Study on duplex process with a single converter

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This paper introduces the production practice of duplex process with a single converter of 120t BOF in steelworks. This work considers the smelting process, oxygen supply, slag-forming practices, and final control of dephosphorization, etc. as the technical characteristics of duplex process with a single converter. The results show that the endpoint [P] content is reduced to 0.018%, and the dephosphorization rate reaches 87.20% by duplex process with a single converter, while compared with the previous smelting process it was increased by 2.01%. At the same time, it also reduced oxygen supply time by 62s and the average amount of lime by 510kg per BOF heat. The consumption of lime and metallic charge materials was also reduced significantly. A correlation analysis is used to investigate the relationship between the consumption of lime and the dephosphorization rate, which is consistent with the industrial production results and proves that the consumption of lime is an important factor for the dephosphorization rate in duplex process with a single converter. It allows the stable production of the steelworks to achieve obvious economic benefits.

KEYWORDS: BOF, THE DEPHOSPHORIZATION RATE, DUPLEX PROCESS WITH A SINGLE CONVERTER.

INTRODUCTION

In order to adapt to the change of the steel market, the domestic and foreign steelworkers[1-4] have been exploring BOF smelting process, looking for ways to improve the quality of molten steel and reduce the smelting cost. Domestic and foreign metallurgical workers[5-8] studied the smelting process of BOF at the early stage of industrial production. They believe that the high-quality smelting process not only improves the quality of molten steel produced from the BOF but also accelerates the smelting efficiency in order to reduce the cost. Therefore, the selection of the smelting process is of great importance to the BOF production. Xue et. al[9] determined (P_2) as one of the main dephosphorization products, while (P_2O_5) and (FeO) in the slag were found to be reduced at high temperature. Wang Minglin [10] studied the dephosphorization behavior in the early stage of converter steelmaking process and concluded that the double slag-retaining method can reduce the consumption of raw materials by lowering the phosphorus content of steel. K. Yoshida[11] developed a simple refining process (SRP) by using two 250t capacity top and bottom

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blown converters, namely dephosphorization and decarburization furnaces, in order to recover the mass production process of both low-phosphorus and conventional steel grades. Low (P_2O_5) lumpy slag obtained from the decarburization furnace was used as a dephosphorization agent in the dephosphorization furnace, which reduced the total lime consumption to achieve stable and quick refining. Fu Qiang[12] investigated on a less-slag smelting technology in 120t converter although the dephosphorization rate at the endpoint was increased. The BOF cycle was prolonged and the smelting time was also enhanced in Beiying Iron&Steel Co. Ltd of ben steel group. However, the process route was not perfect which can stabilize the steelmaking process to reduce the consumption of lime.

In this paper, the smelting process of 120t BOF in steelworks is studied experimentally. The duplex process with a single converter is more scientific and advanced than the original smelting process (Fig. 1a). Slag is dumped after smelting in the original smelting process. The slag is dumped in a small amount after the first blowing in the new process, while the remaining slag is dumped after tapping in the new process, as compared to the original smelting process in which the slag is dumped after the smelting. The duplex process with a single converter reduced the consumption of lime and increased the dephosphorization rate, while the (TFe) and the metallic charge material consumption decreased. Finally, the new process reduces the risk of spatter accident and thus ensures the safety.

ANALYSIS OF DUPLEX PROCESS WITH A SINGLE CONVERTER

Analysis of phosphorus content [P]

From many years of production practice it was found that the dephosphorization effect will be efficient if the product of (CaO) and dephosphorization (P_2O_5) in the slag is stable[13]. The equations describing the dephosphorization process are:

$$2[P] + 5(FeO) + 4(CaO) = (4CaO \cdot P_2O_5) + 5[Fe] \quad 1)$$

$$2[P] + 5(FeO) + 3(CaO) = (3CaO \cdot P_2O_5) + 5[Fe] \quad 2)$$

The stability of ($3CaO{\cdot}P_2O_5$) is weak during the production process in the BOF converter, while the ($4CaO{\cdot}P_2O_5$) is stable at high temperatures. In terms of thermodynamics, two compounds have the same conclusion in an alkaline slag, which are (PO^{3-}_4) in the ionic constitution of slags[14-15].

Therefore, the equilibrium constant Kp can be defined as,

$$K_P = \frac{a_{(4CaO \cdot P_2O_5)}}{a^2_{[P]} a^5_{(FeO)} a^4_{(CaO)}} \quad 3)$$

$$K_P = e^{-\frac{\Delta G^\theta}{RT}} \quad 4)$$

Dephosphorization reaction is the slag steel interface reaction, and the catalytic effect of the early slag making process on the dephosphorization reaction is to increase the distribution coefficient of phosphorus [P] between the slag and steel[14-15].

$$L_P = \frac{(\sum P - W_1 \times [\%P])}{(0.437 \times W_2 \times [\%P])} \quad 5)$$

(L_P,K_P are the distribution coefficient and equilibrium constant respectively, a is the activity, ΔG^0 is the Gibbs energy in the standard state, *R* is a constant, while W_1 and W_2 are the weight of metal and slag respectively.

With the progress of the smelting process, the (CaO) decreases gradually, while the continuously increasing level of slag ($CaO{\cdot}P_2O_5$) also declines the content of phosphorus in the molten steel. Eq. (4) shows that the equilibrium constant of dephosphorization reaction increases sharply when temperature drops, as a result the prominently enhanced dephosphorization was observed. The dephosphorization reaction was exothermic, and the dephosphorization rate decreased with the increase of temperature. The increase of (FeO) content and basicity of slag is beneficial to the dephosphorization process. It is necessary to control the appropriate temperature of the molten pool to avoid the increase of [P] content in the middle and later stages of the BOF smelting process, and the high oxidation and basicity environment can produce high-quality slag.

Analysis of BOF slag - making practices

At the beginning of BOF smelting process, the silicon [Si], manganese [Mn], phosphorus [P], iron [Fe] and other elements in the molten iron produce oxidizing material in the slag, at the same time the addition of slag-making materials such as lime or dolomite also melt gradually. The slag is low alkaline acidic slag with a relatively high composition of (FeO), (SiO_2), (MnO), while the composition of (CaO) is low. The [P] content in the molten iron is also relatively high. By increasing the content of (FeO) in molten slag, the oxidation of [P] in molten iron can be accelerated, as a result the stirring of molten iron can be increased and the kinetic conditions can be improved to facilitate the mass transfer of [P]. It completes the early dephosphorization process, while the oxidation heat of [Si] and [Mn] increases the melt temperature, which ensures that the lime, dolomite and other slag-making materials melt completely. Meanwhile, the basicity of slag increases with the higher (MgO) content. Then the decarburization reaction takes place, resulting in a substantial reduction in oxides such as (FeO). With the increase in BOF temperature and the continuous lime melting, the basicity of slag increases again. How to achieve rapid slag formation is the key to improve the dephosphorization effect. In the later stage of smelting, the [P] content in molten iron decreases, and the slag basicity becomes the key to the dephosphorization process.

DUPLEX PROCESS WITH A SINGLE CONVERTER

Manufacturing process and experimental conditions

In this paper, the 120t BOF industrial production line of a plant is taken as the research object. The manufacturing process is: 1280 m3 blast furnace (BF), 120t basic oxygen furnace (BOF), and 155mm*155mm Continuously Cast billet. The duplex process with a single converter is shown in Figure 1, while the initial molten iron condition is shown in Table 1.

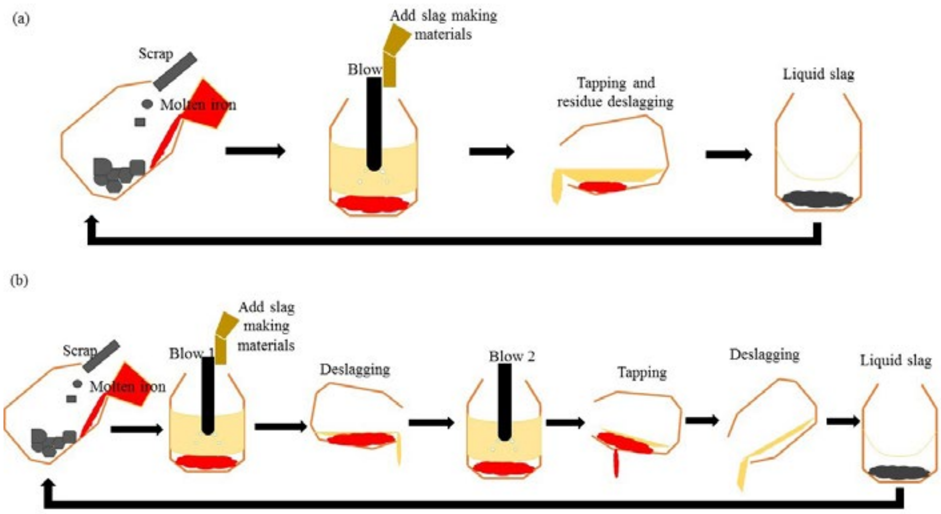

Fig.1 - Duplex process with a single converter (a) the original process flow chart of a factory (b) the process flow chart of a factory using a single converter double method.

Tab.1 - Initial molten iron condition.

	w(C)%	w(Si)%	w(Mn)%	w(P)%	w(S)%
The initial molten iron	3.90-4.62	0.14-1.07	0.22-0.42	0.08-0.24	≤0.07
Smelting target	0.20-0.25	0.30-0.55	1.20-1.55	≤0.02	≤0.02

The experimental plan for the oxygen supply

The plant uses a Laval oxygen lance nozzle with 5 holes and the oxygen outlet pressure was set at 0.88Mpa with the oxygen flow rate of 25000 Nm^3/h -27000Nm^3/h. The [C] content of the final steel was controlled to 0.06%-0.12%. For the initial slag formation, the position of the oxygen lance was adjusted at 1.2m away from the liquid level in the early stage of the BOF smelting process. After 90s, the oxygen lance position was changed to 2.3m from the liquid level. In the middle of the smelting process, the oxygen lance operation was started after 9 min to prevent the slag drying, while its position was adjusted to 0.9m in order to ensure a uniform stirring of the molten pool.

In the duplex process with a single converter, the slag making materials (mainly lime and dolomite) are added in batches. The first batch of the materials (lime =1t and all amount of dolomite) was added after the start of the smelting process, while the remaining lime and other slag materials were added after blowing for 8 min.

RESULT AND DISCUSSION

Oxygen supply

The "low-high-low" is the operation specification of oxygen lance in steelworks. The quick slag formation is the main purpose of low lance position in the early stage of smelting process. The lance position is increased to 2.3m in the middle of smelting to prevent the slag drying and large accumulation of (FeO), as the temperature of the furnace increases. Because the more material is added for the first time, the lance position is increased in order to prevent the rapid increase of temperature, which causes the slag splashing. In the later stage of smelting, the metal and slag were mixed uniformly with the low pressure of oxygen lance. In the first slag pouring, the amount of slag in the furnace will be reduced with thinner slag layer, and oxygen can penetrate the slag layer with an improved utilization rate, resulting in decreased oxygen blowing time.

The constant oxygen pressure, the closed location of the nozzle to liquid surface, the smaller and deeper impact area and the great impact of velocity on the liquid surface are the more favourable factors to enhance the mixing of the molten pool. The mixing intensity also affects the dephosphorization by producing favourable external factors. The comparison of the oxygen blowing time and amount in different manufacturing processes is shown in Figure 2. The blowing time by the duplex process with a single converter is compared with the original process, which reduces from 863s to 801s with the average reduction in oxygen blowing time of 62s. The oxygen blowing amount is also compared with the original process which increases from 5627m^3 to 6516m^3 with an average increase of 889m^3.

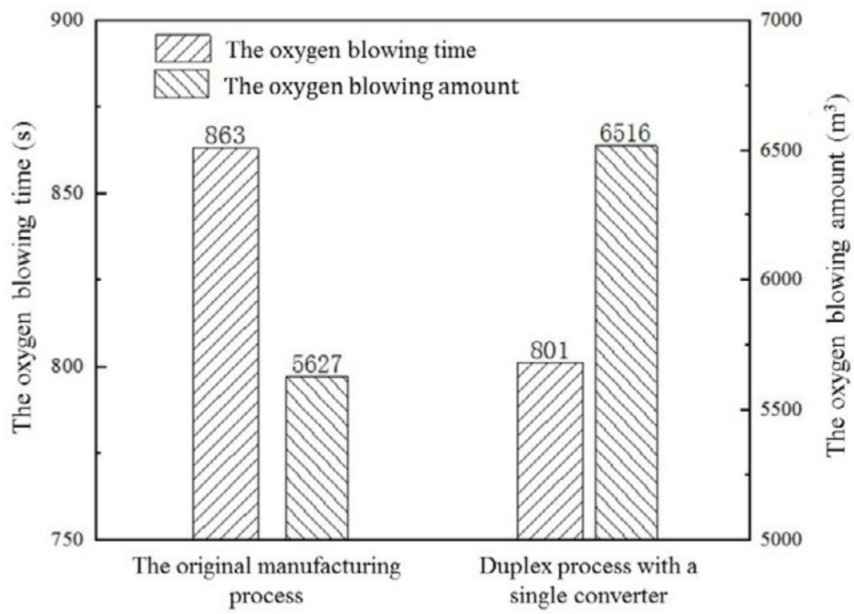

Fig.2 - Comparison of the oxygen blowing time and amount in different manufacturing processes.

Slag-forming

After 100 smelting experiments in steelworks, it was found that the slag fluidity in the duplex process with a single converter is perfect. The speed of converter slag formation depends upon the dissolution rate of lime, especially under the condition of high phosphorus hot metal smelting. The rapid formation of liquid dephosphorization slag with high oxidation property and appropriate slag basicity (R=CaO/SiO_2) is the fundamental guarantee to ensure the timely dephosphorization and no return of phosphorus to the steel.
In the initial stage of smelting, the converter goes through the desiliconization and dephosphorization, and when the slag pouring operation starts the superheat degree of the slag increases with the rise of converter temperature. This phenomenon is beneficial for the lime and slag penetration, as a result the melting point of lime decreases, With the increase of basicity, (MnO) will promote the dissolution of lime when the (FeO) content in slag is sufficient, so the slag formation is fast which cannot dry up easily in the middle of oxygen blowing. Therefore, the high lance position increases the (FeO) in the slag and the slag has good capability of quick dephosphorization. The composition of slag is controlled and the slag system with low melting point is obtained. The new manufacturing process is suitable for the actual conditions of steelworks. In the actual production conditions of molten iron, the average amount of dolomite added in slag making materials per BOF does not change much and it reduces the lime by an average of 510kg per BOF. The consumption of lime is also reduced by 4.36kg/t, which achieves the obvious economic benefits. The comparison of slag making materials is shown in Table 2.

Tab.2 - Comparison of slag making materials (the average of 100 industrial experiments).

	Lime(t)	Dolomite (t)	Consumption of lime (kg/t)	Metallic charge material consumption (kg/t)
The original manufacturing process	3.26	1.64	26.99	1062.95
Duplex process with a single converter	2.75	1.62	22.63	1060.13

The consumption of metallic charge materials is reduced from 1062.95kg/t to 1060.13kg/t, which implies that the duplex process with a single converter improves the metallic yield.
During the smelting process, a part of the slag remained in the furnace for smelting, which means that the slag with high (FeO) content will indirectly participate in the carbon-oxygen reaction. In the slag pouring process, the content of FeO decreases gradually. The (FeO) participates in the reaction to obtain [Fe] in the decarburization stage (phase decarburization), then [Fe] element returns to the furnace, and oxygen is blown again for the complete oxidation of silicon and other elements in the early stage. The lime and other slag making agents have been put into the furnace and the slag amount becomes relatively less than that of the original process. The smaller (TFe) content in the slag leads to a minimum loss of molten iron, which increases the yield of steel, while the iron and steel materials consumption was reduced by 2.82kg/t. The new manufacturing process decreased the basicity of the final slag and (CaO), and also reduced the basicity of the final (TFe) by 1.45%. The (CaO) content decreases with the minor decline of slag basicity in the double method. When the basicity of slag is too high, there will be more (CaO) and (MgO) suspended particles in the liquid slag, which will reduce the fluidity of slag and is not favorable for the dephosphorization. Therefore, it is necessary to understand the influence of slag basicity on the slag dephosphorization ability in a dialectical manner. Overall, this method is suitable for the stable production of a certain plant, its smelting effect is obvious, and the service life of the converter can be improved. The comparison of the slag for different processes is shown in Table 3.

Tab.3 - Comparison of slag (the average of 100 industrial experiments).

	CaO/%	SiO_2/%	MgO/%	MnO/%	TFe/%	R(CaO/SiO_2)
The original manufacturing process	48.48	14.55	8.98	4.05	14.82	3.33
Duplex process with a single converter (the early stage of the slag)	38.75	19.77	7.16	3.11	14.21	1.96
Duplex process with a single converter (the endpoint stage of the slag)	46.45	16.17	7.83	3.48	13.37	2.87

Dephosphorization

Through the correlation statistical test of 100 furnaces, it is found that the lime consumption, endpoint temperature and dephosphorization rate of the converter are significantly correlated. The dephosphorization rate has a significant downward trend with the increase of endpoint temperature. The double method fully utilizes the influence of temperature change on the dephosphorization reaction and reduces the endpoint temperature of the original process by 1.95C. The temperature, phosphorus content, and dephosphorization rate at the smelting end in the original manufacturing process and the duplex process with a single converter are shown in Table 4. It completes the endpoint [P] to 0.018%, and the dephosphorization rate reaches 87.20%, which when compared with the original smelting process increased by 2.01%. The quick slag pouring and retaining after the end of the blowing process can carry out the dephosphorization reaction more thoroughly. By using slag retention operation in the early stage, the residual slag will have a certain temperature and the appropriate composition as shown in Table 3. The process of first slag formation produces a low temperature in the early stage of the molten pool with better dephosphorization ability. The scatter plots for different factors are shown in Figures 3 and 4, while the Pearson correlation test results are shown in Table 5.

Tab.4 - Comparison of dephosphorization (the average of 100 industrial experiments).

	Endpoint temperature/°C	Endpoint [P]/%	Dephosphorization rate
The original manufacturing process	1652.59	0.019	85.19%
Duplex process with a single converter	1650.64	0.018	87.20%

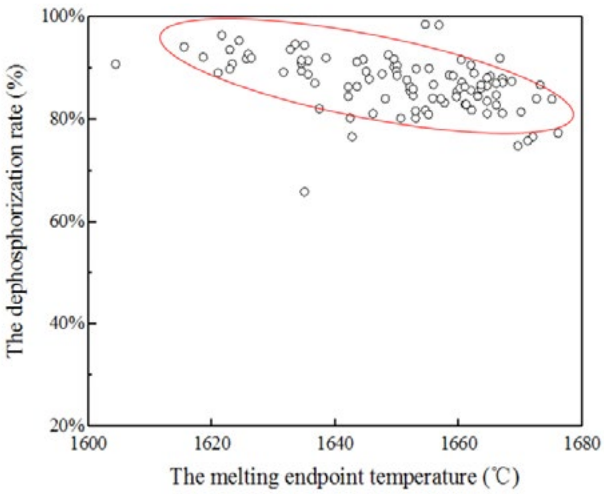

Fig.3 - Scatter plot of melting endpoint temperature and dephosphorization rate.

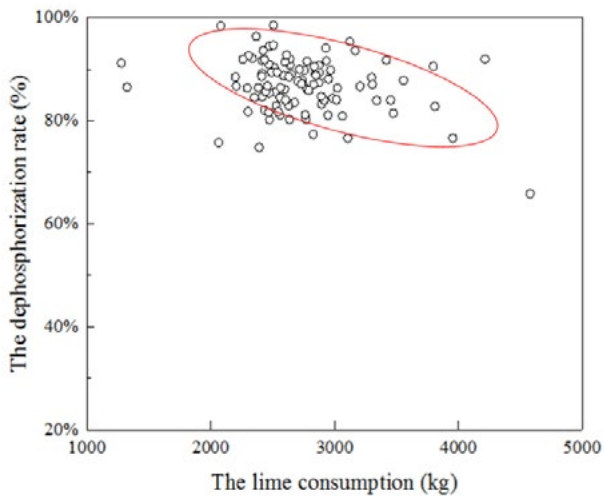

Fig.4 - Scatter plot of lime consumption and dephosphorization rate.

The red scatter region in the figure indicates that there is a linear relationship between the melting endpoint temperature, lime consumption, and dephosphorization rate. The sigma (two-tailed) are 0.002 and 0.000, as the significance value is less than 0.01, thus there is a significant correlation between the two variables [16].

This indicates that the little variation for lime can affect the dephosphorization rate of converter significantly. The correlation coefficient for the added lime and the endpoint temperature was -0.311 and -0.385, which are important factors that affect the dephosphorization rate. The results of correlation statistical analysis are in agreement with the industrial experimental results of the duplex process with a single converter.

Tab.5 - Correlation analysis (**- The correlation was sigma 0. 01 (two-tailed), N-number).

		Consumption of lime (kg)	Endpoint temperature/°C
The dephosphorization rate	Pearson correlation Sigma (two-tailed) N	-0.311** 0.002 100	-0.385** 0.000 100

Analysis of BOF spatter accident

In the actual manufacturing process of steelworks, the oxygen lance position has no normal operation specifications during the oxygen smelting process and the BOF converter spatter accident occurs in 4-5 min during the smelting process. The high [P] content in the molten iron, the low slag viscosity with high slag quantity, and easy slag foam formation lead to a spatter rate of 63.30% in a steel plant. The spatter accident reduces the service life of the converter, damages the oxygen lance and shaft, increases the security-hidden risk during the converter process and has a serious risk to the worker's life safety. In the duplex process with a single converter, (FeO) content is controlled by changing the oxygen lance position. Meanwhile, the second batch of slag making materials should be added in small amounts to stabilize the BOF temperature and carbon reduction rate. A slag pouring is carried out in the smelting process to create a thinner slag layer and reduce the accumulation of (CO^2) under the slag layer which is due to the slag drying and results in explosive spatter. The spatter accident is found to be reduced by 35.40%, which is significantly lower than the original process.

CONCLUSION

(1) Duplex process with a single converter have "low-high-low" operation specification for oxygen lance. The oxygen blowing time was reduced by 62s, which reduced the smelting cost.

(2) The new process reduces the metallic charge material consumption by 2.82kg/t, and also reduces the amount of iron in slag (TFe) by 1.45%, as compared to the original process.

(3) The industrial data show that after using duplex process with a single converter, the consumption of lime is reduced to 4.36kg/t, which is consistent with the results of correlation analysis. The new process reduces lime consumption and slag with increased dephosphorization rate.

(4) The new process reduces the slag amount due to the slag pouring in the smelting process. It lowers the risk of spatter accident rate to 35.40% and avoids the slag drying. It also stabilizes the converter production to ensure the safety of equipment and workers.

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