Effect of Properties of Mold Powder Entrapped into Molten Steel in a Continuous Casting Process

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(Received on February 18, 2009; accepted on April 9, 2009)

Mold powder plays an important role in the continuous casting process for high quality steel production. Qualitatively, it is well known that mold powder entrapment causes surface defects in steel sheets, and high viscosity of the mold powder prevents the entrapment of the mold powder into the molten steel in ultra-low carbon steel.

This paper deals quantitatively with the entrapment of mold powder caused by suction by Karman’s vortex in a laboratory experiment. First, in a water model experiment using oil as a substitute for mold powder, the effects of the viscosity of the oil and the interfacial tension between the water and oil were investigated. Following this, hot model experiments were carried out with mold powder and molten steel. The amount of mold powder entrapment was affected by the viscosity of the molten mold powder and the interfacial tension between the molten steel and mold powder. As the result, the following equation for mold powder entrapment was obtained.

\[ m = 1.06 \times 10^7 \eta^{-0.255} \gamma_{\text{m-s}}^{-2.18} \]

where \( m \): weight of entrapped mold powder (g/100 g-steel), \( \eta \): viscosity of mold powder at 1573 K (Pa·s), and \( \gamma_{\text{m-s}} \): interfacial tension between molten steel and mold powder (mN/m).

The amount of mold powder entrapment decreased when the viscosity and interfacial tension increased. However, the effect of viscosity on mold powder entrapment was larger than that of interfacial tension in the case of an industrial mold powder when viscosity was under 0.5 Pa·s and interfacial tension was from 1200 to 1300 mN/m.

KEY WORDS: continuous casting; mold powder; viscosity; interfacial tension; entrapment.

1. Introduction

Achievement of high speed casting and then improvement of the quality of slabs in a continuous casting process are important issues. Mold powder plays an important role in the continuous casting process for high quality steel production. It is well known that mold powder entrapment causes surface defects in steel sheets, and high viscosity of the mold powder prevents the entrapment of the mold powder into the molten steel in ultra low carbon steel. Many studies have been carried out with the aim of preventing mold powder entrapment in a mold. One technique is control of the molten steel flow in the mold by electromagnetic force.1–4 Several methods which employ electromagnetic force to control the molten steel flow have been proposed, including use of a static electromagnetic field,1,2 traveling magnetic field,3 and stirring magnetic field.4 These electromagnetic methods of molten steel flow control have been applied to the many steel plants. Another method is optimization of the shape of the submerged entry nozzle5–8 to prevent mold powder entrapment. Changes in the shape at the outlet and in the interior of the submerged entry nozzle have been applied. In another method which does not involve control of the molten steel flow, the properties of the mold powder are changed. In general, it is important to increase the interfacial tension between the molten steel and mold powder in order to prevent entrapment of the mold powder into the molten steel. However, because it is very difficult to measure the interfacial tension between molten steel and mold powder directly, many researchers have measured the surface tension9 of the mold powder and tried to increase the viscosity of the mold powder.10 There have been many reports on the mechanism of mold powder entrapment based on water model experiments10,11 and application of high viscosity mold powder.12,13 High viscosity mold powder has been applied to industrial steel production in the continuous casting process when producing high quality slabs, but there have been few quantitative reports.
on the effect of high viscosity mold powder.

The following equation was proposed about the entrapment between slag and molten steel.\(^{14}\)

\[
\frac{1}{2} \left( \rho_p \cdot \frac{4}{3} \pi R_p^2 V_{m}^2 \right) \geq 4 \pi R_p^2 \sigma + g (\rho_m - \rho_p) \left( \frac{4}{3} \pi R_p^2 \right) R_p
\]

\[\text{(1)}\]

where \(\rho_p\): density of mold powder, \(\rho_m\): density of molten steel, \(R_p\): radius of entrapment of molten mold powder, \(V_{m}\): velocity of molten steel, \(\sigma\): interfacial tension, \(g\): acceleration of gravity. The value of critical velocity of molten steel, \(V_{m}\), was calculated 0.72 m/s to get the real number for radius of entrapment of molten mold powder from Eq. (1) \((\rho_p = 3,000 \text{ kg/m}^3, \rho_m = 7,200 \text{ kg/m}^3, g = 9.8 \text{ m/s}^2, \sigma = 1,200 \text{ mN/m})\). Moreover it was reported that the critical velocity of molten steel was 0.48 m/s\(^{15}\) and 0.6 m/s\(^{16}\) from the theory on the Kelvin Helmholtz instability, but these values were too faster than the velocity of molten steel in a mold in the industrial continuous casting.

Therefore, this paper deals quantitatively with the entrapment of mold powder caused by suction by Karman’s vortex in a laboratory experiment. First, a water model experiment was carried out to investigate the effects of the viscosity of oil and the interfacial tension between water and oil. Similar experiments were then carried out using molten steel and mold powder. There are many reports by using water and oil experiment which is simulating mold powder entrapment, but there is few reports by using molten steel and molten mold powder. There are several opinions regarding the mechanism of entrapment of mold powder into the molten steel flow, but in our experiment, suction by Karman’s vortex was simulated, and the amount of mold powder entrapment was investigated quantitatively in laboratory experiments.

2. Experimental Method

2.1. Water Model Experiments

Figure 1 shows a schematic diagram of the experimental apparatus of the water model. Water and oil were selected as substitutes for molten steel and mold powder, respectively, because the viscosity of oil can be controlled over a wide range. A glass beaker with a diameter of 200 mm and height of 180 mm was filled with 400 g water, and 12 g of oil was poured onto the water. The thickness of the oil was 5 mm, and its density was 0.87–0.88 g/cm\(^3\). A J-shaped tube with an inlet diameter of 6 mm was dipped into the water to a certain depth before the oil was poured, and water was then pulled out through the J-shaped tube at a constant velocity (1.9–2.2 m/s). In this experiment, the presence of components of the oil in the sucked liquid was monitored, and the critical distance at which oil suction began was measured against the viscosity of oil and the interfacial tension between the water and oil. Here, “critical distance” means the immersion depth of the J-shaped tube from the water/oil interface where oil begins to be sucked into the tube. Table 1 shows the properties of the oil substituted for molten mold powder. Silicon oil was prepared as the commercial standard oil, the viscosity of which was varied in the range of 0.03–10 Pa·s at 293 K. Distilled water was used to eliminate the effect of impurities in the water.

The interfacial tension between the water and oil was measured by the sessile drop method. In this experiment, 20 g of oil was poured in a schale, 2 g of water was dropped on the oil, and the interfacial tension between water and oil was calculated by the table of Bashforth and Adams\(^{17}\) from the following equation.

\[
\sigma_{w-o} = g (b/2) \cdot (\rho_w - \rho_o) \quad \text{(2)}
\]

where \(\sigma_{w-o}\): interfacial tension between water and oil (mN/m), \(g\): acceleration of gravity (m/s\(^2\)), \(\rho_w\): density of water (kg/m\(^3\)), \(\rho_o\): density of silicon oil (kg/m\(^3\)) and \(b, \beta\): values from the table of Bashforth and Adams. The same experiments were carried out by adding a commercial synthetic kitchen detergent (4 g) containing 27% of a surfactant to the water in order to change the interfacial tension between the water and oil as a constant of the viscosity of the oil.

2.2. Hot Model Experiments

Figure 2 shows a schematic diagram of the experimental
apparatus of the hot model simulating the movement around the meniscus in continuous casting. Hot model experiments were carried out using molten steel and mold powder. An alumina crucible was set in a high frequency induction heating furnace with an inlet diameter of 100 mm and height of 200 mm. In particular, an alumina-graphite sleeve was used at the part in contact with the molten mold powder to prevent damage. Table 2 shows the chemical composition and properties of the mold powder. Several mold powder were selected so that the viscosity could be varied largely from 0.03 to 10 Pa·s at 1573 K. The chemical composition of the molten steel is shown in Table 3. The molten steel (8 kg) was melted in the furnace and kept at 1873 K. Because it is known that oxygen and sulfur in molten steel change the interfacial tension between molten steel and slag,18) carbon addition was used to hold the oxygen content in the steel to a low level of 10–12 ppm by mass. The sulfur content in the steel was changed from 40 to 250 ppm by mass so as to change the interfacial tension between the molten steel and mold powder. The J-shaped silica tube was dipped into the molten steel to a depth of 5 mm from the interface between the molten steel and mold powder. Mold powder was added to a thickness of 10 mm. Samples were taken by pulling the J-shaped tube out of the liquid steel at a constant velocity (1.5–1.7 m/s). The weight of the sampled metal was approximately 100 g.

The metal samples were cooled and remelted using an electric furnace, so that the steel and slag were separated by the difference of their specific gravity. The slag included mold powder and SiO2 from the silica tube. The weight of entrapped mold powder was calculated from the weight of the slag and the ratio of CaO mass% in each mold powder. In this study, the weight of entrapped mold powder was investigated against viscosity and interfacial tension. The viscosity of the mold powder was measured by the Falling Ball Method19) at 1573 K using a platinum crucible and ball. The interfacial tension between the molten steel and mold powder was calculated from the value of the contact angle and the surface tension by the method proposed by Hara et al.20)

\[
\gamma_{s-m} = (\gamma_s^2 + \gamma_m^2 - 2\gamma_s \gamma_m \cos \theta)^{1/2}
\]

where \(\gamma_{s-m}\): interfacial tension between molten steel and mold powder \(\text{(mN/m)}\), \(\gamma_s\): surface tension of molten steel \(\text{(mN/m)}\), \(\gamma_m\): surface tension of molten mold powder \(\text{(mN/m)}\), and \(\theta\): contact angle between molten mold powder and pure iron plate. Surface tension was measured by the maximum bubble pressure method,21,22) and contact angle was measured by high temperature microscope and the value of \(\gamma_m\) was adopted 1464 mN/m.23,24)

3. Results and Discussion

3.1. Water Model Experiments

3.1.1. Interfacial Tension between Water and Oil

First, the interfacial tension between water and oil was measured by the above method. Figure 3 shows the results of these measurements. There is no relationship between the viscosity and interfacial tension between the water and oil. The interfacial tension between the water and oil was changed from 20 to 2 mN/m by adding the above-mentioned surfactant to the water.

3.1.2. Critical Distance

Figure 4 shows an example of photographs of the experimental method used in the water model experiment. It was found that entrapment of oil occurred by suction when the distance from the tip of the J-shaped tube to the water/oil interface was short.

The critical distance, i.e., the immersion depth of the J-shaped tube from the water/oil interface was short.

The critical distance, i.e., the immersion depth of the J-shaped tube from the water/oil interface, was measured for several kinds of oil. The experimental results for viscosity and critical distance are shown in Fig. 5. The results show that viscosity and interfacial tension have a great influence on oil suction. The critical distance decreased with increasing oil viscosity, that is, high viscosity oil is difficult to be entrapped into water. The critical distance decreased when the interfacial tension between the water and oil increased,

<table>
<thead>
<tr>
<th>Mold powder</th>
<th>SiO2</th>
<th>Al2O3</th>
<th>CaO</th>
<th>F</th>
<th>Na2O</th>
<th>MgO</th>
<th>FeO</th>
<th>Li2O</th>
<th>C/S</th>
<th>Viscosity</th>
<th>Surface tension</th>
<th>Interfacial tension</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>30.3</td>
<td>6.1</td>
<td>29.5</td>
<td>7.8</td>
<td>10.0</td>
<td>2.1</td>
<td>0.0</td>
<td>4.1</td>
<td>0.97</td>
<td>0.09</td>
<td>250</td>
<td>1230</td>
</tr>
<tr>
<td>B</td>
<td>44.6</td>
<td>8.0</td>
<td>33.2</td>
<td>3.8</td>
<td>3.7</td>
<td>3.4</td>
<td>0.6</td>
<td>0.4</td>
<td>0.74</td>
<td>1.00</td>
<td>330</td>
<td>1250</td>
</tr>
<tr>
<td>C</td>
<td>50.1</td>
<td>5.8</td>
<td>24.9</td>
<td>10.7</td>
<td>3.3</td>
<td>0.2</td>
<td>0</td>
<td>5</td>
<td>0.50</td>
<td>0.31</td>
<td>270</td>
<td>1206</td>
</tr>
<tr>
<td>D</td>
<td>35.1</td>
<td>4.1</td>
<td>17.4</td>
<td>7.5</td>
<td>2.3</td>
<td>2.1</td>
<td>0</td>
<td>3.5</td>
<td>0.50</td>
<td>0.36</td>
<td>337</td>
<td>1276</td>
</tr>
<tr>
<td>E</td>
<td>36.5</td>
<td>5.4</td>
<td>26.4</td>
<td>4.9</td>
<td>8.5</td>
<td>2.2</td>
<td>0.4</td>
<td>4.4</td>
<td>0.78</td>
<td>0.51</td>
<td>320</td>
<td>1230</td>
</tr>
<tr>
<td>F</td>
<td>39.1</td>
<td>6.0</td>
<td>33.7</td>
<td>7.6</td>
<td>3.8</td>
<td>6.9</td>
<td>0.7</td>
<td>0</td>
<td>0.84</td>
<td>0.40</td>
<td>350</td>
<td>1250</td>
</tr>
<tr>
<td>G</td>
<td>45.7</td>
<td>5.5</td>
<td>35.7</td>
<td>3.6</td>
<td>2.9</td>
<td>1.1</td>
<td>0.5</td>
<td>1</td>
<td>0.78</td>
<td>0.80</td>
<td>320</td>
<td>1230</td>
</tr>
<tr>
<td>H</td>
<td>29</td>
<td>13.1</td>
<td>36.4</td>
<td>3.9</td>
<td>3.7</td>
<td>1.6</td>
<td>3.7</td>
<td>0</td>
<td>4.3</td>
<td>1.26</td>
<td>375</td>
<td>1285</td>
</tr>
</tbody>
</table>

Table 2. Chemical composition and properties of mold powder.

Table 3. Chemical composition of metal.

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>solAl</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13</td>
<td>0.24</td>
<td>0.20</td>
<td>0.012</td>
<td>0.004-0.025</td>
<td>0.055</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Fig. 3. Comparison of interfacial tension between water and oil. Case 1: water/oil. Case 2: water with surfactant/oil.
that is, decreased interfacial tension caused entrapment of the oil into the water. As a result, the following equation was obtained:

\[ L = 8.58 \eta^{-0.086} \gamma^{-0.0552} \]  \hspace{1cm} (4)

where \( L \): critical distance (mm), \( \eta \): viscosity of oil (Pa·s), and \( \gamma \): interfacial tension between water and oil (mN/m).

**Figure 6** shows the relationship among the critical distance, interfacial tension, and viscosity calculated from Eq. (4). The coefficient of viscosity was 1.6 times as large as that of interfacial tension in the water model experiments. It was estimated that the effect of viscosity was larger than that of the interfacial tension between the water and oil.

### 3.2. Hot Model Experiments

#### 3.2.1. Estimation of Interfacial Tension between Molten Steel and Mold Powder

Table 2 shows the interfacial tension between the molten steel and mold powder and the surface tension of the mold powder. These experimental measurement values were plotted as shown in **Fig. 7**. There is no relationship between viscosity and the interfacial tension between the molten steel and mold powder.

#### 3.2.2. Schematic Photographs of Solidified Steel

**Figure 8** shows photographs of the solidified steel after the molten steel was sampled using the J-shaped tube. A microscopic image is shown in **Fig. 9**. It was found that pore and entrapped mold powder were observed in the metal in the hot model experiment.

#### 3.2.3. Amount of Mold Powder Entrapment

**Figure 10** shows the experimental results for the rela-
tion of the weight of entrapped mold powder in the solidified steel sampled with the J-shaped tube and the viscosity of the mold powder. The value of the weight of entrapped mold powder was normalized for 100 g of solidified steel. The sulfur content in the steel is 4–5 ppm. The weight of entrapped mold powder decreased when the viscosity of the mold powder increased, that is, high viscosity mold powder was difficult to be entrapped into the molten steel, which is the same as the result of the water model experiment.

3.2.4. Interfacial Tension and Amount of Entrapment

This experiment was carried out by changing the interfacial tension between the molten steel and mold powder. Sulfur was added to the molten steel to change the interfacial tension. Figure 11 shows the relationship between the sulfur content in the steel and interfacial tension with two kinds of mold powder, powder A (0.09 Pa · s) and powder B (1.00 Pa · s). The interfacial tension between the molten steel and mold powder decreased as the sulfur content in the steel increased. The relationship between the weight of entrapped mold powder and interfacial tension is shown in Fig. 12. The weight of entrapped mold powder decreased with as the interfacial tension between the molten steel and mold powder increased.

3.2.5. Relationship of Entrapment to Viscosity and Interfacial Tension

Figure 13 shows the relationship among the interfacial tension, the viscosity of the mold powder, and the weight of entrapped mold powder. The following equation was obtained by regression analysis:

$$m = 1.06 \times 10^7 \eta^{0.255} \gamma_{m-s}^{-2.18}$$

where $m$: weight of entrapped mold powder (g/100 g-steel), $\eta$: viscosity of mold powder at 1 573 K (Pa · s), and $\gamma_{m-s}$: interfacial tension between molten steel and mold powder (mN/m). In general, the interfacial tension of mold powder in the normal casting conditions was considered to be in the range from 1 200 to 1 300 mN/m. The relationship from Eq. (5) is plotted in Fig. 14. When the viscosity was decreased,
the solid lines calculated by Eq. (5) were very steep. These results show that the effect of viscosity on the entrapment of molten mold powder into molten steel is larger than that of interfacial tension when viscosity is under 0.5 Pa·s and interfacial tension is from 1200 to 1300 mN/m.

4. Conclusions

The phenomenon of the entrapment of molten mold powder in continuous casting was studied by suction experiments using a water model and hot model. The following conclusions were obtained.

(1) Viscosity and interfacial tension have a great influence on the amount of suction of oil in water model experiments and mold powder in hot model experiments.

(2) The effect of viscosity on the entrapment of molten mold powder is larger than that of interfacial tension when viscosity is under 0.5 Pa·s and interfacial tension is from 1200 to 1300 mN/m.

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