Amplitude-modulated Magnetic Field Coupled with Mold Oscillation in Electromagnetic Continuous Casting

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Molten metal meniscus profile and mold flux channel width were measured under high frequency magnetic field by model experiments, then the dynamic pressure in mold flux channel were calculated during one mold oscillation period. It is found that the high frequency magnetic field can decrease the dynamic pressure greatly, which may be one mechanism of improving the billets surface quality by the soft-contact mold electromagnetic continuous casting. Based on this study, a novel technology named Amplitude-Modulated Magnetic Field (AMMF) coupled with mold oscillation in electromagnetic continuous casting was proposed in order to balance the dynamic pressure caused by mold oscillation with a varied electromagnetic force inducted by AMMF. Based on the calculation of mold flux channel dynamic pressure, a model to optimize design of AMMF was proposed. Then continuous casting experiments under AMMF coupled with mold oscillation were carried out. It is shown that AMMF is effective in reducing the friction force during continuous casting and improving the billets surface quality.

KEY WORDS: continuous casting; electromagnetic continuous casting; high frequency amplitude-modulated magnetic field; mold oscillation.

1. Introduction

The continuous casting billets surface is characterized by the presence of oscillation marks which are caused by the dynamic pressure in the mold flux channel due to mold oscillation. The more the dynamic pressure changes, the deeper the oscillation marks are.1)

So far, several technologies have been proposed to reduce the depth of oscillation marks and improve billets surface quality, such as optimize the mold oscillation mode,2,3) introduce new mold structure or new mold materials.4,5) Among these technologies, Electromagnetic continuous casting (EMCC) attracted more attention due to its unique function in improving billets surface quality by imposing high frequency magnetic field from outside of mold.6–8)

Studies on why and how EMCC improve the billet surface concentrated on early solidification process based on two aspects: inducing heat effect and force effect of magnetic field. On the former aspect, investigation showed that magnetic field affects the billets solidification by inducing heat in the casting metal and mold wall, decreasing the heat transfer rate on the interface between the metal and mold wall, which can improve the billets surface quality.9) On the later aspect, investigation showed that electromagnetic force can decrease the dynamic pressure in the mold flux channel due to mold oscillation, which can suppress the irregular motion of meniscus, decrease the oscillation marks formation and improve the strand quality.7,9,10) Usually the magnetic field was continuously imposed in these investigations. Asai and his group proposed and carried out the intermittent imposition of the magnetic field. The magnetic field was imposed intermittently in the same frequency as the mold oscillation. This novel technology was expected to control the meniscus more effectively and save the energy.

In fact, the intermittent imposition transforms the magnetic field into one kind of so called Amplitude-Modulated Magnetic Field (AMMF). AMMF has a varied amplitude and produces varied magnetic force in the melt, which my couple with the mold oscillation and improve billets’ surface effectively. Therefore, in this paper Amplitude-Modulated Magnetic Field (AMMF) was introduced to EMCC by imposing it outside the mold coupled with mold oscillation on base of studies of dynamic pressure of mold flux channel. In this process, a varied electromagnetic force inducted by AMMF is proposed to balance the dynamic pressure caused by mold oscillation in order to control the early solidification process more precisely, decrease the depth of oscillation marks and improve billets surface quality. A model to optimize design of AMMF is proposed, and then continuous casting experiments under AMMF coupled with mold oscillation were investigated to validate the new technology.

2. Model of Dynamic Pressure Calculation and AMMF Design

2.1. The Meniscus Profile Measurement and Mold Flux Exit Width Calculation

The experiments device to measure the meniscus profile under magnetic field is showed in Fig. 1. The 4 turns water-cooling coil (inner diameter is 100 mm, height is 80 mm) provide the high frequency (18 kHz) magnetic field, whose
magnetic flux density $B_e$ is measured by microvolt meter and little coil placed near the point where meniscus meet the container wall. The bottom of the water-cooling coil is at the same level with the molten Sn bottom, and the depth of the molten Sn adhere to the container wall is 60 mm under no magnetic field. The container is a corundum tube (inner diameter is 70 mm) sealed by refractory at the bottom. Start up the high frequency inducing heating to heat up Sn till melt it and controlled its temperature at $280 \pm 20^\circ \text{C}$. The meniscus profile is measured mainly by the bottom electrode, Ohmmeter and a two dimensional (up and down, left and right) movable probe (diameter is 0.5 mm). After putting the probe at a given position at the horizontal coordinate, let the probe descended down slowly until the ohmmeter is switched on, then get the probe position from a stable meter as the meniscus position. Due to shielding effect of melt to high frequency magnetic field, the meniscus position is measured every 2 mm along the diameter dimension in 10 mm near the container wall and every 5 mm at others positions. The average of symmetry point value along the axes is the meniscus profile, as shown in Fig. 2. In the figure, points are the measurement results and solid lines are mathematical fit results. The meniscus profile under no magnetic field is determined by Bikerman Equation after experimentally determine the position where the molten Sn starts to contact the container wall.

According to Fig. 2, the greater the magnetic flux density is, the larger the electromagnetic pressure on molten metal is, and the meniscus turned more convex. Because the molten Sn is uncompressed, the whole molten Sn volume must be constant at different meniscus profile. In Fig. 3, the meniscus profile under no magnetic field is the curve CED, which can be calculated by Bikerman equation$^{11)}$ as:

$$h(x) = -\sqrt{2a^2 - x^2} + \frac{\sqrt{2a^2}}{2} \ln \left\{ \frac{\sqrt{2a^2} + \sqrt{2a^2 - x^2}}{x} \right\} + 0.3768a$$

(1)

where $\alpha = 2\sigma / (\rho_1 - \rho_2)$ is capillary constant. $\sigma$ (N/m) is interfacial tension between molten Sn and silicone oil, $\rho_1$ and $\rho_2$ (kg/m$^3$) are density of molten Sn and silicone oil, respectively, $g$ (m/s$^2$) is acceleration of gravity.

With imposing magnetic field, due to the electromagnetic pressure, the shape of molten Sn turns to be $A'B'C'E'D'A'$. In this case, the convex part $C'E'D'C$ can be determined by mathematical fit equation. The volume conversation is showed by Eq. (2),

$$V_{\text{column}} + V_{\text{bulge}} = V_{\text{CED}} + V_{\text{bulge}}$$

(2)

$$\pi R^2 H + V_{\text{bulge}} = \pi (R - \Delta R)^2 H' + V_{\text{bulge}}$$

(3)

Then the mold flux channel width is derived as Eq. (4).

$$\Delta R = R - \frac{\pi R^2 H + V_{\text{bulge}}}{\pi H'}$$

(4)

Mold flux channel width at different magnetic flux density calculated according to Eqs. (2), (3) and (4) is showed in Fig. 4, where the channel width under no magnetic field is assumed to be 0.02 mm,$^{17)}$ and the width is assumed to be the same along the coil height. Figure 4 shows that the magnetic field can widen the mold flux channel obviously, and the greater the magnetic flux density is the wider the mold flux channel is.

2.2. Mold Flux Channel Dynamic Pressure Calculation Model

In order to establish the mathematical model about the dynamic pressure in the mold flux channels, the right boundary of the channel is simplified as the curve shown in Fig. 5, which is described by function $h(x)$ with varied exit width of mold flux $h_l$ along with change in magnetic flux.

Fig. 1. Experiment device to measure profile of meniscus.

Fig. 2. Meniscus profile at different magnetic flux density.

Fig. 3. Determine mold flux channel width by meniscus profile.
The meniscus is a rigid solid skin and its shape does not change during mold oscillation. The meniscus profiles and the mold flux profile under no magnetic field is determined by Eq. (3) during one mold oscillation period under no magnetic field.

The boundary conditions in the mold flux channel shown in Fig. 5 are:

(I) \( l \leq x \leq l' \), \( y = 0 \), \( u = V_m - V_s \)

(II) \( l \leq x \leq l' \), \( y = h(x) \), \( u = 0 \)

(III) \( x = l' \), \( 0 \leq y \leq h_l \), \( P_{in} = P_t \)

(IV) \( l \), \( 0 \leq y \leq h_l \), \( P_{out} = P_t \)

Boundary conditions (I) and (II) are statement of “no slip” on the surface of mold wall and solid meniscus. \( l \) and \( l' \) are the inlet and outlet positions of mold flux channel, respectively. Under these boundary conditions, the mold flux channel pressure distribution can be derived from Eqs. (5) and (6) as:

\[
P(x) = p_i + \rho_s g x + 6 \mu_s (V_m - V_s) \varepsilon(x)
\]

\[
- \left[ \rho_s g l + 6 \mu_s (V_m - V_s) \cdot \varepsilon(l) - (p_t - p_i) \right] \frac{\xi(x)}{\xi(l)}
\]

\[
\varepsilon(x) = \int_l^x \frac{1}{h^2(x)} \, dx, \quad \xi(x) = \int_l^x \frac{1}{h^3(x)} \, dx
\]

where, \( P_i \) and \( P_t \) are pressures at inlet and outlet of the mold flux channel (\( P_p \)), respectively.

The flux channel pressure shown in Eq. (7) consists of three parts. The former two parts are the inlet pressure and static pressure caused by the liquid depth, they do not change during the mold oscillation. It is the third part that changes along with the mold oscillation, and is termed as dynamic pressure of flux channel caused by mold oscillation:

\[
P_D(x) = 6 \mu_s (V_m - V_s) \varepsilon(x)
\]

\[
- \left[ \rho_s g l + 6 \mu_s (V_m - V_s) \cdot \varepsilon(l) - (p_t - p_i) \right] \frac{\xi(x)}{\xi(l)}
\]

**Figure 6(a)** showed the flux channel dynamic pressure during one mold oscillation period under no magnetic field according to Eq. (9). The values of parameters in Eq. (9) are given as following: molten Sn’s density \( \rho_s \) is 6940 kg/m³, surface tension \( \sigma_i \) is 0.642 N/m.\(^{12}\) Silicone oil’s density \( \rho_i \) is 960 kg/m³, surface tension \( \sigma_i \) is 0.02 N/m viscosity \( \mu_i \) is 0.96 Pa·s.\(^{13}\) The mold oscillated in sinusoidal style, the frequency \( f_m \) is 1 Hz, maximum oscillation speed \( V_{max} \) is 0.0187 m/s (=1.12 m/min), then the mold oscillation speed can be described as \( V_m = V_{max} \cos 2\pi f_m t \), casting speed \( V_c \) is 0.0167 m/s (=1 m/min), then the negative strip is 15%. The outlet width of the mold flux channel under no magnetic field is assumed to be 0.02 mm.

According to Fig. 6(a), the dynamic pressure in mold flux channel is positive during negative strip of mold oscillation (curve BCD in Fig. 6) and reaches its maximum value when mold moves down in its maximum speed (point C), the dynamic pressure is negative during mold oscillation positive strip (arc AB and DE) and reaches its maximum value when mold moves up in its maximum speed (point A and E). When the mold oscillates in the same speed as the casting speed, the mold is static relatively to the billet, so the dynamic pressure is zero just as there is no mold oscillation. The dynamic pressure in mold flux chan-
nel varies periodically between maximum positive pressure and maximum negative pressure along with mold oscillation. In the negative strip period, the meniscus is pushed away from the mold wall by the positive pressure generated in the mold flux, and it is drawn back to the mold wall due to the negative pressure in the positive strip period. It is the pushing-away-from and drawing-back movement of the meniscus that causes the formation of oscillation marks.\textsuperscript{1)}

When there is magnetic field in the mold, the dynamic pressure distribution in mold flux along with mold oscillation obeyed the same equations and boundary conditions, but the shape of mold flux channel and exit width of mold flux changed under magnetic field. Figure 6(b) shows the dynamic pressure in the mold flux channel during one mold oscillation period when the magnetic flux density is 27.3 mT (the mold oscillated in the same style as shown in Fig. 6(a)). According to the figure, the dynamic pressure in the mold flux channel changes in the same way no matter with magnetic field or not, but the value of dynamic pressure decreased greatly under magnetic field.

Oscillation marks formation lies more on the maximum positive pressure in negative strip (point N in Fig. 6(a)) and maximum negative pressure in positive strip (point M). The reason is that the larger the positive pressure in negative strip is the more the early solidification shell be pushed away from the mold wall and the stronger the negative pressure in positive strip the more the early solidification shell be drawn back, then the oscillation marks got deeper. So it is more important to learn the maximum value of the dynamic pressure in mold flux channel. Figures 7(a) and 7(b) show the peak pressures in the mold flux channel during one mold oscillation cycle under different magnetic flux densities. It is noticed that the dynamic pressure varies between +94.9 Pa and −1680.3 Pa when there is no magnetic field, while the range of the dynamic pressure variation becomes narrow in the case of magnetic field. For example, the dynamic pressure varies between +50. Pa and −89.3 Pa when magnetic flux density is 27.3 mT and it varies between +2.1 and −37.1 Pa when magnetic flux density is 46.7 mT.

Previous studies have proved that EMCC can improve billets surface quality greatly by imposing high frequency magnetic field from outside of mold.\textsuperscript{5–8,14} From the view of dynamic pressure in the mold flux channel, one possible mechanism of the technology improve the surface quality is that the magnetic pressure toward inner molten metal caused by high frequency magnetic field can widen the flux channel exit width, change the shape of meniscus, then decrease the positive and negative dynamic pressure in mold flux channel, which may decrease the depth of oscillation.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig6}
\caption{Dynamic pressure in mold flux channel during one mold oscillation period under (a) no magnetic field, (b) magnetic flux density is 27.3 mT.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{fig7}
\caption{Peak pressure of mold flux channel during one mold oscillation cycle under: (a) no magnetic field, (b) under different magnetic flux density, and (c) peak negative pressure along with magnetic flux density.}
\end{figure}
marks.

Figure 7(c) shows the influence of magnetic flux density on the maximum negative pressure (The points in Fig. 7(b)). It can be seen that although the maximum negative pressure decreases with increasing magnetic flux density, it cannot decrease unlimitedly with the increasing of magnetic flux density. So, there are still dynamic pressure due to the mold oscillation which will cause the oscillation marks even impose high density magnetic field. In order to eliminate the oscillation marks, there must be a kind of dynamic force to balance the dynamic pressure cause by mold oscillation. This demand can be met by introducing Amplitude-Modulated Magnetic Field when whose amplitude is varied along with the mold oscillation.

2.3. Model to Optimize Design AMMF Coupled with Mold Oscillation

Figure 8 shows schematically the circumstances around the meniscus of melt in the EMCC. In the case of no oscillation of the mold and constant amplitude electromagnetic field \( B_e \), following equation at the tip of the shell is held, neglecting the strength of the shell:

\[
P_{\text{em}} + P_{\text{flux}} = P_{\text{metal}} \text{ i.e. } B_e^2 \mu /2\mu + P_{\text{flux}} = P_{\text{metal}} \quad \text{(10)}
\]

Where, \( P_{\text{flux}} \) is the static pressure of the flux; \( P_{\text{metal}} \) is the static pressure of the liquid steel; \( P_{\text{em}} \) is the electromagnetic pressure; \( B_e \) is the maximum of the electromagnetic field; \( \mu \) is the magnetic permeability of the melt.

With oscillation of the mold, additional dynamic pressure \( P_D \) presents, hence in order to keep the balance the electromagnetic pressure should vary accordingly by variation of the field, i.e., AMMF field \( B_{\text{AMMF}} \):

\[
P_{\text{AMMF}} + P_D + P_{\text{flux}} = P_{\text{metal}} \text{ i.e. } \frac{B_{\text{AMMF}}^2}{2\mu} + P_D + P_{\text{flux}} = P_{\text{metal}} \quad \text{(11)}
\]

Where, \( P_{\text{AMMF}} \) is the electromagnetic pressure due to the AMMF.

Comparing Eq. (10), Eq. (11) yields effective magnetic field flux of AMMF as:

\[
B_{\text{AMMF}} = \sqrt{\frac{B_e^2}{2\mu}} - 2\mu P_D \quad \text{(12)}
\]

The dynamic pressure \( P_D \) has been described above in Eq. (9). Finally, Eq. (13) is obtained,

\[
B_{\text{AMMF}}(t) = \sqrt{2} \cdot \sqrt{\frac{B_e^2}{2\mu}} - 2\mu P_{D-xm}(t) \cdot \cos 2\pi f t \quad \text{(13)}
\]

Where, \( P_{D-xm}(t) \) is the maximum of the dynamic pressure in the channel; \( f \) is the modulation frequency of the AMMF. Addition of coefficient \( \sqrt{2} \) turns the effective magnetic field flux to the maximum one.

Equation (13) is the AMMF coupled with the sine oscillation of the mold. In the negative strip of mold oscillation, the dynamic pressure in the flux channel is positive, and the intensity of the coupled AMMF decreases, i.e., \( B_{c-\text{AMMF}} > B_{\text{em}} \) so that the solid shell is prevented being pushed away from the wall of the mold; in the positive trip, while the dynamic pressure in the flux channel is negative, the intensity of AMMF increases, i.e., \( B_{c+\text{AMMF}} > B_{\text{em}} \) so that the solid shell will not move back to the wall of the mold due to the static pressure of the liquid steel. Therefore, the solid shell is unmoved and oscillation marks on the surface of the billet may be eliminated completely.

Figure 9 is the calculated result of the AMMF wave under the condition of \( B_e = 27.3 \) mT. With this type of AMMF the negative pressure in the flux channel is zero and the solid shell tip will keep stationary while the mold oscillating. Figure 10 shows the calculation results on amplitude contour of the AMMF waves with several \( B_e \) values. It is shown that along with increase of the \( B_e \), the variation of the AMMF is reduced.

3. Experiments

3.1. Experimental Device

The experimental apparatus for EMCC is shown in reference.\(^{15}\) Tables 1 and 2 list the experimental parameters. The friction forces of continuous casting and oscillation marks depth on the billets were measured. The signal of the friction force was analyzed by Fourier transformation and the frequency spectrum was obtained.

4 classes of experiments were carried out as shown in Table 3. The roughness of billet surface and the friction forces during continuous casting were measured.
3.2. Results and Discussion

Figure 11 shows the oscillation mark depth of the billets. One can learn that with the silicon oil the oscillation mark depth was the largest, even larger than that without silicon oil. With electromagnetic field the oscillation marks were significantly reduced. It seems that imposing AMMF was more effective than normal EMF.

In Table 4, the coefficients of the second terms of the formulas represent the amplitude of the varied friction forces during continuous casting. One can learn that along with input of silicon oil, imposing of normal magnetic field and AMMF, the variation in friction force decreased apparently in turn. This is beneficial to the surface quality of the billets.

Figure 12 shows the amplitudes of the friction forces under the conditions listed in Table 3. The friction force without silicon oil was large and the positive pressure was equal to the negative one. With the silicon oil only, the negative pressure was reduced significantly and the positive one seemed no change. With silicon oil and constant EMF or AMMF, both positive and negative pressures were reduced further. It is interesting that with AMMF the negative pressure was larger than the positive one.

Under the condition 1, dry friction between the metal and the wall of the mold occurred because the less of lubrication. With oil, under the condition 2, the oil lubricated the friction between the metal and the mold wall. Nevertheless, the positive friction was still large, therefore, during the positive strip of mold oscillation the meniscus still restored its position and produced the marks. With constant EMF, the flux channel was widened and both positive and negative dynamic pressures were reduced, hence the marks were reduced. With AMMF, on the positive strip, the EMF was imposed and the friction force was reduced; in the negative strip, it is interesting to notice, the friction force was relatively large, because on this strip the EMF was small. This suggests that the friction during positive strip of mold oscillation is critical for formation of the marks.

4. Conclusions

(1) Molten metal meniscus profile and mold flux channel width are measured under high frequency magnetic field by model experiments, then the dynamic pressure in mold flux channel is calculated during one mold oscillation period. It is shown that high frequency magnetic field can decrease the dynamic pressure greatly, which may be one possible mechanism of improving the billets surface quality by the soft-contact mold EMCC.

(2) A novel technology named AMMF coupled with mold oscillation in electromagnetic continuous casting was proposed in order to decrease depth of oscillation marks or even to eliminate it. A model to optimize design of AMMF...
is proposed based on the study of influence of the magnetic field on the dynamic pressure in mold flux channel.

3) Experimental results of continuous casting of Sn showed that imposition of AMMF coupled with mold oscillation could deduce the friction force during continuous casting and improve the billets surface quality.

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