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Effects of Slag Removal Method on the Process Parameters of Energy Optimizing Furnace

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ABSTRACT

Energy Optimizing Furnace (EOF) is one of the primary steelmaking technologies exists to produce the crude steel other than basic oxygen furnace (BOF) and electric arc furnace (EAF). Continuous slag removal during the oxygen blowing is an important feature of this technology that warrants lower tap phosphorous levels. Constructional design of the furnace enables the slag FeO level in the process of about 30% and the blow time is about 35 minutes. The present work focuses on studying the effects of restricting the slag removal on the tap phosphorous, slag FeO level, lime and basicity, coolant and yield of the process.

Keywords: Primary steelmaking; energy optimizing furnace; slag removal.

INTRODUCTION

It was around 1980s, KORF group initially modified the Siemens-Martin (Open Hearth) structure by means of changing the coating of furnace, operation through a combination of regenerative processes and pneumatics then called it as KORF OXI-REFINING FUEL process. This new process shortened the tap to tap time, doubled the productivity, reduced the heat loss, the need for fuel and reduced the operating costs. With all those experiences along with some additional improvements, KORF group developed a new process in Pains plant at Brazil and named it as Energy Optimizing Furnace [1]. It has gone through continuous modifications and got a form with single stage preheating setup, water cooled panels above the refractory wall and three different ways of oxygen supply through supersonic lance, submerged tuyeres and atmospheric injectors. In the scrap preheating setup, the scrap that will be charged for the next heat was filled and with the help of the heat generated during the process, the temperature of the scrap was raised [1], [2]. It is also one of the main reasons behind the naming of the technology. After the successful usage at Brazil, there was some more installations were carried out at Aliperti-Brazil, RIFS-USA, TISCO-India and AFS-Italy but those were not commercially successful [2]. But the installations at JSW (formerly SISCOL) and Hospet, India were commercially successful that made the technology's existence at present. But in Indian Furnaces, the scrap preheating setup was removed because of the melting of the scrap during the process, resultant blockage of the exhaust gases and the leakage of water in the water-cooled fingers. The water cooling systems were introduced before the gas cleaning inlets and the scrap charging system to reduce the outlet temperature of the off gas. The construction design of the furnace allows the continuous slag removal during the blowing of oxygen. The hot metal charging and steel tapping are done by using the separate launders [2]. Even though without performing the tilting operation the slag can come out of the furnace because of the design. The present furnace setup can be visualized with the help of the schematic cut section view as shown in Figure 1 [3].

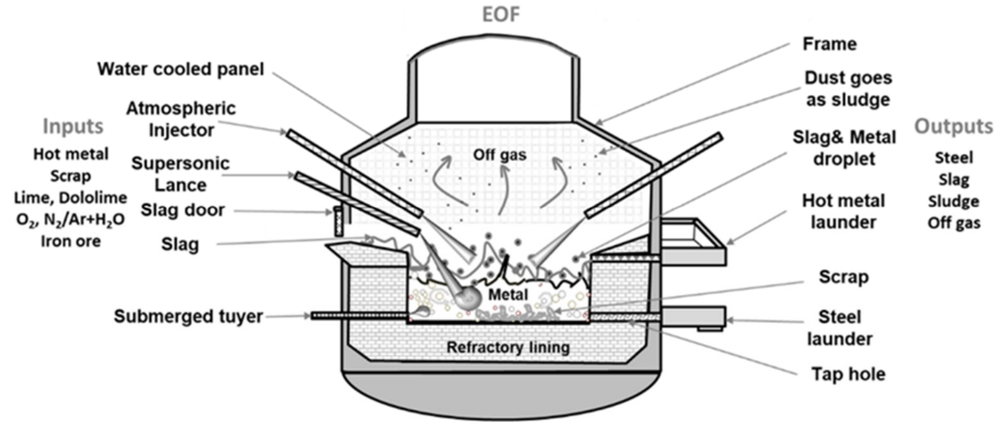


Figure 1. Schematic cut section view of EOF [3].

The input charge mix consists of 80-85% hot metal and 15-20% scrap. The scrap is charged at first from the top through the scrap bucket. Then the hot metal is poured via hot metal launder and the oxygen blowing starts once the hot metal reaches the tuyeres. The oxygen is supplied through top by means of Supersonic lances (2 Nos.) and Atmospheric Injectors (4 Nos.) and bottom (i.e., side) by means of submerged tuyeres (2 Nos.). The blow strategy has three different periods namely initial blow, boiling and peak blow period. During the rapid carbon removal period (boiling) the slag becomes foamier due to the formation of carbon monoxide gas bubbles. During that boiling period the flowrate is decreased to avoid the metal that goes out of the furnace along with the slag. It makes the blow time of 27-35 minutes to convert the hot metal and scrap to steel. The flux materials such as lime and dololime are added to make the slag during the blow and iron ore is added as a coolant to adjust the tapping temperature to 1630 to 1680°C.

The furnace has a tilting arrangement that tilts the furnace to ±8° to flush out the slag via slag door and tap out the steel through tap hole. The present furnace refractory life is about 1200 heats per campaign that is higher than the previously reported heat numbers (i.e.,800)[4]. The continuous slag removal process results in the average tap phosphorous level of 0.0077% (i.e., 33 heats) as per the supporting information given by Vidhyasagar et al.[3]. In the same experiments, at lower tapping temperatures, the tap phosphorous levels can go even below that. It can also because of high FeO level maintained in the process during the entire blow time along with the continuous slag removal during the blow. When we compare the slag FeO level of EOF with the basic oxygen furnace (BOF), EOF slag FeO levels are higher. The slag-metal-gas emulsions similar to BOF cannot be seen in the EOF process. The slag door is just above the bath level of the furnace and even for the high flow rates, the slag along with the metal can come out of the furnace. This continuous slag removal can also increase the slag quantity as well as the metal loss through the slag door and it can directly affect the cost and productivity of the process but the lower tap phosphorous is the notable outcome of this feature [3].

In general, phosphorous in the molten metal at oxygen furnace is removed with the help of the oxygen that is blown along with the flux that is added into the furnace. The direct removal of phosphorous with the help of the supplied oxygen might not happen because of the thermodynamic restrictions. When blowing the oxygen into the hot metal, the phosphorous pentoxide (P_2O_5) forms and gets reduced immediately at the steelmaking temperatures. Hence the activity of P_2O_5 is reduced with the help of liquid calcium oxide (CaO) that usually added in the form of lime and dololime. The iron oxide that is generated during the oxygen blowing reacts with the calcium oxide supplied through flux and reduces the melting point of lime and the associated reaction is given in Equation 1 [5]. Dephosphorization starts to happen when the silicon in the metal gets oxidized. But the formed silica reduces the activity of CaO.

$$2P + nCaO + 5(Fe_tO) = (nCaO.P_2O_5) + 5[Fe] \tag{1}$$

where ni is the number moles of the component i. Phosphorous removal in the process can also be identified by the degree of dephosphorization (η_P) and phosphorous partition coefficient (L_P) as shown in Equation 2 and Equation 3, respectively.

$$\eta_P = \frac{(Hot\ metal\ \%P - Steel\ \%P)}{Hot\ metal\ \%P} * 100 \tag{2}$$

$$L_P = \frac{(\%P)}{[\%P]} \tag{3}$$

where $(\%P)$ is the percentage phosphorous in slag and $[\%P]$ is the percentage phosphorous in metal. The recent equilibrium phosphorous partition equation reported by Assis et al. [6] is given by Equation 4 below indicates the effect of the oxides such as CaO, MgO, FeO, P_2O_5, SiO_2 and Al_2O_3 and temperature on the phosphorous partition ratio.

$$\log\left(\frac{L_P}{Fe_t^{2.5}}\right) = 0.073 \times [(\%CaO) + 0.148 \times (\%MgO) + 0.96 \times (\%P_2O_5) + 0.144 \times (\%SiO_2) + 0.22 \times (\%Al_2O_3)] + \frac{11570}{T} - 10.46 \pm 0.1 \quad (4)$$

where Fe_t is the total iron in the slag and T is the temperature of the slag system. At high temperatures, phosphorous from slag can revert back to the steel. The phosphorous reversion phenomena happens in the EOFs[4] is similar to the BOFs [7] but this continuous slag removal can help in reducing the reversion by removing out the phosphorous containing slag in the furnace system. To reduce the tap phosphorous levels in BOFs, the double slag practice is followed in which the slag is taken twice during the blow [8]–[12]. The double slag practice has the sequence of activities such as addition of light burned dolomite, slag splashing, lime and scrap addition, hot metal pouring, blowing, deslagging, lime addition, again blowing, tapping the steel and slag retention. During the initial blowing, dephosphorization happens along with the silicon removal. Once the dephosphorization is completed, the slag is removed out from the furnace and the blowing will start for the decarbonization. After tapping the steel, the remaining slag is retained for the dephosphorization of the next heat [8], [12]. The experimental studies with double slag practice in a 150-metric ton converter at the Tang Steel Group, China reported that for 0.11 to 0.12% hot metal, the tap phosphorous levels were improved from 0.018% to 0.011% [12]. The double slag practice helps in the reduction of the tap steel manganese also and this practice is also effective in reducing the hot metal with 0.7-1.3%Mn and 0.136% P to the steel with 0.11% Mn and 0.012-0.016% P [11]. The experiments reported by Hong et al.[13] reported that the tap phosphorous level of 0.001% from the low initial hot metal phosphorous of 0.07 to 0.10%.

With respect to EOF, the phosphorous levels are lower than the double slag refining process (0.007%) and it is also with high input phosphorous (0.17%). The degree of dephosphorization and phosphorous partition ratio of EOF are also higher[3] when it is compared with the other BOF technologies reported by Urban et al.[5]. So, decreasing the slag removal rate decreases the metal that goes out of the furnace along with the slag but it may significantly affect the degree of dephosphorization as well as the tap phosphorous level. It will be critical for the grades with the phosphorous requirement of 0.015% maximum in the final end product. From the previous improvement actions reported by Vijay Sharma [2] to optimize the steelmaking practices in EOF for increasing its productivity and cost of the process under Indian conditions. Catch carbon practice, selecting the proper hot metal in terms of its chemistry and temperature and reducing the liquid metal through the slag door especially when there was excessive boil inside the EOF. These improvement ideas were used in EOF-1 of 45 metric tons (i.e., previously) resulted in the liquid yield improvement from 90.2 to 92.2% and the blow time was reduced from 36 minutes to 31 minutes. Here the liquid yield indicates that the steel weight measurement after the tapping additions. The catch carbon practice, the tap carbon of >0.1% with 85% consistency and reduced the slag FeO level of 22%. The heats with the carbon contents ranges below 0.1%, FeO level was about 28%. In EOF-2 (i.e., 65 metric tons), the liquid metal yield was improved to 90.1% for the input charge of 80.11 % hot metal and 19.89% solid scrap with the blow time of 38 minutes, oxygen consumption of 66 m^3/MT and lime consumption of 58 m^3/MT. The lowest tap phosphorous level of 0.008% was achieved in this process and it can go up to 0.05% also.

Vidhyasagar et al.[4] reported the typical performance of EOF with the help of heat and mass balance studies based on the measurements and average data of fifteen heats which were taken at EOF-2. Continuous slag removal practice was followed in those experiments. The average yield of the process considering the tap additions was about (i.e., Liquid yield) about 90.71%. The typical FeO level in the process was about 29.81%. The blow time and tap to tap time of the process were 35 and 65 minutes respectively. Lime and oxygen consumptions were 53.29 and 53.14 kg per metric tonne of steel and if it is taken per ton of crude steel (excluding the tap additions), it will increase. The experiments that were done for the modelling of EOF has given the low tap phosphorous levels of 0.005% with the tap temperature of 1620°C and the continuous slag removal practice was followed in those heats [3]. But it is not yet explored that whether the continuous slag removal practice is significantly required for the lower tap phosphorous level or some frequent slag removals is enough for that. It has given scope for the present work to explore it further.

In the present work, the slag removal is done only at the end of the blow and it is compared with the normal continuous slag removal practice to study the effect of the slag removal method on the process parameters of EOF. The main process parameters include tap phosphorous, degree of dephosphorization, flux, coolant, yield and slag FeO level of the process. The possible reasons behind the changes in the process parameters due to the single slag removal and the challenges involved in the slag holding inside the furnace are also discussed.

EXPERIMENTAL

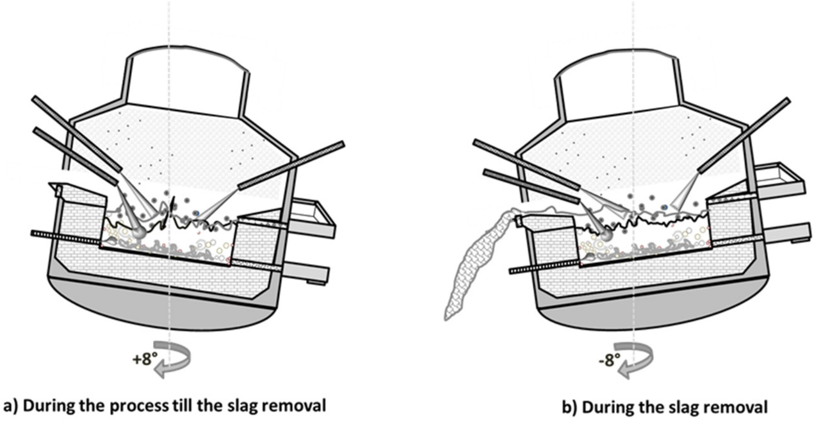
The experiments of the present work were carried out in EOF-2 of JSW Steel Limited, Salem works, India. Two different methods were practiced in the process to study the effect of slag removal method on the process parameters of EOF. In the first method, during the blow time, the slag that comes out of the furnace was stopped by adjusting the furnace positioning and flow rates of the oxygen carrier parts namely supersonic lance, atmospheric injectors and submerged tuyeres. The slag was removed at the end of the tapping only. It is simply termed as the controlled slag removal practice. In the second method, the slag was allowed to flow out of the furnace as similar to that of the normal EOF steelmaking process. It is termed as continuous slag removal practice. In each method, six heats were taken and in each heat the slag samples were collected during the blow time of 6-10 minutes (Sample No. 1), 17-20 minutes (Sample No. 2), 24-28 minutes (Sample No. 3) and at the end of the blow (Sample No. 4) methods of slag removal were carried out. The chemistry of slag samples was analyzed by using Thermo Fisher Advant XP-2454 X-Ray Fluorescence spectroscopy. The elemental analysis of metal at the tapping stage after the tapping was performed by using ARL-4460 make spectrometer. The dissolved oxygen in steel is measured by using the CELOX probe (Heraeus Electro-Nite)-SIDERTOP oxygen analyzer and it can give the corresponding carbon level also. The flux, oxygen, coolant and other consumption details were recorded for the twelve heats (i.e., in total).

CONTROLLING THE SLAG INSIDE THE FURNACE

The slag removal is the easy step in the EOF and it is performed just by the tilting the furnace and the carbon monoxide gas evolution during the blow ease this process. Apart from these two, oxygen blowing from the submerged tuyeres cause the bubbling in the surface of the bath along with the squirts formation. The injection of gas using the tuyeres reduces the effective density of the liquid metal bath and it contributes the bath movement in the furnace. The supersonic lance flow creates a deep ditch in the molten metal bath that also churns the slag and metal [1].

The slag that goes out of the furnace is controlled by keeping the furnace positioning at the tap hole side (+8°) till the carbon level reaches 0.1% as shown in Figure 2. In the normal continuous slag removal process the furnace position usually goes to 0° after the boiling period. The online carbon measurement was done by using the Quick Carbon analyzer from Heraeus Electro-Nite by taking the molten metal by using a cup attached with a tong and pouring it in the pouring cup of Quick carbon analyzer. During carbon sampling, the furnace is positioned at 0 to -8°. Even though the furnace is tilted towards the tap hole side, the slag can come out of the system and this scenario is mitigated with the help of oxygen-flow rate adjustments in supersonic lance, atmospheric injectors and submerged tuyeres.

Typical supersonic lance flow rates of the controlled as well as continuous slag removal method with respect to the blow time and the period are given in Figure 3. Similarly, the flow rates are controlled in the atmospheric injectors and submerged tuyeres to avoid the slag overflow from the furnace. In the initial period, large amount of silica forms and increases gradually the slag volume. In this period, the flow rates are bit reduced than the normal continuous slag removal process to avoid the slag overflow. In the boiling period, flow rate is decreased so that the CO bubbles generation is reduced and the slag can stay inside the furnace. In the peak blow period, the flow rates were increased to the maximum for reducing the blow time and in this period the slag comes out of the furnace is also comparatively lower than the initial and boiling periods. The combined effect of furnace positioning and flow rates adjustments restricted the slag flushing out of the furnace.



a) During the process till the slag removal

b) During the slag removal

Figure 2. Furnace positioning in the controlled slag removal process.

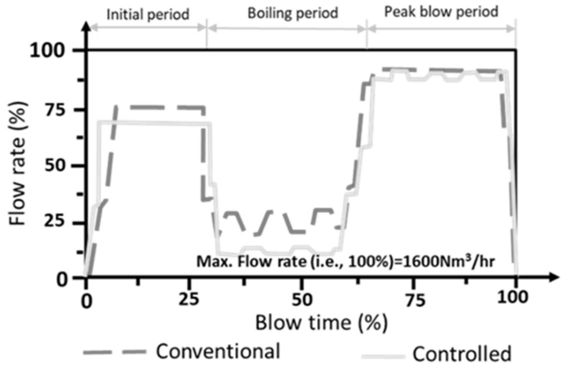


Figure 3. Flow rate of oxygen in a supersonic lance.

RESULTS AND DISCUSSION

The effect of changing the slag removal method on the process parameters such as tap phosphorous, slag composition (FeO, CaO and basicity), yield, flux, oxygen, coolant, tap temperature and blow time of the process are studied. The effect of controlled slag removal on each of the above mentioned parameters is discussed by comparing this with the continuous slag removal process. The data points of both the process are given in the box plots with the mean, median and range as shown in Figure 4 (a-k) and it is discussed further in detail. The challenges involved in holding the slag during the blowing process are also discussed.

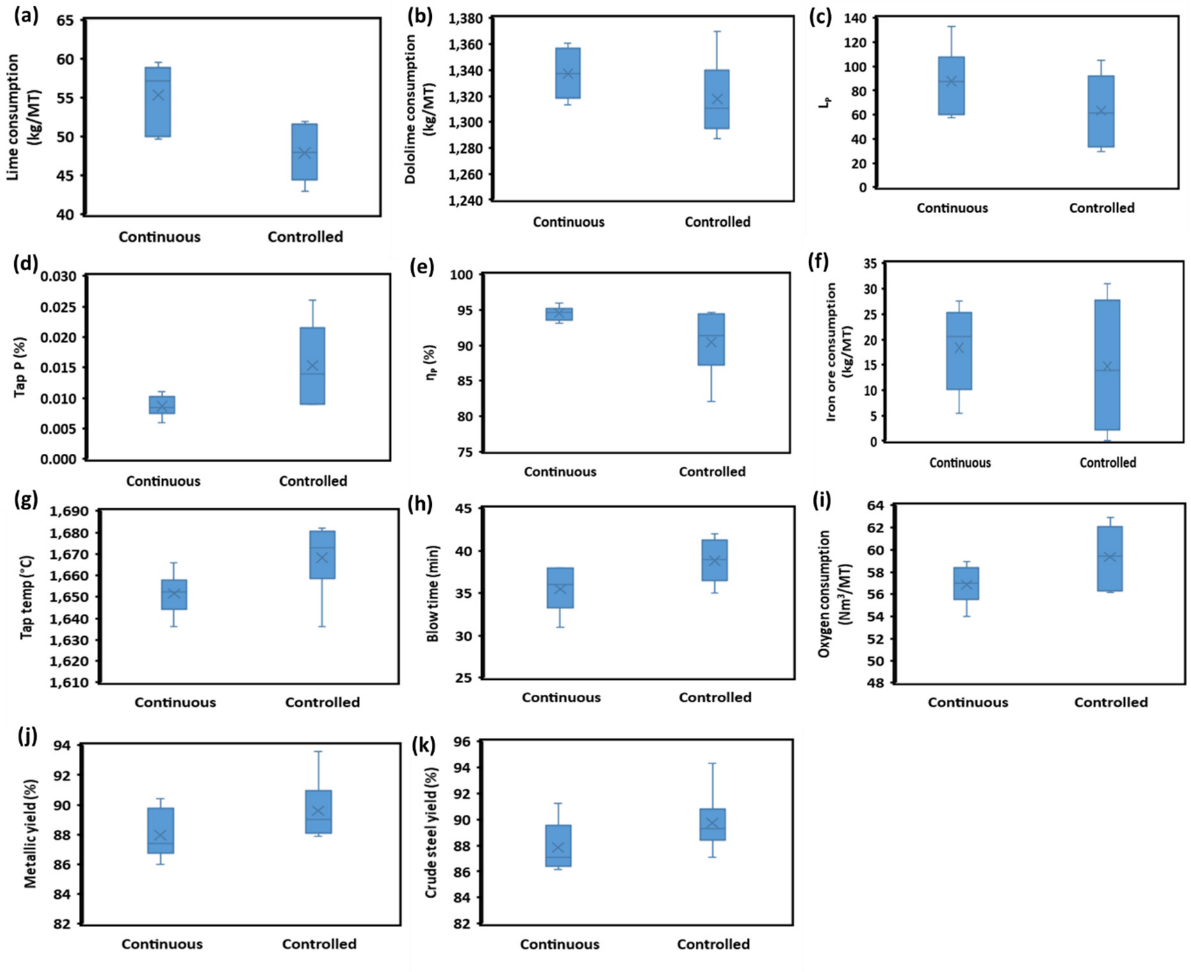


Figure 4. Comparison between the continuous and controlled slag removal practice on the process parameters.

Effect on CaO and MgO Level of the Slag

The slag evolution during the blow in both the methods by means of CaO and MgO are shown Figure 5(a-d). There is a progressive dissolution of lime (with 93% CaO& 1% MgO) increases the CaO level in the slag in both the controlled and continuous slag removal methods. Maximum CaO level in the slag has reached to ~45% in the continuous slag removal method whereas CaO level in the controlled slag removal reaches to 40%. With reference to Figure 4(a), the reflection of the input lime consumption is directly seen in the slag CaO levels as shown in Figure 5(a-b). Dololime addition was increased to mitigate the furnace erosion since the slag stays more time inside the furnace in the controlled slag removal in half of the heats and it can be seen with the higher mean dololime consumption in Figure 4(b). In the heat numbers A37360 and A36652 (Figure 5(c-d)), there were no dololime addition but there is a significant MgO in slag and it can be due to the erosion of the refractory and very minor quantity of MgO can only come from the lime. In case, if CaO from the dololime (~35% CaO) addition is considered then the CaO addition of controlled slag removal method can go to the maximum of ~50 from 47 kg/metric ton of steel and still it is lower than continuous slag removal practice. It can also affect the dephosphorization and basicity levels that will be discussed further.

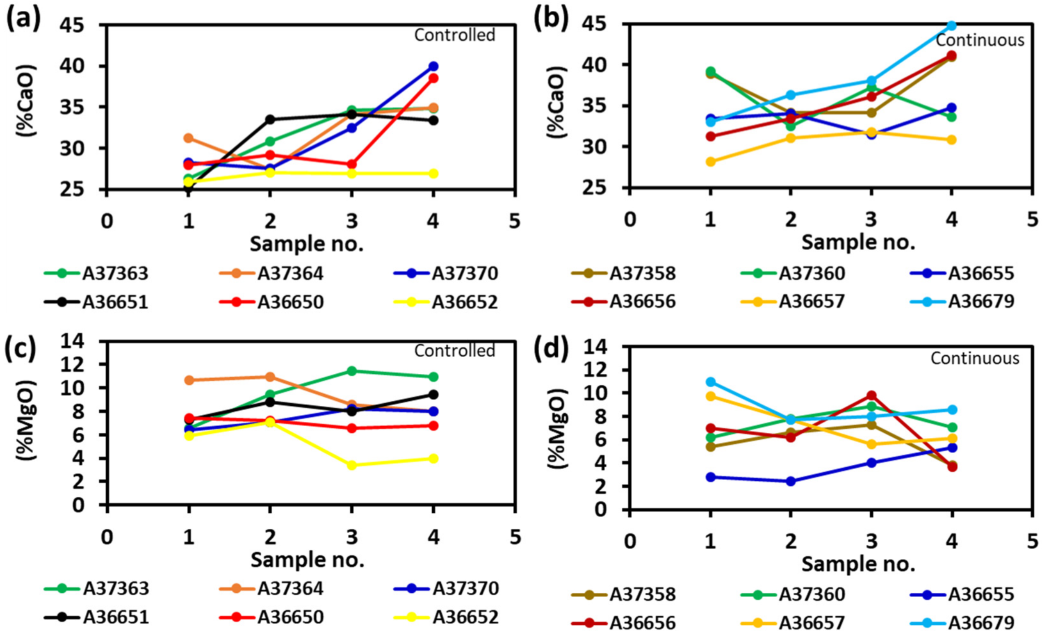


Figure 5. CaO and MgO levels of continuous and controlled slag removal process.

Effect on FeO Level and Basicity of the Slag Along With Dephosphorization

The dephosphorization of steelmaking mainly depends on the temperature, FeO and basicity of the slag and it can be described by using Equation 4. The phosphorous removal efficiency of the controlled slag removal process is lower when compared with the continuous slag removal process. It can be identified with the help of L_P, tap P and η_P values as shown in Figure 4(c-e). FeO levels in the controlled slag removal is comparatively lower than the continuous slag removal (Figure 6(a-b)) and the decrease in FeO level can happen because of the reaction between the carbon present in the metal and FeO in the slag then it forms CO gas along with the liquid iron as shown in Equation 5.

$$[C] \ + (FeO) = CO_g + Fe \qquad (5)$$

In EOF process, very high FeO presence in the slag may not be needed for the dephosphorization but the design itself is creating the high FeO levels during the process and it is not easy to reduce it drastically. As shown in Figure 6(a-b), the spread in the slag FeO level is bit higher in continuous slag removal process compared to the controlled slag removal process. The slag basicity is also quiet narrow spread in the controlled slag removal process as shown in Figure 6(c-d) and it is comparatively lower. Increase in basicity will increase the degree of dephosphorization but FeO will not do the same after some point [14]. Urban et al. [5] reported that in BOF, for the basicity of 3.4-3.6 at the temperature of 1680-1710°C for, there is a decrease in L_P level after the total Fe content in the slag reaches 23-25% that corresponds to 29.6-32.1%FeO. But in case of EOF, the tap temperature can go to 1630°C that my increase the L_P level but FeO level to get maximum L_P level can remain the same.

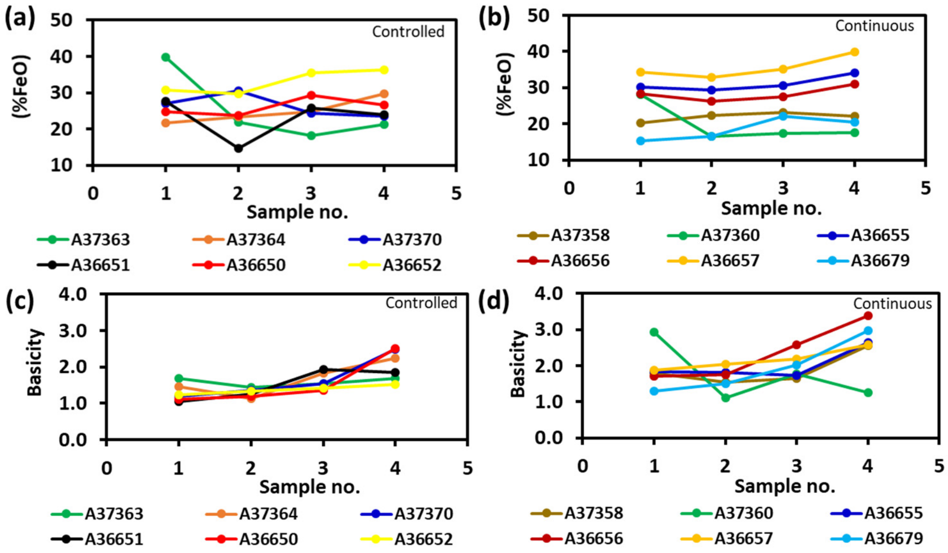


Figure 6. FeO and basicity of continuous and controlled slag removal process.

Effect on the Iron Ore Consumption and Tap Temperature

The temperature control in the controlled slag removal is bit challenging since the slag tapping is done only at the end of the blow. In EOF technology, the controlled slag removal is newer and also the iron ore is only added as a coolant to control the temperature of the bath. Sometimes, the coolant addition can be adjusted based on the appearance of the slag that comes out of the furnace and in this case the slag will not come out of the furnace and it can affect the quantity of addition. As shown in Figure 4(f), there is a wider spread in the iron ore consumption in the controlled slag removal process even though its mean value is lower than the continuous slag removal. The variations in the iron ore consumption is reflected in increased tap temperature of controlled slag removal as seen in Figure 4(g). It is also because of reduction of the heat that goes out with the slag.

Effect on the Oxygen Consumption and Blow Time

To hold the slag inside the furnace, apart from the furnace positioning, the flow rates were mainly adjusted as shown in Figure 3 (example). In fact, during the boiling period it is reduced in such a way that the slag should not come out of the furnace. In the initial period also the flow rates were reduced a bit and to compensate this delay, the flow rates are increased to the maximum in the peak blow period. But the final blow time is still higher than the continuous slag removal process (Figure 4(h)). This slow blow also increased the oxygen consumption (Figure 4(i)). The slag amount that will be held inside the furnace is higher when the controlled slag removal is followed. Even though the slag temperature is expected to increase and the viscosity can decrease but because of increasing the slag volume the resistance offered by the slag to the oxygen jets may increase. It can also affect the oxygen consumption.

Effect on the Yield

The yield of the process is considered into two categories namely metallic yield and crude steel yield. Metallic yield is the percentage of steel tapped as an output from the input hot metal and scrap and it is shown in Figure 4(j). Crude steel yield is the percentage of steel tapped as an output from the input hot metal, scrap and iron ore as shown in Figure 4(k). In the normal continuous slag removal process, when the slag comes out of the furnace, the metal can also come with it. The quantity of the metal that goes out of the furnace along with the slag is extremely difficult to quantify. It varies significantly in every heat based on the input materials' quality, tap requirements, furnace tilting and the blow strategy. It is expected that the metal comes along with the slag is about 1-2% of the tap steel weight and it is based on the data of steel recovered from the slag pits in the plant. Indirectly, it can be decreased by reducing the slag flushing frequency of the furnace. In the present study, since the slag removal was performed only at the end of the blow, the metal goes along with the slag is expected to be lower than the continuous slag removal practice. As shown in Figure 4(j-k), by doing the slag removal at the end resulted in about ~2% increase in the crude steel yield and it is excluding the tap additions that was added in the stream of tapping steel. This controlled slag removal has some of the challenges to overcome further for the improvement that will be discussed further.

Challenges of Holding the Slag Inside the Furnace

By controlling the furnace positioning and adjusting the flow rates the slag holding was performed but apart from that some of the other challenges were also involved in this process.

1. As shown in Figure 2, holding the furnace always towards the tap hole side increases the possibilities for the slag to go towards the hot metal launder hole because of the arrangement of supersonic lance and injectors system. The supersonic jet forces the slag and metal towards the tap hole side in both the continuous as well as controlled slag practices. But in the controlled slag removal, because of increasing the residence time at this position, the slag can coat in the hot metal launder hole and reduces the hot metal intake rate bit lower for the next heat.
2. The atmospheric injectors in the tap hole side have lower distance to the molten slag and metal bath when the furnace is tilted towards +8°. It increases chances of slag splashing on to the top of the injectors.
3. The slag that coats on the refractory wall once the tapping is over being lesser. It can affect the erosion pattern of the refractory wall.
4. The slag is completely drained in this process because of the more fluid in nature that ease the tap hole closing for the next heat since there will not be any accumulation of slag after tapping.
5. The minor adjustments in the coolant based on the appearance of the slag that comes out of the furnace is difficult since it is not visible.
6. When the input hot metal silicon levels are as high as 1% the slag generation increases and the slag can come out of the furnace automatically even though furnace is tilted towards +8° and flow rates are reduced.

CONCLUSIONS

1. Continuous slag removal is one of the salient features of the EOF technology that can be directly assessed with the help of the experiments in the present work. Low tap phosphorous levels can be obtained by using this method since the phosphorous containing slag continuously goes out of the furnace and it reduces the reversion of phosphorous from the slag to the metal.
2. By reducing the slag that goes out of the furnace and holding the slag inside the furnace, the parameters such as yield of the process, tap temperature, tap phosphorous, oxygen consumption and blow time will increase and the parameters such as degree of dephosphorization, phosphorous partition coefficient, lime, basicity, CaO and FeO of the slag will decrease. The parameters such as dololime and iron ore additions fluctuate wider because of these changes. The possible reasons behind these changes are discussed.
3. Holding the slag inside the furnace increases the difficulty to perform the blowing operation and it was performed with some of the challenges (required in future also) that are discussed briefly.
4. A fraction of slag flushing at the end of the silicon removal can help in further improvement in the dephosphorization that will be explored in future.

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