Mechanism of Mold Powder Entrapment Caused by Large Argon Bubble in Continuous Casting Mold

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1. Introduction

Mold powder entrapment into molten steel is known to lower the quality of finished steel products significantly. A lot of investigations have been carried out on this subject.1–5) Figure 1 shows five types of mold powder entrapment known to date. The most popular one is indicated by (1), being caused by a flow reversing from the narrow face of the mold.1) The mold powder which covers the molten steel layer is carried into the molten steel due to strong shear stress acting on the interface between the mold powder and molten steel. The second one, (2), is caused through the effect of high shear stress induced by unsteady reversing flow.2) The well-known Kelvin–Helmholtz instability is the main cause of this type of entrapment. The third one, (3), is the entrapment induced by the Karman vortex streets shed regularly behind the SEN.3) The Karman vortex streets are generated by the uneven meniscus flow which is uniquely related to uneven discharging molten steel flow at the ports of the SEN. The forth one, (4), is the entrapment caused by attack of a large argon bubble coming from the ports of the SEN to the interface.4) The fifth one, (5), is also caused by the uneven discharging flow.5) The mold powder descends along the outer surface of the SEN due to pressure decrease on the rear surface of the SEN, and it is entrained in the discharging molten steel flow at the ports of the SEN.

Among the five types of mold powder entrapment mentioned above the mechanism of the fourth type is not fully understood yet even in model experiments. The findings obtained so far on this entrapment are briefly reviewed here. Argon gas is supplied in the SEN in order to prevent attachment of nonmetallic inclusions such as alumina to the inner wall of the SEN. The gas sometimes becomes a large bubble at the port of the SEN and rises in the molten steel layer. This argon bubble passes through the interface between the molten steel and mold powder layers and causes entrapment of the mold powder into the molten steel layer. Unfortunately, the effects of the physical properties of mold powder, the thickness of the mold powder layer and the size of the argon bubble on the entrapment are not known. The main objective of this study therefore is to clarify these effects.

2. Experimental Apparatus and Procedure

Figure 2 shows a schematic of the experimental apparatus. The vessel is made of transparent acrylic resin and it has a square cross-section of 0.200 m×0.200 m and a height of 0.600 m. This 0.200 m was chosen as a representative thickness of the real continuous casting molds. Water was used as a model for molten steel and some kinds of silicone oils as models for mold powder. The physical properties of them are listed in Table 1. The water was filled to a depth of 0.280 m and one of the silicone oils was placed on the water layer. The depth of the silicone oil layer was 0.070 m for all measurements. A square plate of 8×10⁻³ m in thickness and 0.190 m×0.190 m in cross section was horizontally immersed in the silicone oil layer. The plate is used as a simplified model for the real non-melted mold powder layer though the layer consists of partly sintered powder. The distance from the interface between the water and silicone oil to the lower surface of the plate, h₀, was set to be 0.020, 0.040 or 0.060 m. These 0.020 and 0.060 m

![Fig. 1. Schematic of mold powder entrapment.](image1)

![Fig. 2. Schematic of experimental apparatus.](image2)

| Liquid     | Kinematic viscosity (mPa·s, @20°C) | Density (kg/m³) | Interfacial tension (mN/m) |
|------------|-----------------------------------|-----------------|-----------------------------|
| Water      | 1.0                               | 996             |                             |
| Silicone oil 2 | 2.0                               | 873             | 52.7                        |
| Silicone oil 10 | 10                                | 915             | 52.7                        |
| Silicone oil 100 | 100                               | 965             | 53.0                        |
were chosen to be smaller and larger than the equivalent diameter of an approaching bubble, respectively.

Measurements were also carried out in the absence of the plate. The thickness of the silicone oil layer, $h_o$, was 0.020, 0.040 or 0.060 m. This situation corresponds to the case that the non-melted mold powder layer does not exist.

Air was collected in a cup with a syringe to a predetermined volume. The cup was turned over to release a single air bubble into the bath. The bubble attacked the interface between the water and silicone oil layers at a terminal velocity to cause entrapment of the silicone oil into the water layer. Such a series of events was observed with a CCD camera at 30 frames per second.

3. Experimental Results and Discussion

3.1. Photographs Showing Entrapment of Mold Powder

Figures 3(a) and 3(b) show photographs of silicone oil entrapment with and without the horizontal plate in the silicone oil layer, respectively. The volume of a bubble, $V$, was $45 \times 10^{-6}$ m$^3$ (45 ml) and the distance from the initial interface between the water and silicone oil layers to the plate, $h_o$, was 0.020 m. The silicone oil 2 was used as a model for mold powder. This numerical value, 2, means that the kinematic viscosity of the silicone oil is 2 mm$^2$/s. The same is true for the remaining silicone oils. It is evident that the maximum penetration depth of the mold powder droplets, $H_o$, is nearly independent of the existence of the plate but the penetration sites are different in the two cases.

3.2. Mechanism of Mold Powder Entrapment

Figure 4 shows a series of events of silicone oil entrapment in the absence of the horizontal plate schematically.

The silicone oil covering the water layer is entrapped in the water layer by the falling water film, Fig.4(c), along the upper surface of the bubble. On the other hand, Fig. 5 illustrates that the silicone oil is entrapped mainly due to collision of the water moving along the horizontal plate to the side wall. Consequently, the mechanism of silicone oil entrapment in the absence of the horizontal plate is different from that in the presence of the plate.

3.3. Penetration Depth of Mold Powder

In the real continuous casting molds the maximum penetration depth of mold powder droplets, $H_o$, is one of the
most important factors for producing clean steel. Figure 6 shows the penetration depth, $H_o$, against the volume of the bubble, $V$, and an equivalent diameter of the bubble, $D_e$, where $D_e$ is expressed by:

$$D_e = \left(6V/\pi\right)^{1/3} \quad \text{(1)}$$

As the error inherent in this kind of measurement is considerably larger ($\pm 30\%$), it can be concluded that $H_o$ is nearly independent of the physical properties of water and silicone oils and the existence of the plate under the experimental conditions considered. The maximum penetration depth is approximately three times as large as the equivalent bubble diameter.

According to the above experimental results, the non-melted mold powder layer would cause the mold powder entrapment near the wide face of the mold. The mold powder droplets thus generated may be trapped in the solidifying shell or trapped in the reversing flow.

If a large argon bubble rises near the SEN and the mold powder layer is completely melted, mold powder droplets are generated near the SEN and they may be trapped in the discharging molten steel flow near the ports of the SEN.

In the real processes the maximum equivalent bubble diameter is estimated to be nearly equal to the port diameter. If the present finding is applicable to the real processes, the maximum penetration depth would be approximately $12 \times 10^{-2}$ m. This depth is approximately equal to the immersion depth of the SEN, and, hence, mold powder entrapment would occur. However, the interfacial tension is much higher than the value considered here, and, hence, the deformation of the interface between the molten steel and mold powder would be highly suppressed. Accordingly, the presently observed situation is the worst scenario for the mold powder entrapment. Further experimental investigations must be carried out on the mold powder entrapment in the real continuous casting molds.

4. Concluding Remarks

Cold model experiments were carried out to clarify the mechanism of mold powder entrapment caused by a large argon bubble approaching the interface between the molten steel and mold powder. The maximum penetration depth of silicone oil was approximately three times as large as the equivalent bubble diameter regardless of the physical properties of liquids and the existence of a horizontal plate immersed in the silicone oil layer. This plate was used as a model for the non-melted mold powder layer. However, the mechanisms of the mold powder entrapment were different in the presence and absence of the plate, and the penetration sites also were different.

Nomenclature

- $D_e$: Equivalent bubble diameter (m)
- $H_o$: Maximum penetration depth of silicone oil droplet (m)
- $h_o$: Distance from the initial silicone oil–water interface to the horizontal plate (m)
- $V$: Bubble volume (m$^3$)

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