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Effect of properties of mold powder entrapped in molten steel in a continuous casting process

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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 sheet and the high viscosity of mold powder prevents the entrapment of mold powder in molten steel in ultra low carbon steel.

This paper deals with the entrapment of mold powder caused by suction by Karman's vortex in a laboratory experiment. At first the effect of the viscosity of oil and interfacial tension between water and oil was investigated in a water model experiment. Then hot model experiments were carried out by mold powder and molten steel. The amount of mold powder entrapment was affected by the viscosity and the interfacial tension between molten steel and mold powder. As a result, the following equation of the mold powder entrapment was obtained.

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

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

Introduction

It is important to achieve high speed casting and then improve the quality of slab in a continuous casting process. 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 sheet and high viscosity of mold powder prevents the entrapment of mold powder in molten steel in ultra low carbon steel.

There are many investigations to prevent the mold powder entrapment in a mold. One is the control of molten steel flow in a mold by electromagnetic force[1–4]. There are several proposals and methods of electromagnetic force to control molten steel flow by static electromagnetic field[1–2], travelling magnetic field[3] and stirring magnetic field[4]. These electromagnetic methods of molten steel flow control have been applied to many steel plants.

Another method is the optimization of the shape of the submerged entry nozzle[5–8] to prevent the mold powder entrapment. The change of shape at the outlet and inside submerged entry nozzle was applied. The last method applied did not control the flow of molten steel but changed the properties of the mold powder.

In general, it is important to increase the interfacial tension between molten steel and mold powder in order to prevent the entrapment of mold powder in molten steel. But it is very difficult to measure the interfacial tension between molten steel and mold powder directly, so that many researchers have measured the surface tension[9] of mold powder and tried to increase the viscosity of mold powder[10]. There are many reports about the mechanism of mold powder entrapment by using water model experiment[10] and the application of high viscosity mold powder[11]. High viscosity mold powder has been applied to a industrial steel production in, continuous casting process when high quality slab was produced, but there are few reports about the effect of high viscosity of mold powder.

This paper deals with the entrapment of mold powder caused by suction by Karman's vortex in a laboratory experiment qualitatively. First the water model experiment was carried out on the effect of the viscosity of oil and interfacial tension between water and oil. Finally, similar experiments were carried out using molten steel and mold powder. There are several opinions about the mechanism of the entrapment in molten steel flow, but our experiment simulated the suction by Karman's vortex and the amount of mold powder entrapment was investigated in both laboratory experiments.

Experimental

Water model experiments

Figure 1 shows the schematic diagram of the experimental apparatus of the water model. Water and oil were selected as a substitute for molten steel and mold powder because the viscosity of oil could be changed. A water bath was filled with water of 3000 g and oil of 100 g. The thickness of oil was 5 mm and density was 0.87–0.88 g/cm^3. The J-shape tube whose inlet diameter was 6 mm was dipped into water to a certain depth before the oil was poured. Water

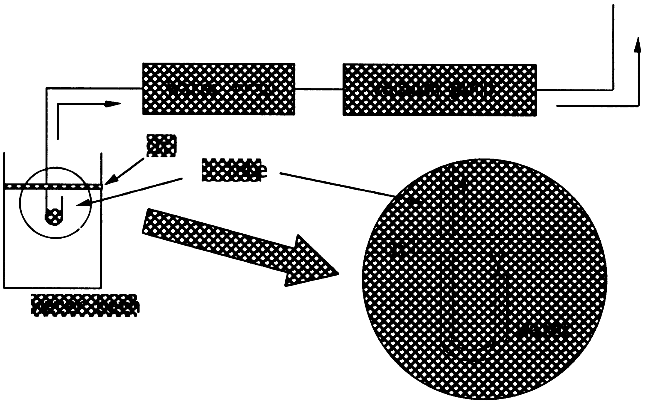

Figure 1. Schematic diagram of water model experiment for mold powder entrapment

was poured out through the J-shape tube at a constant velocity (1.9–2.2 m/s). These experiments determined whether the components of the oil were detected in the sucked liquid or not, and the critical submergence was measured against the viscosity of oil and the interfacial tension between water and oil. The critical submergence means the immersion depth of the J-shape tube from the water/oil interface where the oil begins to be sucked into the tube or not.

Silicon oil was prepared as the commercial standard oil, whose viscosity was 0.04–10 Pa.s at 293K. Distilled water was used to remove the effect of impurities in water. The interfacial tension between water and oil was measured by the sessile drop method. The 20 g of oil was poured in a sharee and 2g water was dropped on the oil, the interfacial tension between water and oil was calculated by the table of Bashforth & Adams[13] from the following equation,

$$\sigma_{w-o} = g\left(b^2 / \beta\right) * \left(\rho_w - \rho_o\right) \qquad [1]$$

where σ_{w-o}: the interfacial tension between water and oil (mN/m), g: the acceleration of gravity (m/s^2), ρ_w: the density of water (kg/m^3), ρ_o: the density of silicon oil (kg/m^3), b and β: the values from the table of Bashforth & Adams. The same experiments were carried out by adding an activator of 4 g into water to change the interfacial tension between water and oil as a constant of viscosity of oil.

Hot model experiments

Hot model experiments were carried out using molten steel and mold powder. An alumina crucible was set in the high frequency induction heating furnace whose inlet diameter was 100 mm and the height was 215 mm. The part in contact with the molten mold powder was set in an alumina-graphite sleeve to prevent damage. Table I shows the chemical composition and properties of the mold powder. These mold powders were selected so as to change the viscosity largely from 0.03 to 10 Pa.s at 1573 K. The chemical composition of molten steel is 0.13% C, 0.24% Si, 0.20% Mn, 0.012% P and 0.055% sol.Al. Molten steel of 8 kg was melted in the furnace.

It is known that oxygen and sulphur in molten steel changed the interfacial tension between molten steel and slag[14]. Therefore the sulphur 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 Oxygen content in the steel was kept constant at 10–12 ppm by mass in addition to carbon to ignore the effect of oxygen content. The J-shape silica tube was dipped into the molten steel 5 mm beneath the interface between molten steel and mold powder. Mold powder was added and the thickness of molten mold powder was 10 mm.

The J-shape tube was sucked out of the liquid steel as a constant velocity (1.5–1.7 m/s). The metal sample which was sucked by the J-shape silica tube was cooled and dissolved by hydrochloric acid, so that steel and slag were separated. These slags included mold powder and SiO_2 form silica tube. The weight of the 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 in terms of the viscosity and interfacial tension.

The viscosity of the mold powder was measured by the Falling Ball Method at 1573 K. The surface tension was measured by the maximum bubble pressure method. It is difficult to measure the interfacial tension between molten steel and mold powder, so the contact angle between molten mold powder and pure iron plate was measured. 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[15].

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

where γ_{s-m}: the interfacial tension between molten steel and mold powder (mN/m), γ_m: the surface tension of molten steel (mN/m), γ_s: the surface tension of molten mold powder (mN/m), θ: the contact angle between molten mold powder and pure iron plate.

Results and discussion

Water model experiments

Interfacial tension between water and oil

At first, interfacial tension between water and oil was

Table I
Chemical compostion and properties of mold powder

Mold powder	SiO_2	Al_2O_3	CaO	F	Na_2O	MgO	Fe_2O_3	Li_2O	C/S	Viscosity	Surface tension	Interfacial tension
	(mass%)								(-)	(Pa.s)	(mN/m)	
A	30.3	6.1	29.5	7.8	10.0	2.1	0.0	4.1	0.97	0.09	250	1230
B	44.6	8.0	33.2	3.8	3.7	3.4	0.6	0.4	0.74	1.00	330	1250
C	50.1	5.8	24.9	10.7	3.3	0.2	0	5	0.50	0.31	270	1206
D	35.1	4.1	17.4	7.5	2.3	2.1	0	3.5	0.50	0.36	337	1276
E	36.5	5.4	28.4	4.9	8.5	2.2	0	4.4	0.78	0.21	320	1230
F	39.1	6	33	7.6	3.8	6.9	0.7	0	0.84	0.40	350	1250
G	45.7	5.5	35.7	3.6	2.9	1.1	0.5	1	0.78	0.80	320	1230
H	29	13.1	36.4	3.9	1.6	3.7	0	4.3	1.26	0.28	375	1285

measured by the above method. The interfacial tension between water and oil was changed from 20 mN/m to 2 mN/m by adding 27% activator into the water. There is no relation between viscosity and interfacial tension between water and oil.

Critical submergence

The critical submergence, i.e., the immersion depth of the J-shape tube from the interface between water and oil was measured for several kinds of oil. The experimental relation between viscosity and critical submergence is shown in Figure 2. The result shows that the viscosity and interfacial tension have a great influence on the oil suction. The critical submergence decreased with increasing oil viscosity, that is, high viscosity of oil is difficult to entrap in water. Then the critical submergence increased when the interfacial tension between water and oil decreased, that is, the decrease of interfacial tension caused the entrapment of the oil into water. As a result, the following equation was obtained,

$$L = 8.58\eta^{-0.0886}\gamma^{-0.0552} \qquad [3]$$

where L: the critical submergence (mm), η: the viscosity of oil (Pa.s) and γ: the interfacial tension between water and oil (mN/m). The effect of viscosity was larger than that of interfacial tension between water and oil.

Hot model experiments

Estimation of interfacial tension between molten steel and mold powder

Table I shows the interfacial tension among molten steel, mold powder and surface tension of mold powder. There is no relation between viscosity and interfacial tension between molten steel and mold powder.

Amount of mold powder entrapment

Figure 3 shows the experimental results for the weight of entrapped mold powder against viscosity of mold powder. The weight of entrapped mold powder decreased when the viscosity of mold powder increased, that is, high viscosity of mold powder was difficult to entrap in molten steel (the same as the results of the water model experiment).

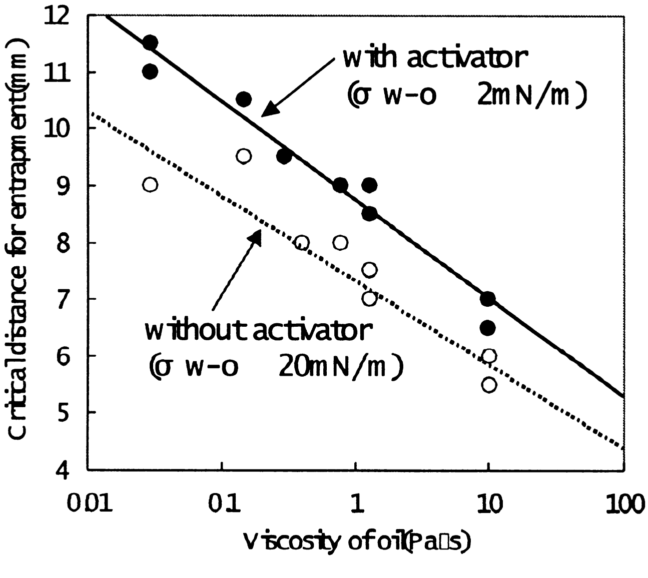

Figure 2. Relation between viscosity of oil and critical distance for entrapment

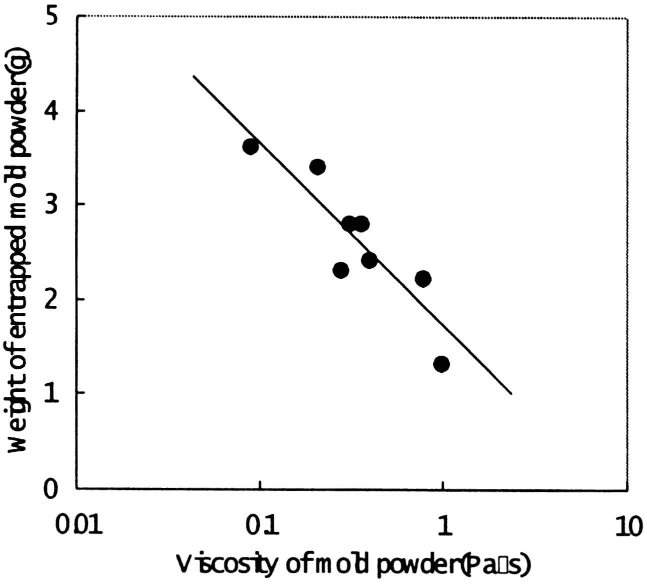

Figure 3. Relation between viscosity of mold powder and weight of entrapped mold powder

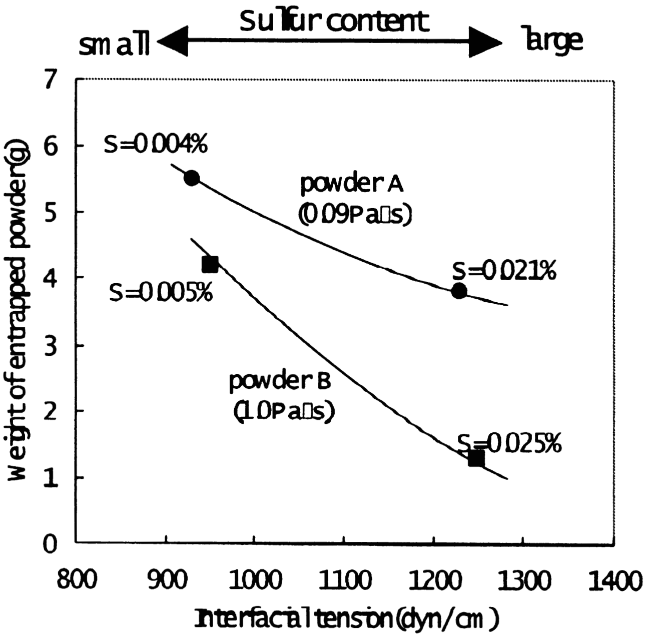

Figure 4. Relation between interfacial tension and weight of entrapped mold powder

Interfacial tension and the amount of entrapment

Figure 4 shows the relation between the weight of entrapped mold powder and interfacial tension using two kinds of mold powder, powder A(0.09 Pa.s) and powder B(1.00 Pa.s). The interfacial tension between molten steel and mold powder increased with the increasing sulphur content in steel. The weight of entrapment of the mold powder decreased with the increasing the interfacial tension between molten steel and mold powder.

Effect of entrapment against viscosity and interfacial tension

Figure 5 shows the relation among the interfacial tension,

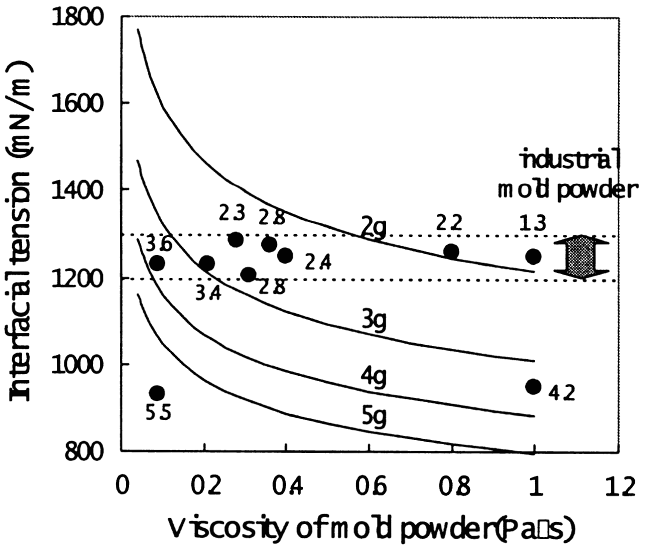

Figure 5. Relation among viscosity of mold powder, interfacial tension and weight of entrapped mold powder

viscosity of mold powder and the weight of entrapped mold powder. The following equation was obtained by regression analysis,

$$m = 1.06\text{x}10^{7}\eta^{-0.255}\gamma_{m-s}^{\;\;-2.18} \qquad [4]$$

where m: the weight of entrapped mold powder (g), η: the viscosity of mold powder at 1573 K (Pa.s) $\gamma_{m\text{-}s}$: the interfacial tension between molten steel and mold powder (mN/m). In general, the interfacial tension was considered to be in the range from 1200 to 1300 mN/m in the normal casting conditions. The results show that the effect of viscosity is larger than that of interfacial tension on the entrapment of molten mold powder whose viscosity is under 0.5 Pa.s and interfacial tension is from 1200 to 1300 mN/m.

Conclusions

The phenomenon of the entrapment of molten mold powder was studied by suction experiments in the water model and the hot model. The following conclusions are obtained:

- The viscosity and interfacial tension have a great influence on the amount of suction of the oil and mold powder in the water and hot model experiments.
- The effect of viscosity is larger than that of interfacial tension on the entrapment of molten mold powder whose viscosity is under 0.5 Pa.s and interfacial tension is from 1200 to 1300 mN/m.

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