conversion process, as usual.

When the blowing resumes after the first slag removal, the liquid metal will contain a lower silicon concentration (approximately 0.2%), rendering the slag less viscous and preventing the instability conditions that lead to slopping.

For a better understanding, three experimental trials were performed on the current operating practice. The hot metal samples were taken through a sampler at different times during the conversion process. The first two data points correspond to pig iron, the third to the in-blow, and the last was taken at the end point. The chemical analyses were performed using a quantometric analysis SPECTRO X-LabPro, (Figure 1), which were recorded as reference data. All of the analyses pointed to the same trend for the evolution of the chemical analyses.

It is worth noting that at the first slag removal (vertical red line on Figure 1 graphs), the silicon concentration dropped to an average of 0.2%. This emphasizes that the first slag removal corresponding to 30% of the overall blown oxygen could represent the correct operational choice.

As anticipated, this practice has presented some disadvantages: first, a longer process time (i.e., lower productivity) and a decrease in process gases recovery, which is associated with a consequent increase in the overall emissions, since unrecovered gas has to be burnt in special burners. Moreover, the use of a greater number of slag pots for each treated heat complicates the management process due to the requirement to keep a large stock of these devices.

3. The Proposed New Method

The proposed new practice aims to extend the limit on the silicon concentration beyond that at which performing the double slag removal becomes mandatory. The limit has been extended from 0.7 to 0.9%.

A typical chemical composition of hot metal that requires a double-deslagging operation is reported in Table 1.

When the silicon concentration of the hot metal exceeds 0.7%, actions will need to be performed to prevent instabilities in the slag. Thus, a dedicated blowing pattern has been defined (Figure 2).

The features of this new blowing pattern include the following:

1. The oxygen flow rate being decreased, when compared with the traditional pattern (Figure 2), after 15% of the

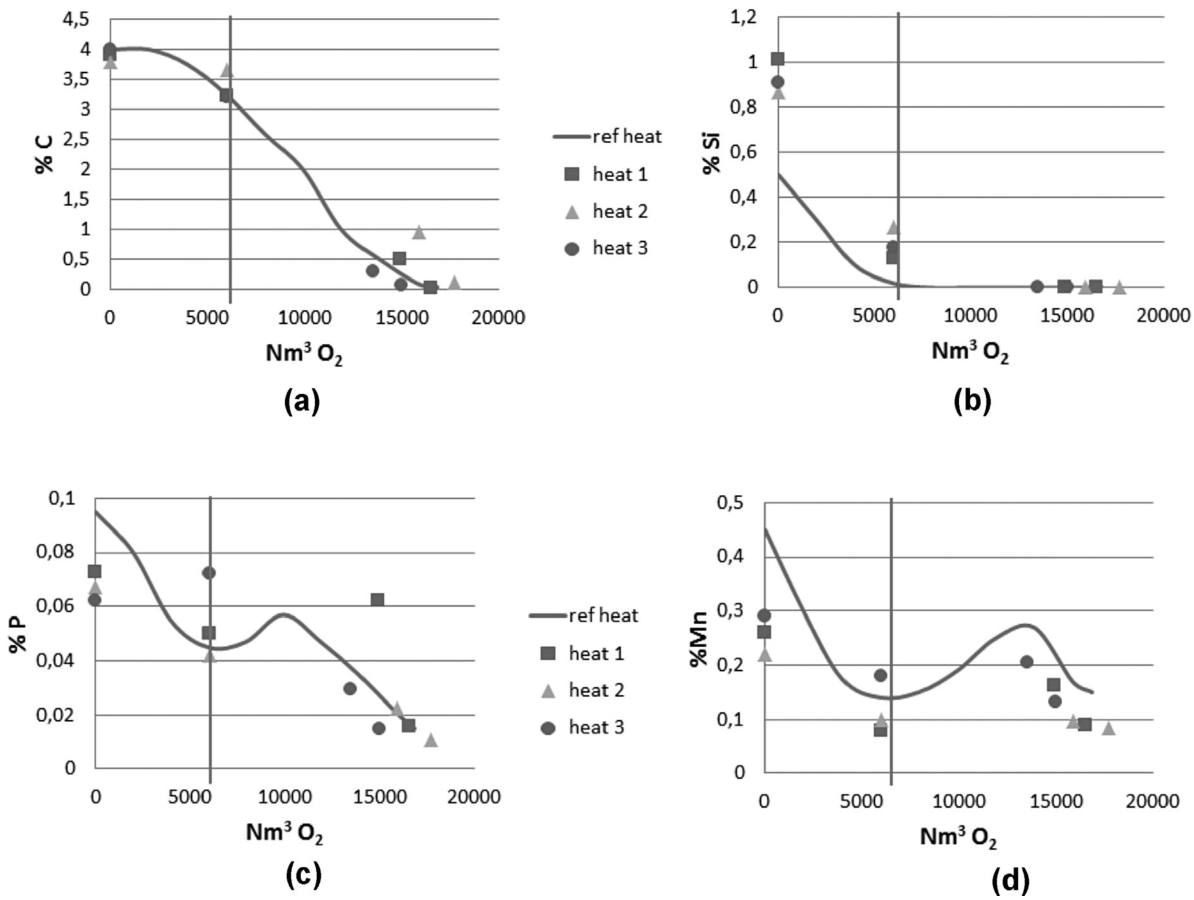

Figure 1. Evolution of C, Si, P, and Mn content for trial heats and comparison with bibliographic trend.[13] The red line represents 30% of the overall injected oxygen volume, when the first slag removal is realized.

overall injected oxygen has been blown. This decrease is intended to obtain a lighter decarburization and to decrease the off gas flow rate crossing the slag.

2. The lance height being set at a lower value after 25% of the overall injected oxygen has been blown. By managing the lance height, a lower quantity of oxygen will be supplied to the slag helping to avoid excessive foaming and helping its collapse due to the mechanical effect performed by the oxygen jet on the foaming slag.

Element	Mean [%wt]
C	4.59
Si	0.89
Mn	0.29
P	0.085
S	0.02

Table 1. Chemical composition of double-deslagging hot metal.

The new procedure was validated through its application in 30 steel conversion procedures.

4. Discussion of the Experimental Testing Results

The following operating parameters were analyzed and measured: the slopping tendency (through the oxygen lance vibration system[14] and the measured CO–CO_2 pattern), *tap-to-tap* time, and the off-gas recovery. These parameters are related to the efficiency of the process. In addition, the quality of the steel obtained through the new oxygen blowing pattern has been estimated as a function of the phosphorus removal.

The slopping tendency as measured by the increase in the oxygen lance vibration is the main controlling factor because this parameter is directly associated with the undesired emission phenomena.[15] The imminent slopping was revealed by the expert system mounted on the oxygen lance of the BOF, giving operators a real time warning of the onset of slop and its severity.

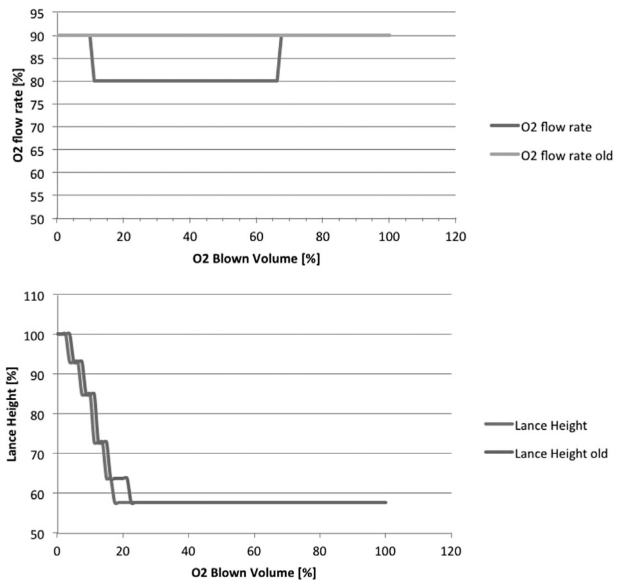

Figure 2. Blowing pattern for the hot metal featured by high silicon concentration.

Moreover, the slopping tendency also can be associated with the trends of the carbon monoxide (CO) concentration revealed in the off-gas, during the run of each analyzed heat. The off gas analyzer is placed inside the exhaust hood and if there are abrupt decreases or irregular patterns in the CO concentration in the fumes, this results in the off gases not being able to reach the probe and ending up trapped in the slag (slopping risk). Thus, an abrupt decrease of CO concentration in the off-gas is a clue that slopping phenomenon is developing.

Through a comparison of the obtained trends, clear differences can be seen between the double-deslagging and single-deslagging patterns. An example is given in Figure 3.

The single-deslagging procedure realized by the new tested pattern does not indicate shaper variation of the CO concentration when compared with the traditional double-deslagging practice. The slopping phenomenon actually did not occur in any of the 30 tests carried out.

The average *tap-to-tap* time for heats utilizing a double-deslagging practice was 94 min, which compares with an average value of 81 min for the heats undergoing a single-deslagging (Table 2).

Heats with a high silicon concentration in hot metal usually recur within a single day. If, on this day, five heats are treated by the single-deslagging practice, instead of the double-deslagging practice, a total of 65 min can be saved. This time is sufficient to treat one additional heat per day. Thus, the proposed new method can lead to an increase in daily productivity.

Off gases of the conversion process are recovered, if possible, and sent to the power plant located inside the factory to be used as fuel. Gas recovery is subject to two conditions that must be simultaneously verified: the oxygen content in the off gas should be less than 0.5%, to

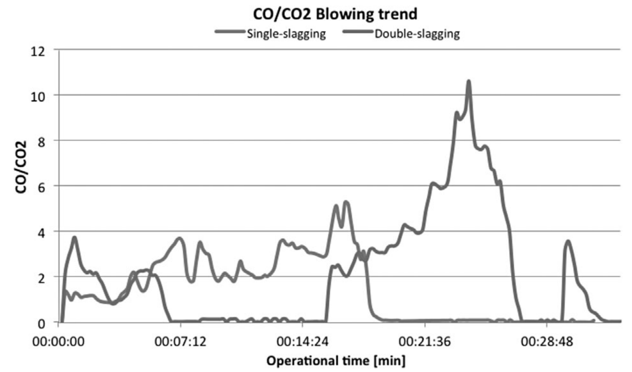

Figure 3. CO over CO_2 ratio trends for single- and double-slagging process.

avoid triggering explosions which could cause heavy damage, and the concentration of CO in the fumes must be greater than 25% to avoid combustion difficulties associated with an excessive presence of CO_2. When gases do not comply with these requirements, they cannot be recovered and necessarily must be burnt in the atmosphere by dedicated torches.

The recovery conditions are not verified at the beginning and the end of each blowing pattern and, if a double-deslagging practice is adopted, there are two transitory periods. This situation increases the overall period in which the recovery conditions are not verified and the final consequence is that a great amount of gas is burnt in the atmosphere.

For these reasons, the average percentage of recovered gas equals 51% for heats with a double slag removal practice and 70% for heats with a single slag removal (Table 3).

Finally, as an index of the steel quality obtained by the proposed new method, the dephosphorization ratio has been chosen, which is defined as follows:

$$\mathrm{deP\%} = \frac{P|_{\text{hot metal}} - P|_{\text{end point}}}{P|_{\text{hot metal}}} \times 100$$

where:

1. deP% is the percentage of dephopshorization
2. $P_{\text{hot metal}}$ is the phosphorus quantity present in the hot metal

	Tap–to-tap time [min]	
	Double-deslagging	Trial heats
Mean	94	81
Standard deviation	11	9

Table 2. Comparison on tap-to-tap time.

	Off-gas recovery [%]	
	Double-deslagging	Trial heats
Mean	51	70
Standard deviation	9	7

Table 3. Comparison on off gas recovery.

3. $P_{end\ point}$ is the phosphorus quantity present in the steel at the end point.

The phosphorus concentration has been chosen as a quality index because the practice that utilizes two slag removals is definitely very efficient. The average treatment temperature is lower and the second slag is P free.[16] Thus, in a practice that includes double slag removal, the first removed slag contains a high concentration of phosphorus. A dephosphorization reaction is favored at the beginning of blowing, especially at a low temperature, and when the first slag is eliminated, the subsequently formed slag is P-free. In this way the rephosphoration is definitely avoided, and the partition ratio favors a further P removal during the blowing of metal bath.[17,18] Although this thermodynamic indication appears to favor double slag removal, the comparison of the dephosphorization ratios shows that the two practices are equivalent: the average percentage of dephosphorization is 84% (5% standard deviation) for both. This surprising result can be attributed to the lower thermal pattern associated with a softer oxygen blowing pattern resulting from the single-deslagging procedure.

For a general idea of the evolution of the steel chemical composition obtained by a single-deslagging (single slag removal), it is possible to compare the trends of the most significant elements during the process (Figure 4) with a typical one.[8] From the comparison, it is possible to argue that at the end point the chemical composition of the molten metal obtained with the new practice is comparable with those obtained with the old one.

5. Conclusion

The feasibility of a new operating practice to convert high silicon hot metal without utilizing a double slag removal has been evaluated. The results were obtained from the comparison of 30 double-deslagged heats and 30 single-deslagged heats. In particular, tap-to-tap time, off gas recovery, and phosphorus concentration at the end-point were analyzed as operation parameters.

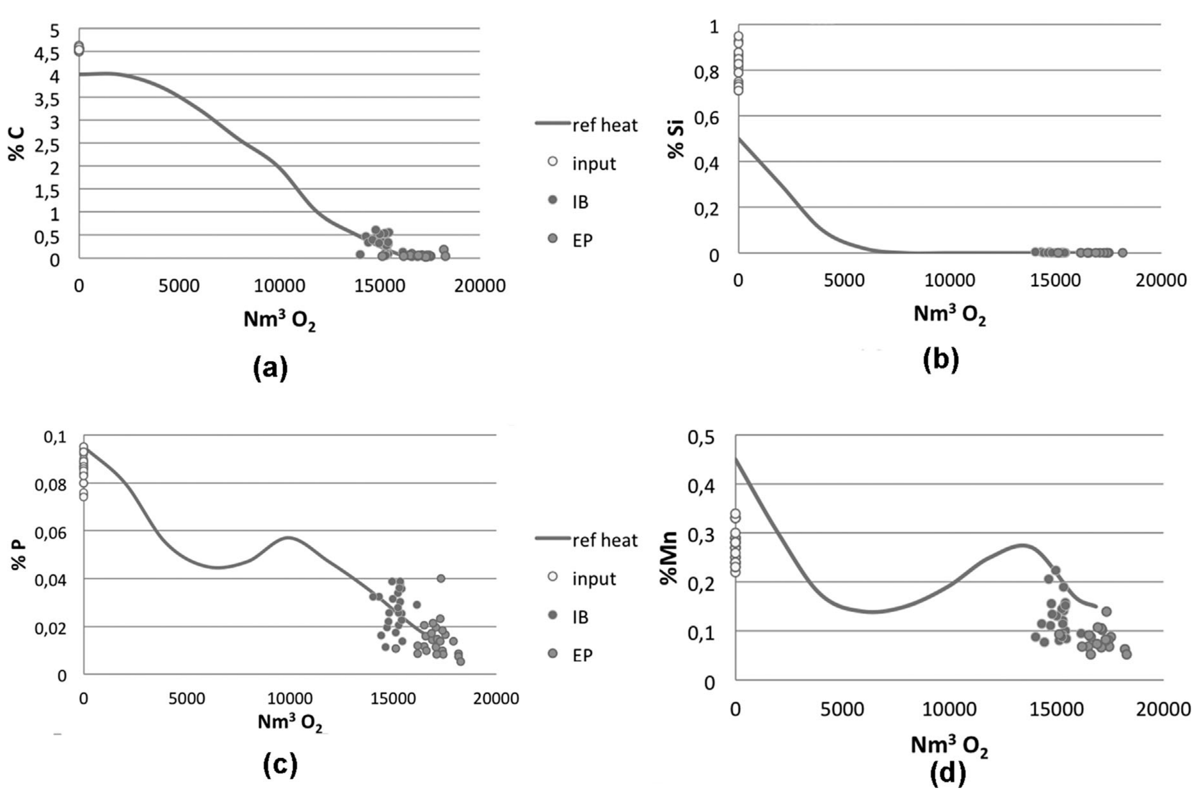

Figure 4. Evolution of C, Si, P, and Mn content for trial heats and comparison with conventional trend[13] at in-blow (IB) and end-point (EP).

The new practice includes just one deslagging and an oxygen blowing pattern different from that imposed during the double-deslagging procedure.

Utilizing the single slag removal practice with soft oxygen blowing:

1. provides a 13 min time savings for each heat when compared with the double-deslagging practice, thus increasing productivity;
2. allows for greater off gas recovery, implying economic (greater quantity of fuel available for the power plant situated in the factory) and environmental (lower emissions) benefits;
3. prevents the slopping phenomenon;
4. provides good steel quality, and providing a phosphorous removal efficiency that is similar to the double slag removal practice.

The newly proposed single slag removal operating procedure associated with a soft oxygen blowing has been found to be suitable and reliable for steelmaking activities and its use would lead to benefits such as a reduction in the operating cycle, an increase in the off gas recovery, and improved slopping control, without affecting the efficiency of phosphorus removal.

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References

[1] Blast furnace iron (BFI) production 2014–2015, URL www.worldsteel.org.
[2] A. Ghosh, A. Chatterjee, *Ironmaking and Steelmaking: Theory and Practice*, PHI Learning Private Limited, New Delhi, **2008**, 203–211.
[3] A. Klymczyk, R. Stachura, M. Bernasowski, A. Łędzki, *J. Achiev. Mater. Manuf. Eng.* **2012**, *55*, (*2*), 712.
[4] C. M. Wai, S. G. Hutchison, *J. Chem. Educ.* **1989**, *66*, 546.
[5] E.T. Turkdogan, *Fundamentals of Steelmaking*, The Institute of Materials, London, **1996**.
[6] *The Making, Shaping and Treating of Steel*, 11th ed., The AISE Foundation, 2013, p. 489
[7] *Treatise on Process Metallurgy*, 1st ed., Elsevier **2013**, *3*, 223.
[8] T. Iida, H. Sakai, Y. Kita, K. Shigeno, *ISIJ Int.* **2000**, *40*, S110.
[9] R. Donayo, A. Data, A. Gómez, W. Balante, J. Pérez, *La Rev. Métall.* **2010**, *107*, 319.
[10] K. C. Mills, L. Yuan, R. T. Jones, *J. South. Afr. Inst. Min. Metall.* **2011**, *111*, 649.
[11] S. Barella, A. Gruttadauria, C. Mapelli, D. Mombelli, *Ironmak. Steelmak.* **2012**, *39*(*6*), 463.
[12] W. Hwang, K. Chang, Win-Jay Hwang, Ku-Ling Chang, Wen-Hsien Chou, *China Steel Tech. Rep.* **2010**, *23*, 1.
[13] M. S. Millman, A. Overbosch, A. Kapilashrami, D. Malmberg, M. Brämming, *Ironmak. Steelmak.* **2011**, *38*(*7*), 499.
[14] Patent US 8,808,421 B2, **2014**.
[15] M. Brämming, B. Björkman, *Iron. Steel. Technol.* **2010**, *7*, (*11*), 66.
[16] Mapelli, Siderurgia, AIM, Milano, **2011**, 172.
[17] S. Basu, A. K. Lahiri, S. Seetharaman, J. Halder *ISIJ Int.* **2007**, *47*, (*5*), 766.
[18] S. Basu, A. K. Lahiri, S. Seetharaman, *ISIJ Int.* **2007**, *47*, (*8*), 1236.