Progress in Slag-Free Tapping Technologies for Basic Oxygen Furnace

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During the tapping process, slag flows to the ladle through the tap hole. When slag reacts with liquid steel in the ladle, it affects the composition of the steel. By using slag-free tapping technologies, the outflow of slag to the ladle can be effectively reduced. CSC mainly uses slag darts to execute slag-free tapping. To achieve the goal of high-value refined steel production, we aim to improve the effectiveness of slag-free tapping through four main strategies. These are to increase the hit rate of dart dropping at the tap hole, optimize the shape of darts, develop the repair method for replacing the tap-hole sleeve, and improve the shape of the tap hole. By enhancing the slag-controlling process through the above-mentioned methods, CSC can not only reduce the quality failure rate but also improve the yield of the steelmaking process.

Keywords: Slag-free tapping, Dart, Sleeve, Flow contraction

1. INTRODUCTION

The Basic Oxygen Furnace (BOF) uses oxygen to oxidize impurity elements and form slag. However, during the tapping process, a portion of slag flows into the ladle through the tap hole. When slag reacts with liquid steel in the ladle, it affects the phosphorus composition in the steel due to a reduction reaction. This phenomenon is often called phosphorus reversion. In addition, slag with high oxygen potential easily oxidizes alloying elements such as aluminum, silicon, and manganese. The above-mentioned phenomena not only affect the quality of steel but also increase the cost of steel production. Therefore, it is important to reduce the outflow of slag during the tapping process.

There are several common practices for slag-free tapping, such as slag balls, slag darts, pneumatic slag stoppers, and slide gates(1). The CSC steelmaking plant uses slag darts to perform the slag-free tapping process. The density of a slag dart lies between that of liquid steel and slag. When it is dropped into the tap hole, it positions itself at the interface between the steel and the slag. It reduces the suction of slag caused by the liquid flow eddy and then blocks the tap hole at the end of tapping (2). There are several channels around the dart, and the residual liquid steel flows into the ladle after the dart blocks the tap hole; thus, the steel flow exhibits a contraction behavior. The flow contraction is also helpful in identifying the ending time of tapping.

Recently, there have been increasing demands for clean steel products. It is very important to increase the success rate of slag-free tapping. However, there have been few studies on slag darts in the past. This study aims to analyze the damage mechanism of used darts and to simulate the coupled behavior among the dart, liquid steel, and liquid slag. Finally, CSC proposes four strategies: to increase the hit rate of dart dropping in the tap hole, improve the shape of the dart, develop new repair methods for replacing the tap-hole sleeve, and optimize the design of tap-hole sleeves. This article discusses the advantages and disadvantages of these strategies.

2. RESEARCH METHODS

The success rate of slag-free tapping is related to three critical indicators: the hit rate of dart dropping at the tap hole, flow contraction caused by the dart, and the slag dart retention rate. Table 1 presents the detailed data for these three critical indexes.

The first indicator represents the proportion of darts that successfully drop into the tap hole. The second indicator represents whether the steel flow exhibits a contraction behavior when the dart successfully drops

Table 1 Three critical indexes for the success rate of slag-free tapping.

Success rate of slag-free tapping	Hit rate of dropping in the tap hole	flow contraction by dart	slag dart retention rate
Before improvement	Standard	Standard	Standard
After improvement	+5.0%	+3.5%	+0%

into the tap hole. Effective contraction helps reduce the amount of slag carried over. The third indicator represents whether the contraction continues until the end of tapping.

This research includes four strategies to improve slag-free tapping technologies.

2.1 Increasing the Hit Rate of Dart Dropping at the Tap Hole

At CSC, the original dart machine used a pneumatic motor and a contact-type stopper. Because of the contact-type stopper, deviation in the dropping position was often observed, and operators could not precisely adjust the dart dropping position. CSC upgraded the dart machine, which is now driven by an electric motor and uses an encoder to record the dart dropping location.

2.2 Analyzing the Erosion Mechanism of the Slag Dart and Improving the Dart Shape

A slag dart consists of a dart head and a dart stick. During the tapping process, the slag dart comes into contact with liquid steel for a maximum of about five minutes. Therefore, it is not necessary to use the refractory material with excellent high-performance characteristics. We analyze the damage mechanisms used by dart heads and sticks. Based on the analysis results, we developed improvement strategies for dart design and materials.

2.3 Developing a New Repair Method for Replacing the Tap-Hole Sleeve

When replacing a tap-hole sleeve, a gunning material with phosphate-based binders was generally used to fill the gap between the sleeve and wall bricks. Figure 1 shows that pits can form around the sleeve when this gunning material becomes severely eroded. The sleeve is easily damaged by the shear stress of the steel flow, preventing the dart can't completely blocking the tap hole. This study explores to use of a gunning material with organic binders and an MgO-C-based hot repair mix to reduce the pit formation.

2.4 Optimizing the Design of the Tap-Hole Sleeve

Slag-free tapping performance is closely related to the erosion of the tap-hole sleeve. The Dynamic Fluid Body Interaction (DFBI) model in ANSYS Fluent was employed to simulate the coupled behavior between the slag dart and the surrounding liquid.

As the molten steel level drops during tapping, the slag dart moves toward the tap hole and displaces nearby liquid steel. This study simulates the flow field and pressure variations for both straight and taper sleeve designs, and calculates the descent velocity of the slag dart and the tapping volume. These results were used to evaluate the steel contraction flow conditions.

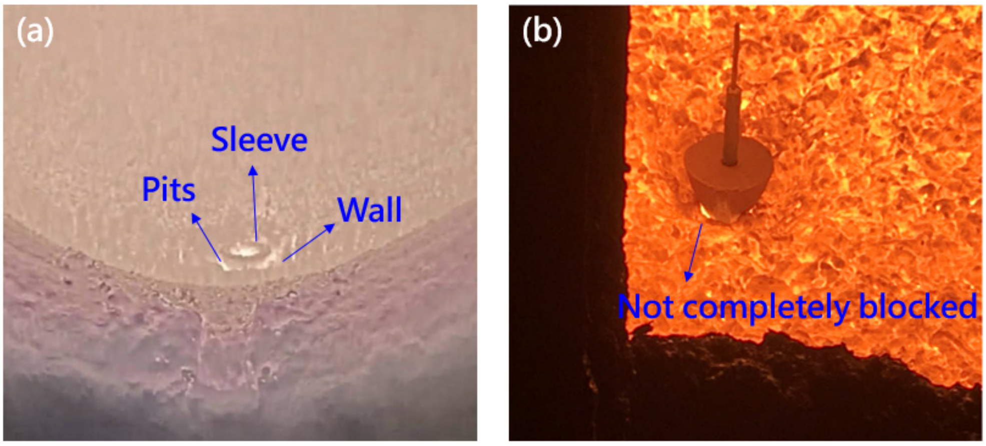

Fig.1. Sleeve shape after erosion damage: (a) pits formed around the sleeve, (b) incomplete blockage after dart dropping.

3. RESULTS AND DISCUSSION

3.1 Increasing the Hit Rate of Dart Dropping at the Tap Hole

CSC upgraded the dart machine to one that uses an electric motor. The dart can now be dropped into the tap hole with much higher precision. The dropping location can be set using remote control rather than by manually adjusting the stopper. In addition, the operation information is displayed on the control panel.

Operators can easily compare positional difference before and after replacing the tap-hole sleeve. Cameras have been installed to monitor the dart dropping process, allowing operators to adjust the dropping location safely and precisely, as shown in Figure 2. Table 1 shows that the hit rate of dropping into the tap hole increased by 5%.

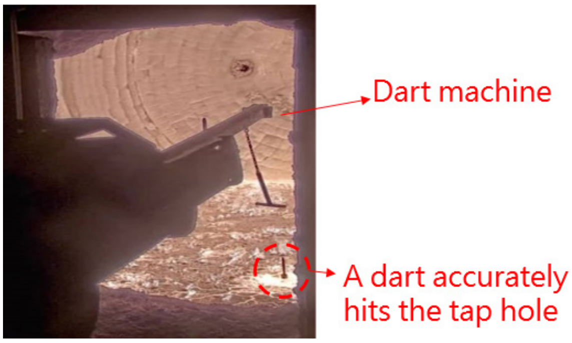

Fig.2. Monitoring of the dart dropping process using an installed camera system.

3.2 Analyzing the Erosion Mechanism of the Slag Dart and Improving the Dart Shape

By observing the cross-section of a used dart that contacted slag and steel at 1700°C, Figure 3 shows that its diameter decreased by 12% and several cracks were observed on the surface. Penetration of steel and slag into the interior of the dart was not observed. The damage mechanism is likely due to the combined effects of surface erosion and thermal stress, which caused cracking or structural collapse.

In addition to investigating the damage of the dart head, it was found that the positioning function is affected if the dart stick separates from the dart head. Operators occasionally observed dart sticks flowing into the ladle with liquid steel. Based on past observations of used darts, the steel bars of the dart sticks were completely preserved, indicating that the refractory material of the stick could withstand erosion by high-temperature liquid steel. However, liquid steel can penetrate the gap between a dart head and stick, causing separation.

A new design was developed to decrease this gap by 60%. Figure 4 shows that the plug remained completely intact, and neither liquid steel nor slag penetrated the dart head. The new design prevents dart separation and ensures that the positioning function remains effective until the end of tapping.

3.3 Developing a New Repairing Method for Replacing the Tap-Hole Sleeve

Figure 5 shows three refractory designs around the sleeve, Table 2 presents the erosion indexes for three repairing materials from the laboratory tests. To reduce pit formation around the sleeve, a gunning material with organic binders (Figure 5(b)) was used to replace the conventional phosphate-based gunning material (Figure 5(a)). Although the gunning material with organic binders exhibited excellent erosion resistance in laboratory tests, field tests showed that it required approximately 40 minutes to sinter and failed to form a smooth surface. Moreover, after only 66 heats, the gunning material was damaged and gaps formed due to shrinkage (Figure 6).

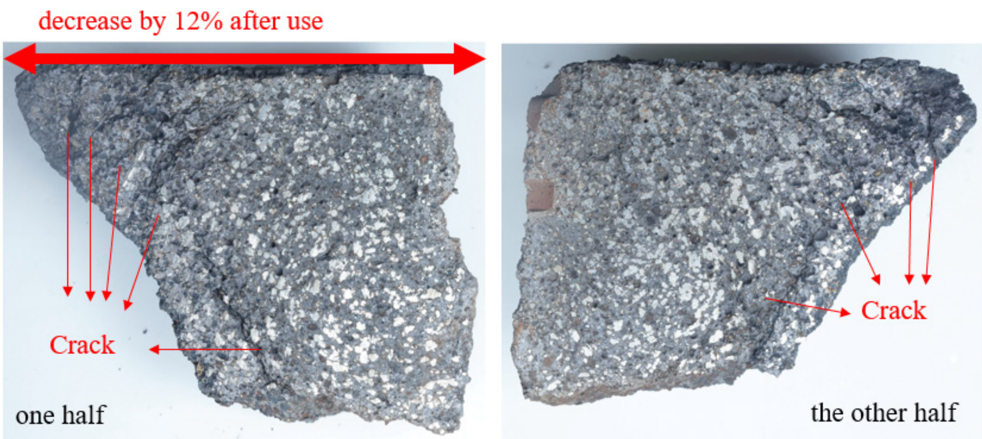

Fig.3. Cross-section of the used dart head.

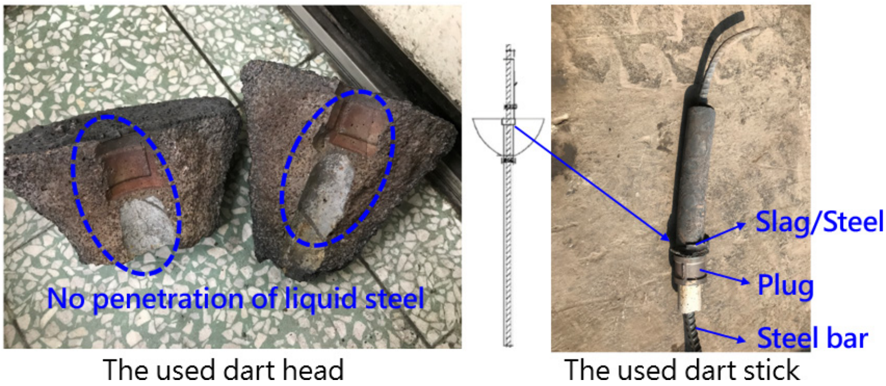

Fig.4. Cross-section of the used dart head and stick.

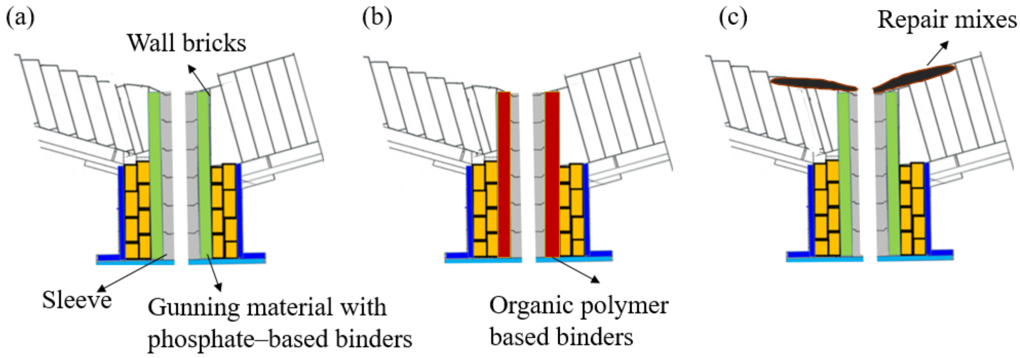

Fig.5. Three structures around the sleeve. Use the gunning material with (a) phosphate-based binders, (b) with organic polymer binders, (c) the hot repair mixes.

Table 2 Erosion index of three repairing materials from laboratory tests.

Material Type	Gunning Material with phosphate-based binders	Gunning Material with organic binders	Hot repair mixes
Erosion index	100%	88%	28%

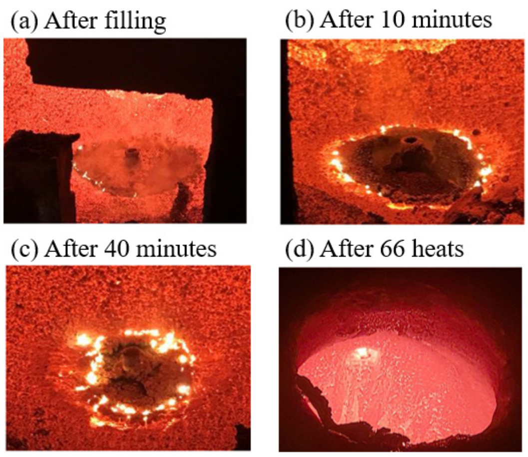

Fig.6. Use of organic polymer-based gunning material. (a) after filling the gap between a sleeve and the wall bricks, (b) after 10 minutes, (c) after 40 minutes, (d) after 66 heats of operation.

Therefore, the gunning material with organic binders was deemed unsuitable to replace the phosphate-based binder material.

Another method to reduce the pit formation was to use MgO-C-based BOF hot repair mixes. These repair mixes were manually thrown to cover the surface of the gunning material, bricks, and sleeve. They only required 15 minutes to sinter— significantly less than that of the gunning material with organic polymer binders. The operation procedure is shown in Figure 7. The success rate of the flow contraction increases by about 5%. However, further improvement is required to eliminate the safety risk of manually applying the repair mixes in extremely high-temperature environments.

3.4 Optimizing the Design of the Tap-Hole Sleeve

By simulating the flow field interactions among steel, slag, and the dart, the design of the tap-hole sleeve was theoretically improved. Figure 8 shows the simulation results of the flow field and static pressure. Compared with the straight sleeve, the taper sleeve features different diameters at both ends. Simulation analysis indicates that the taper sleeve exhibits a higher vorticity magnitude at the top of the dart than the straight sleeve. The higher vorticity magnitude enhances the contraction of the steel flow.

The simulation result also shows that the taper sleeve generates a higher negative static pressure at the top of the tap hole compared with the straight sleeve. This negative static pressure provides stronger suction. As shown in Figure 9, the taper sleeve achieves a better steel flow contraction rate than the straight sleeve, without affecting production efficiency.

Fig.7. Application of hot repair mixes. (a) after replacing the sleeve, (b) throwing the hot repair mixes, (c) after sintering for 15 minutes.

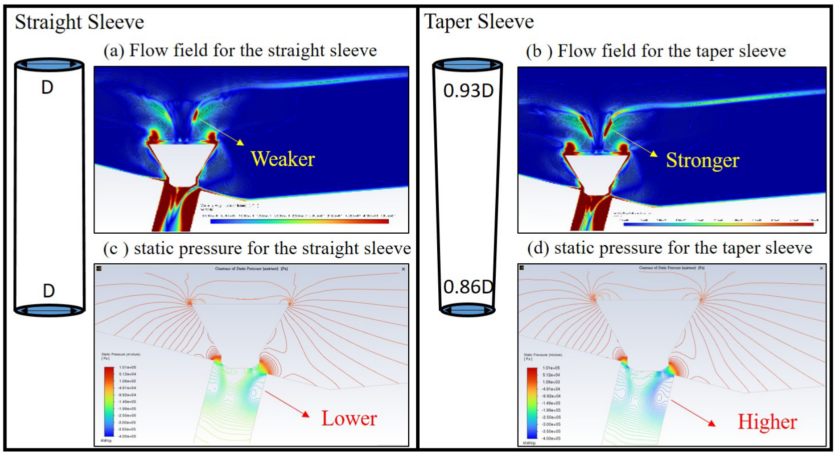

Fig.8. Comparison of flow field and static pressure distribution for different sleeve shapes: (a) flow field of the straight sleeve, (b) flow field of the taper sleeve, (c) static pressure of the straight sleeve, (d) static pressure of the taper sleeve.

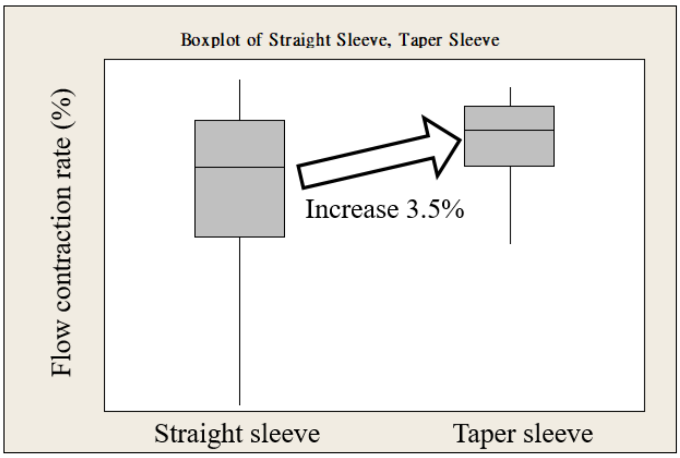

Fig.9. Variation in flow contraction rate for sleeves of different shapes.

4. CONCLUSION

The progress of slag-free tapping technologies plays a very important role in basic oxygen furnace (BOF) steelmaking. Several breakthroughs in this field have been achieved through the analysis of used darts and simulation results.

(1) Upgrading the dart-dropping machine with electric control:
The dart can now be dropped into the tap hole much more precisely. The hit rate of dropping in the tap hole increased by 5%.

(2) Reducing the gap between the dart head and the dart stick by 50%:
This improvement prevents the separation of the dart and ensures that the positioning function—keeping the dart at the tap hole—remains effective throughout the tapping process.

(3) Using hot repair mixes to protect the surface of the filling region:
The gunning material is no longer severely eroded. This new repair method effectively prevents the formation of gaps between the sleeve and wall bricks, thus preventing sleeve damage caused by the shear stress of liquid steel.

(4) Optimizing the sleeve design through flow field and static pressure simulation:
The taper sleeve exhibits higher negative static pressure and greater vorticity magnitude. These characteristics enhance the contraction of the steel flow.

Through the above-mentioned strategies, slag-free tapping can be effectively applied to BOF steelmaking to prevent phosphorus reversion. These advancements in slag-free tapping not only reduce the rate of quality failures but also increase the yield of the steelmaking process.

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