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Improvement in Free Opening Performance of Ladle Filler Sand

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Even though ladle filler sand in CSC No.1 B.O.F (Basic oxygen steelmaking) Plant has a free opening rate of 98%, the ratio of oxygen lancing is still high, leading to an increase in the steelmaking cost, and an unsafe operating environment. Therefore, this study aimed to develop a ladle filler sand with a high free-opening efficiency.

After investigation, the causes of non-free opening were concluded to be due to longer holding time of molten steel in the ladle, deterioration of well blocks, first casting after ladle repaire, direct charging of molten steel on filler sand, and solidified scrap around the ladle well nozzle. The first three causes can be further solved by improving the qualities and properties of the filler sand. Based on the current chromite-based filler sand, a new filler sand was developed with a higher Cr2O3/SiO2 ratio as well as the amount of sintering agent being increased by 0.12 and 1%, respectively. The superior properties of the new filler sand achieved an appropriate softening temperature T0 that can fit with the preheating temperature of ladles, and an optimum thickness of the sintered layer, 7~ 8 mm. Finally, a free opening rate of 99% was achieved in No.1 Steel Plant after nearly five hundreds ladle tests.

Keywords: Filler Sand; Free Opening Rate; Oxygen Lancing

1. INTRODUCTION

Ladle filler sand is used to fill up the well block and upper nozzle to keep the slide gate system separated from the molten steel. When filler sand contacts with molten steel, it can quickly react to form a softened layer and a sintered layer to prevent the molten steel from penetrating into the slide gate system. When the slide gate is opened, the unsintered sand falls out first and then the sintered layer is crushed by the static pressure of the molten steel, which results in the molten steel being able to flow quickly through the well nozzle. This process is called free opening. The blocking of the ladle well sometimes happens due to the inappropriate sintering of filler sands. Ultimately, the flow of molten steel must be re-established by using an oxygen lancing process, which would contaminate the steel and disrupt the casting schedule.(1-3)

Ladle filled sand is one kind of dry monolithic refractory. Three kinds of filler sands are widely used in steel ladles, including silica, zircon, and chromite based sands. An excellent filler sand must have a balance between refractoriness and liquid sintering, which can form the sintered layer with an appropriate thickness. A thicker sintered layer requires a greater static pressure by the molten steel to be broken, which is unfavorable for free opening during the casting process. Therefore, it is necessary to understand the sintering behavior of filler sands. Several properties of filler sands, such as composition, particle size distribution, and packing density have a greater impact on the formation of the sintered layer. Furthermore, physical properties of particles, including low thermal expansion and low angle of repose, are required for filler sands in order to avoid bridging of unsintered filler sands in ladle nozzles.(4-6)

Even though ladle filler sand in CSC No.1 B.O.F. Plant has a free opening rate of 98%, the ratio of oxygen lancing is still high, resulting in quality deterioration of the slab, disruption to the casting schedule, and an unsafe operating environment. Therefore, this work aims to develop a ladle filler sand with high free-opening efficiency. We first investigated the reasons of non-free opening in CSC No.1 B.O.F. Plant, and then improved the sintering characteristics of the filler sand, including an adjustment to the main composition ratio and the amount of sintering aid, in order to increase the free opening rate.

2. EXPERIMENTAL METHOD

2.1. Materials

The starting materials used in this study to fabricate the filler sands are chromite, silica, and feldspar. Chromite and silica having spinel and quartz structures respectively are the main ingredients of filler sands. Feldspar is used as a sintering agent for filler sands in order to form the sintered layer quickly when the sand comes into contact with the molten steel. Most of the filler sands in this study have a particle size distribution ranging from 0.1 mm to 1 mm.

2.2. Characterization

In order to evaluate the packing state and flowablitity of the filler sands in the ladle well, this study analyzed the characteristics of the sand particles, including the angle of repose and packing density. The experimental procedures are described as follows.

2.2.1. Angle of repose

500g of the filler sand were weighed and filled into a funnel. And then the filler sand fell freely from the mouth of the funnel to a circular platform (radius: r). After all particles of the filler sand had fallen, the height (h) of the cone formed by the filler sand on the circular platform was measured in order to calculate the angle of repose (α) with the following formula: $\tan\alpha = h/r$.

2.2.2. Packing density

1000g of the filler sand was weighed and poured into a volumetric cylinder with a fixed cross-section. After the packing volume of the filler sand was obtained by reading the scale mark of the volumetric cylinder, the packing density was determined by the packing weight and volume.

2.3. Observation of sintering behavior

In order to understand the mechanism of the sintered layer formation after the filler sand contacts the molten steel, this study also observed the sintering behavior of the filler sand, including the sintering shrinkage, density/porosity, refractoriness under load (RUL). The difficulty of the sintered layer being crushed by static pressure of the molten steel was evaluated by measuring the cold crushing strength of the filler sand after sintering. Furthermore, the experiment was designed to observe the sintered filler sand in contact with the molten steel. The experimental procedures are described as follows.

2.3.1. Sintering shrinkage, density/ porosity, and cold crushing strength

The filler sands were poured into several ceramic crucibles and then sintered at 1600°C/2h in an electric furnace. The sintering shrinkage, density/ porosity, and cold crushing strength of the sintered bodies were then measured. Both the microstructure and phases of the sintered filler sands were confirmed by a scanning electron microscope (SEM) with energy dispersive spectrometer (EDS).

2.3.2. Refractoriness under load

The aforementioned specimens of filler sands sintered at 1600°C/2h were cut into cylindrical bars (50φ×50h mm) for verifying refractoriness (softening temperature) under load of 0.2MPa (static pressure of the molten steel) by commercial equipment with the temperatures ranging from 25°C to 1600°C. Based on the RUL testing curve, the characteristic T_0 temperature can be determined when the RUL curve reached maximum expansion. The characteristic T_2 temperature can be determined from the RUL curve where 2% shrinkage is reached after the maximum expansion.

2.3.3. Analysis of the molten steel penetration

A refractory brick with an appropriate size (140L×132W×64H mm) was drilled with several holes (φ30×50H mm) which were then filled with the filler sand, and pre-heated at 1100°C/2h in an electric furnace. After preheating, steel was put on the holes of the brick and then heated by a gas burner until molten. Each testing cycle was keep at 1600°C for 60 mins. After the residual steel was poured out, new steel was put on the holes of the brick in order to start the next testing cycle. After finishing the 3 testing cycles, the brick was cut through the center of the hole to observe whether the molten steel had penetrated into the sintered layer of the filler sands.

3. RESULTS AND DISCUSSION

3.1. Root cause analysis of non-free opening in No.1 B.O.F. Plant

The free opening rate of CSC No.1 B.O.F. Plant filler sand has never been able to exceed 98.5%, and the ratio of oxygen lancing is relatively high. In order to further understand the reasons for the non-free opening in No.1 B.O.F. Plant, this study conducted an overall survey of ladle operating parameters from 2018/09 to 2018/11 when the free opening rate did not reach 98%. 7076 heats of ladle operation data were collected for statistics. Finally, 145 heats were focused on for reasons of non-free opening, as shown in Table 1. Further description is as follows.

(1) Longer holding time of molten steel in ladle

According to investigations, the average holding time of molten steel in No.1 B.O.F. Plant was 150mins. Due to the refining of high-grade steel, the holding time

Table 1 Root cause analysis of non-free opening in CSC No.1 B.O.F. Plant.

Causes of non-free opening	Ladles belong to non-free opening	Ladles belong to non-opening (Slide gates do not open even by using O_2 lancing)
Longer holding time of molten steel (≧150mins)	32 (22%)	2 (9%)
Deterioration of well blocks (≧30 heats)	39 (27%)	3 (13%)
First casting after ladle repairing	8 (6%)	2 (9%)
Direct charging of molten steel on filler sand	9 (6%)	9 (39%)
Solidified scrap around ladle nozzle	1 (<1%)	1 (4%)
Other	56 (39%)	6 (26%)

was up to 200mins or even 300mins. When the molten steel remains in the ladle for a longer time, the sintered layer of the filler sand would be too thick and cannot be broken by the static pressure of the molten steel.

(2) Deterioration of ladle well blocks

When the ladle well block was used for longer times (>30 heats), the sintered layer would be formed in a lower position, resulting in the surface area of the sintered layer decreasing due to the smaller diameter of the hole. Therefore, the sintered layer would become more difficult to be crushed.

(3) First casting after ladle repairing

The preheating temperature of the ladle after repairing would be lower due to insufficient heat storage during the first casting. If the temperature at which the filler sand starts to sinter is higher, the sintering layer will not be completely formed during the first casting. In this case it will result in the molten steel penetrating into the slide gate.

(4) Direct charging of molten steel on filler sand

When the refining temperature of a ladle was insufficient, the molten steel would be poured into another empty ladle that has been preheated and filled with the filler sand. This is called the "re-ladle" process. In this case, the molten steel would directly rush into the well block, causing a large amount of the filler sand to be scattered. Therefore, the "re-ladle" process often results in the sliding gate no been able to be opened.

(5) Solidified scrap around ladle well nozzle

When the temperature of the ladle was too low, the molten steel would be directly solidified around ladle well nozzle. Therefore, the filler sand cannot protect the slide gate.

(6) Other

In this study, some reasons of non-free opening are still not clearly understood. One of them could be the interaction between the liquid steel and the filler sand. Some literatures report that the molten steel could enhance the sintering of the sand and the dissolved elements, such as Mn and Al, have a greater impact on the sintering behavior.(7-9) However, there are so many steel grades in No.1 B.O.F. Plant, that it is difficult to statistically summarize the composition changes of all steel grades.

3.2 Development of filler sand with high free opening rate

Based on the root cause analysis of non-free opening, this study modified the composition of the current filler sand used in No.1 B.O.F. Plant. The root cause analysis revealed that the two major reasons for non-free opening, which related to the filler sands were as follows: (1) larger thickness of the sintered layer (Longer holding time of molten steel in ladle); and (2) easy penetration of the molten steel through the sintered layer (deterioration of ladle well blocks; and first casting after ladle repairing). In summary, this research proposes two directions for modifying the current filler sand as follows.

(1) Increasing the chromite phase with high refractoriness can be conducive to the stability of the filler sand at high temperature and slow down the thickening rate of the sintered layer.

(2) Increasing the amount of sintering agent in the filler sand can reduce the temperature of liquid phase formation to match the preheating temperature of the ladle.

According to the composition of the current chromite-based filler sand, the new filler sand was developed with a higher Cr_2O_3/SiO_2 ratio and the amount of sintering agent increased by 0.12 and 1%, respectively. Slightly increasing the Cr_2O_3/SiO_2 ratio of the current material formula by 0.12 can maintain a sufficient silica phase, which is still conducive to the formation of the dense sintered layer.

Further analysis of the characterization and sintering behavior of the current and new filler sands in this work are shown in Table 2 and Fig.1. In terms of particle characterization, Table 2 shows that the slight increase in the ratio of Cr_2O_3/SiO_2 and the amount of sintering agent does not affect the flowability. The angles of repose of the two kinds of filler sands are both 35°. The packing densities of the 2 type filler sands are ranging from 2.28 g/cm^3 to 2.29 g/cm^3. The modification in the composition of the filler sand does not cause changes in the packing of particles.

In terms of sintering behavior, Table 2 reveals that the bulk density and shrinkage of the new filler sand are also higher than those of the current filler sand by increasing the amount of sintering agent, facilitating sintering of the filler sand. According to the RUL analysis as shown in Fig.1, it can be found that the softening temperature T_0 of the current filler sand is reduced from 1250°C to 1100°C by increasing the amount of sintering agent. In other words, the liquid phase formation temperature of the new filler sand can coincide with the preheating temperature of the ladles. As shown in Fig.1, it can be also found that the softening temperature T_2 (the temperature at which 2% shrinkage is reached) of the current filler sand is slightly higher than that of the new filler sand. These results would indicate that the new filler sand has a slightly thicker sintered layer due to higher liquid phase fraction. When the formation temperature of the filler sand is higher than the preheating temperature of the ladle, penetration of the molten steel can easily occur, which results in the slide gate being completely inoperable even with the use of oxygen

Table 2 The characterization and sintering behavior of the current and new filler sands

	The current filler sand	The new filler sand
Characterization of filler sands particles		
Angle of repose (°)	35	35
Packing density (g/cm^3)	2.28	2.29
Sintering behavior of filler sands (@ 1600℃/2h)		
Bulk density (g/cm^3)	2.86	2.88
Porosity (%)	27.81	26.96
Shrinkage (%)	-5.00	-6.11
Cold crushing strength (MPa)	15.3	19.3

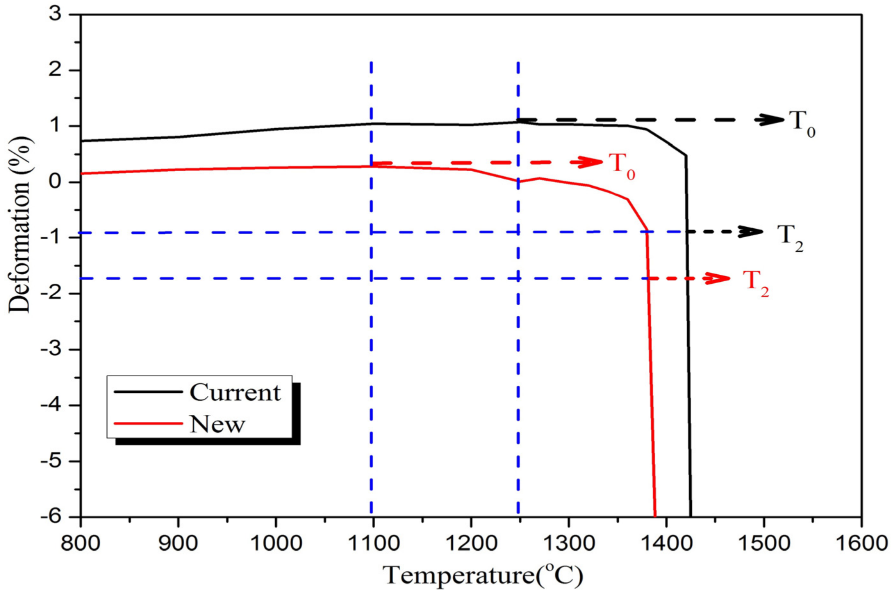

Fig.1. RUL curves of the current and the new filler sands.

lancing. This is the most undesirable situation during the refining process. In this study, it is preferred to modify T_0 of the filler sand to coincide with the preheating temperature of the ladle.

Figure 2 shows the ability of the two kinds of filled sands to hinder the penetration of molten steel. It can be observed that the pre-heated (1100ºC) current filler sand is still partially penetrated (denoted by red circles) when the high-temperature molten steel is poured, as shown in Fig.2(a). Because the T_0 of the current filler sand is higher than the pre-heating temperature (1100ºC), the sintered layer of the current filler sand cannot form during pre-heating. In this case, it can easily result in the penetration of molten steel. The new filler sand with adjusted composition can hinder the penetration of high-temperature molten steel, as shown in Fig.2(b).

Figure 3 displays the SEM and EDS mapping analysis of the sintered filler sands. Figure 3(a) shows that most of the chromite-based discontinuous phase in the sintered layer of the current filler sand is surrounded by the silica-based continuous phase. As shown in Fig.3 (a), some large pores are still in the microstructure of the sintered current filler sand, and can be the positions that are easily penetrated by the molten steel. Figure 3(b) displays that the chromite-based discontinuous phase in the sintered layer of the new filler sand is dispersed uniformly in the silica-based continuous phase. As shown in Fig.3(b), the overall microstructure of the sintered filler sand is relatively dense, which also explains why the new filler sand can hinder penetration of the molten steel.

Figure 4 displays the SEM images of the bulk sample corresponding to Fig.3(b), which reveals penetration of the molten steel can be hindered by the sintered layer of the new filler sand. As shown in Fig.4, it can be observed that the molten steel (the area above the red dashed line) is blocked by the dense sintered layer, which has a thickness of 1mm (the area enclosed by the red and yellow dashed lines). The porous sintered layer is under the dense sintered layer. The thickness of the porous layer is about 6~7mm (the area below the yellow dashed line).

The following equation reveals the relationship between the static pressure of the molten steel and critical thickness of the sintered layer;(10)

$$P = P1 + P2 + P3 = \frac{2\gamma_1}{R_1}\delta_1 + \frac{2\gamma_2}{R_2}\delta_2 + \frac{2\gamma_3}{R_3}\delta_3$$

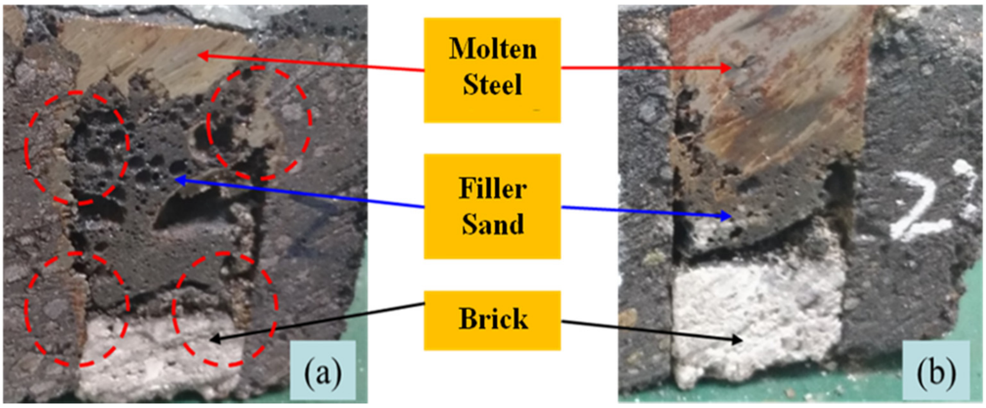

Fig.2. Molten steel penetration experiment of (a) the current and (b) the new filler sands.

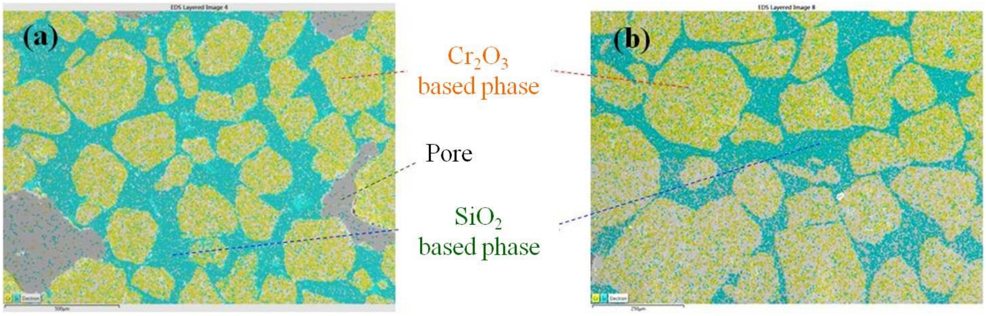

Fig.3. SEM images of the sintered (a) current filler sand and (b) new filler sand.

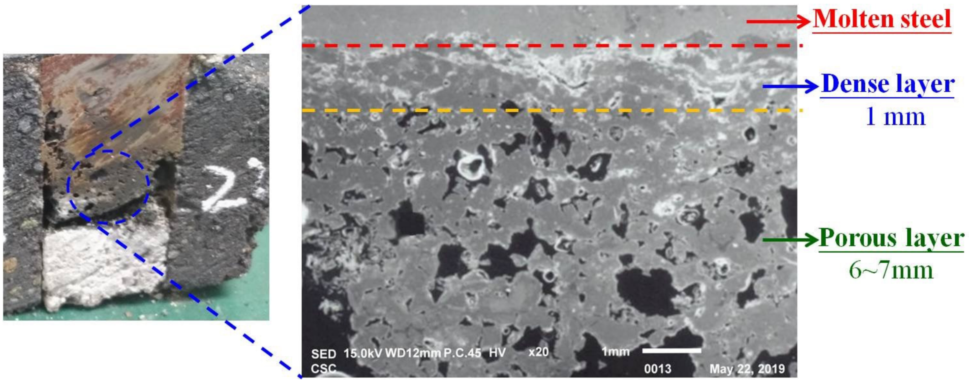

Fig.4. Observation of the interface between the steel and the sintered layer of new filler sand.

where P is the static pressure of the molten steel, γ_1 the thickness of the freezing layer of molten steel, γ_2 the thickness of the penetration layer from the molten steel to the filler sand, γ_3 the thickness of the sintered layer of the filler sand, $\delta_{1,2,3}$ the shear stress of each layer, $R_{1,2,3}$ the limit radius of each layer when the sliding gate is opening, $P_{1,2,3}$ the partial pressure of each layer. According to the above model, when the hydrostatic pressure of the steel is 0.2 MPa in No.1 B.O.F Plant, the critical thickness of each layer is: γ_1=0.5 mm, γ_2=1 mm, γ_3=9 mm. This calculation also reveals that the thickness of the sintered layer of filler sand must be controlled within 10.5mm ($\gamma_1+\gamma_2+\gamma_3$) in order to freely open. Based on the SEM result of Fig.4, the sintered layer thickness of the new filler sand is 7~8mm, which is less than the maximum critical thickness of 10.5mm, derived from the theoretical calculation.[10] Therefore, the new filler sand is suitable for the refining process in No.1 B.O.F Plant and can be conducive to free opening.

3-3 Performance of the new filler sand in CSC No.1 B.O.F Plant

The new filler sand developed in this work was tested in 2019/05. After testing 499 ladle heats cycles, only 5 were non-free opening, resulting in a new record for a free opening rate of 99% being achieved in CSC No.1 B.O.F Plant. The average number of oxygen lancing operations per heat caused by the current filler sand was 1.95 from 2017/09 to 2017/11. In this work, only 1 oxygen lancing operation was necessary. The decrease in the number of oxygen lancing operations will greatly reduce the cost of steelmaking. The development of new filler sand is expected to save the annual steelmaking costs in No.1 B.O.F Plant by about 8-10 million NT$, and further avoid an unsafe operating environment.

4. CONCLUSIONS

In CSC No.1 B.O.F Plant, causes of non-free opening were concluded by a longer holding time of molten steel in the ladle, deterioration of well blocks, first casting after ladle repairing, direct charging of molten steel on filler sand, and solidified scrap around ladle well nozzle. According to the root cause analysis, the new filler sand was developed with a higher Cr_2O_3/SiO_2 ratio and the amount of sintering agent increased by 0.12 and 1%, respectively.

Compared with the current filler sand, the new one has a lower softening temperature T_0 that can fit with the preheating temperature of the ladles. The new filler sand also reveals the denser microstructure of the sintered layer that can hinder penetration of the molten steel. By summarising the experiment result and theoretical calculation, the sintered layer of the new filler sand has an appropriate thickness that can be crushed by the static pressure of the molten steel in CSC No.1 B.O.F Plant. Finally, a new record for a free opening rate of 99% was achieved in No.1 Steel Plant after 499 heat cycles of ladle testing.

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