Continuous Casting of Billet with High Frequency Electromagnetic Field

Hoyoung KIM, Joon-Pyo PARK, Heetae JEONG and Jongkeun KIM
Research Institute of Industrial Science and Technology (RIST), RIST PO Box 135 Pohang, 790-600 Korea.

(Received on June 22, 2001; accepted in final form on October 23, 2001)

In order to develop the high frequency electromagnetic continuous casting technology for applying to steel, numerical analysis of the magnetic field and casting experiments using various parameters have been conducted. The method of using cold inserts was well established to lead to a reliable numerical model. According to this numerical model, it was predicted that while casting, the magnetic field would be concentrated on the common region occupied by the coil and the melt and further its maximum value would be seen just below the melt level. Casting experiments have been carried out using tin as a simulating material for steel. No oscillation mark was observed on the billets because the solidification started without hook. Under an optimum condition, billet surface roughness was improved to 1/10 of the conventionally cast billets. The surface quality of the billet was heavily dependent on the melt level, the casting speed, and the coil current. In case of the excessive coil current, wave marks other than the oscillation mark appeared on the billet surface. The billet with proper electromagnetic conditions showed a thinner solid shell at the early stage of the solidification and a thicker shell at the mold bottom in comparison with the conventional cast billet. It has been concluded that the Joule heat is a more dominant factor than the magnetic pressure in determining the surface quality of cast products in the high frequency electromagnetic continuous casting process.

KEY WORDS: continuous casting; electromagnetic field; Joule heat; oscillation mark; billet.

1. Introduction

Continuous casting process is widely employed in producing commercial materials owing to its low cost and high productivity. However, surface defects of the products such as oscillation marks, cracks and so on, should not be overlooked in considering the total cost and environmental effects of the material handling process. For example, the whole surface of an aluminum slab needs to be machined before rolling. In the steel industry, a major part of the slab cannot be fed to the hot rolling mill without pre-conditioning the surface. Thus, any defect in the surface of continuous cast product is considered as one of major obstacles in the material processing for minimizing the cost and pollution and maximizing the productivity.

Electromagnetic processing of materials is greatly highlighted due to its outstanding performance to enable the product quality and the productivity to be enhanced, and its potential application to the cost reduction through the energy saving and the stream-lined process. As one of such technologies, the electromagnetic continuous casting (EMC) technology is considered as a potential process to drastically improve the surface quality of its products and to eventually increase the productivity of the continuous casting process. Since early 1970’s, it has been well established and commercially applied to the aluminum casting process in two types. The first one is a mold-less casting at about 3 kHz electric frequency to enable cast products with clean surface to be manufactured. The second type is to use the commercial frequency electricity with a mold for products with the clean surface and of the improved microstructure. Attainment of the EMC technology in these two types has been mainly dependent upon the role of magnetic force/pressure of the electromagnetic field.

The EMC technology for the steel industry also emerged by focusing on the magnetic force although it was considered to use the mold owing to the material properties, such as the relatively low electric conductivity, the heavy specific weight, and the high melting temperature. Research works have been carried out by using two approaches: the use of the low frequency electricity below 1 kHz and the use of the high frequency above 20 kHz. The first approach has a convenience in making a mold but has difficulties in treating the meniscus because of the induced metal flow, while the second one is easy to operate but has difficulties in building the power supply and designing and manufacturing the mold. Recently, an international project in Japan and a series of projects carried out by POSCO & RIST gave a gleam of success in commercialization of the EMC technology to be applied to the continuous casting of steel.

This study is the first step of a series of projects for developing the electromagnetic continuous casting technology to be applied to the steel industry. The EMC technology using the high frequency electricity has been examined to
identify effects of the electromagnetic field on the cast products and the working mechanism thereof. A sophisticated copper mold of the cold crucible type was fabricated, and continuous casting experiments were carried out by using tin as a simulating material of steel. The magnetic field in the mold was analyzed by using the experimental method and the numerical method respectively, and the cast products were examined to evaluate the effectiveness of the EMC process. Finally, a working principle has been proposed that the role of Joule heat should be more dominant than the magnetic force in determining the surface quality of the cast products in the continuous casting with the high frequency electromagnetic field.

2. Working Principle of EMC

The working principle of the EMC to be applied to the steel industry is shown schematically in Fig. 1. The left side represents the conventional casting and the right side represents EMC. The EMC needs special devices to apply the magnetic field to the melt; a coil is provided additionally and the mold needs to be segmented like the cold crucible using the high frequency EMC. Meanwhile it is also similar to the conventional mold using the low frequency EMC. The magnetic field generated from the coil induces the electric current in the melt. Then, this current heats the melt in terms of Joule heating and further generates the body force together with the external magnetic field in the melt, which is the Lorentz force, wherein the force always directs inward. Thus, the EMC can utilize such energy and force simultaneously to attain the intended purpose.

In the conventional casting, the meniscus is in touch with the mold wall almost at a right angle. Its solidification initiates with a hook, known as a root of oscillation marks and surface defects, and consequently oscillation marks appear on the surface of cast products. In the EMC, the inward Lorentz force deforms the meniscus so much as to be curved near the mold wall, helping the flux infiltrate well into the gap between the shell and the mold wall. The Joule heat causes the solidification to take place below the meniscus without any hook, and the extra energy is supplied to the mold powder without sacrificing the temperature of the melt. Therefore, the EMC process is expected to yield cast products with neither oscillation marks nor related surface defects. And it is also anticipated that the EMC process would cause the powder consumption amount to be increased, helping the casting speed get to be faster.

3. Experimental Method

Figure 2 is a schematic view of the experimental apparatus for the electromagnetic continuous casting. A submerged entry nozzle and a stopper rod were employed to supply the molten metal into the EMC mold. The mold with the 0.1 m square casting area and the 0.004 m corner radius comprised 20 pieces of 0.4 m long copper blocks, and each block has its own cooling channel therein. The EMC coil, which was of six turns of 85 mm height, was installed to apply a high frequency magnetic field, where the electricity was supplied in the range of 20 kHz.

In the study on the magnetic field intensity in the mold, cold charges with several cross-sectional areas were machined and inserted into the mold as a simulating material for casting, where the cold charge was cooled independently. The magnetic field intensity was evaluated by using a magnetic probe of the induction coil type. In the study on the effect of the electromagnetic field on the continuous casting process, tin was employed as a casting material with silicon oil as a lubricating substance. The casting speed was in the range of 0.3–0.8 m/min, and the mold oscillation was fixed at 1 Hz of 0.008 m stroke. Casting experiments were carried out by using various coil currents, relative locations between the coil top and the melt top, and casting speeds. To capture the shape of the solidified shell, the molten Sn–46wt%Pb alloy was poured just before the casting was finished.

The oscillation mark was selected as a measure of the...
surface quality of the cast products. For evaluation of the surface quality of the cast products, depths of the oscillation marks were measured in the 80mm long region by using a stylus, and the average value was calculated.

4. Results and Discussion

4.1. Magnetic Field Intensity in the Mold

The magnetic field in the mold is one of the critical factors in designing the apparatus and determining the casting conditions for the EMC. Particularly, for evaluation of the on-casting condition, numerical methods are widely used since it is not easy to use the experimental method owing to the molten metal occupying the mold. However, the magnetic field, which was evaluated by using a numerical model, was found to be different from the measured one in a partially filled mold, even though the model had already been verified in the empty mold. To overcome this difficulty with the numerical model, it was devised to use cold charges. A commercial code of OPERA3D\(^2\)) was employed for this purpose. The element size and distribution of the numerical model were adapted to show the coincidence between the results of the numerical model and the measured ones in various sizes of cold charges.

Figure 3 shows a typical result of measuring the magnetic field intensity along the casting direction in the mold where the coil top was located at 50 mm below the mold top. Symbols denote the measured value at 0.002 m apart from the mold wall, where the empty one is for the corner and the solid one for the wall center of the mold. And lines denote the calculated value at the same locations, where the dot line is for the corner and the solid one for the wall center of the mold. The coil current was 640 A and its frequency was 20 kHz at the empty mold (no charge). In the case of no charge, the maximum value was observed at a position near the middle of the coil length. As the mold was filled with the charges, the magnetic flux density got to be concentrated at the common part of the coil and the charge, and the maximum value position moved to the top part of the charge. It was also observed that the difference in values between the corner and the wall center disappeared with the mold being filled, excluding the top part of the charge. The magnetic flux density during casting (with the mold being fully filled with the molten tin) was expected to have the maximum value just below the melt level of 0.037 T at 640 A, and also the magnetic flux density at the corner was expected to be less than that at the wall center in the top part of the melt.

Figure 4 shows the magnetic flux density at the wall center of the mold along the casting direction as the location of the charge top was changed relatively to the coil location. As the charge location moved down from the coil top to the coil center, the magnetic flux density got to be concentrated within the common part of the coil and the charge, and its maximum value was increased, while it remained almost unchanged outside such part. This implies that the Joule heat amount and the magnetic pressure near the meniscus may be heavily dependent on the location of the melt level at a given coil current, since they are proportional to the square of the magnetic flux density.

4.2. The Effect of the Coil Current

Figure 5 shows a typical appearance of tin billets, which were cast respectively at coil currents of 0, 500, and 620 A with the other conditions being the same. No oscillation mark was found in the surface of the billet as cast at 500 A, while oscillation marks were found in the whole surface of the billet as cast at 0 A. At 620 A, new marks other than oscillation marks took place in the surface of the billet. They were formed to be apparently flat surface in a wavy pattern, thus they were named as wave marks. The wave marks seemed to be traces of the line where the melt was in touch with the mold when the coil current was excessive. The
forming mechanism is discussed later. Figure 6 shows the surface roughness of cast billets at various coil currents and the casting speed of 0.5 m/min, where its nominal value was 190 \( \mu m \) at 0 A and it was reduced to 20 \( \mu m \) at 500 A. Above 500 A, the surface roughness had a tendency to be higher due to wave marks. The experimental results demonstrate that the surface quality of billets is not improved any more at an excessive coil current, and that an optimal range of the coil current is available for such casting.

4.3. The Effect of the Melt Level and the Casting Speed

Figure 7 shows tin billets as cast at the coil current of 500 A and different melt levels in the mold. The melt level of Fig. 7(a) was 0.02 m above the coil top, that of (b) was equal to it, and that of (c) was 0.02 m below it. Although the nominal coil current was the same, oscillation marks were found in (a) while no oscillation mark was found in (b). In (c), wave marks, which were usually seen in the case of the excessive coil current, were observed. This experimental results support the assumption inferred from Fig. 4 that the Joule heat amount and the magnetic pressure at a part near the meniscus may be heavily dependent on the location of the melt level. Figures 8 and 9 show the effect of the casting speed on the surface roughness of tin billets at various melt levels and coil currents. It seems that the faster the casting speed gets to be, the less the magnetic field is required. This phenomenon seems similar to the fact that in the conventional casting, the depth of the oscillation mark is decreased as the casting speed is increased. Since the so-called hook of the early-solidified shell is reduced at a higher casting speed, the magnetic field intensity required for good surface is also decreased.

4.4. The Solidified Shell

Figure 10 shows the shapes of the early-solidified shell of tin billets. Compared with the shell at the coil current of 0 A as shown in Fig. 10(a), the shell of EMC billet as shown in Fig. 10(b) is relatively thin and uniform, which is recognizable from the position below the meniscus level, where the Joule heating worked. The solid shell for the coil current of 0 A in Fig. 10(a) does not show the hook at the shell tip. It seems that the casting conditions, such as casting speed, mold oscillation, mold flux and so on, were not proper to form the hook. Figure 11 shows the solid shell thickness at the location of the mold bottom for various casting speeds, where EMC billets yielded thicker shells. Figures 10 and 11 shows that the solid shell of the EMC billet is thinner near the meniscus, while it is thicker at the mold bottom. This can be well explained by the fact that the flat surface with no oscillation mark worked to decrease the total heat transfer resistance between the strand and the mold. The gap between the strand and the mold is bigger at the root of the oscillation mark than at the top of the oscillation mark. Since the heat transfer resistance between two plates is proportional to the gap, a flat surface without the oscillation marks has smaller resistance than a corrugated surface with the oscillation marks if the air gap of EMC billet is the same as the distance between the mold and the hill of the oscillation mark. Thus, it is concluded that EMC billets have a thicker solid shell in the mold, although the energy was added to the melt. This experimental evidence may support the possibility that a higher casting speed can take place with the EMC technology.

4.5. The Wave Mark and the Early Solidification

Figure 12 shows again typical wave marks observed in the tin billet at an excessive coil current. Careful observation gave that the mark comprised two parts; one part, \( w_1 \) in (b), was covered with tin oxide, and the other part, \( w_2 \) in (b), had no oxide. The spacing between marks was referred as \( S \). In similar casting experiments carried out at various
casting speeds, these parameters for wave marks produced a relation as shown in Fig. 13. Since $S$ was proportional to $v/f$, where $v$ denotes the casting speed and $f$ is the mold oscillation frequency, it was concluded that the wave mark was similar to the oscillation mark. Furthermore, it was seen that the variation in the length of $w_2$ depending upon
the casting speed was corresponding to that in the casting length during the positive strip time ($t_p$) of the casting, and that of $w_1$ was also corresponding to that in the casting length during the negative strip time ($t_n$). Thus, it was concluded that $w_1$ was formed during the negative strip time and that $w_2$ during the positive strip time.

Based on these observations, formation of wave marks was depicted schematically in Fig. 14. Since the coil current is larger than the optimal one, the Joule heat amount and the magnetic pressure are excessive. As for the wavy shape of $w_1$ and $w_2$, it seems the trace of the lines where the melt is in touch with the mold. The difference of the magnetic field intensity between the slit and the segment causes this line to be curved, which is similar to what was observed in the cold crucible levitation melting.21) Focusing on the excessive Joule heat between these two effectives, it is assumed that the liquid metal in touch with the mold wall exists between the meniscus and the solidified shell. This assumption is feasible if the Joule heat amount is larger than the energy extracted by the mold. Now follow the sequence drawn in Fig. 14. During the negative strip time, due to the frictional force of the mold, a part of the molten metal in touch with the mold wall is dragged down, which causes the adjacent part of the free surface with the tin oxide on it to move toward the mold wall. Thus, a new-solidified shell has the tin oxide on it, which is corresponding to $w_1$. However, during the positive strip time, due to the frictional force, the molten metal in touch with the mold wall is dragged up, which causes the melt of the internal melt to come out toward the mold wall. Then, a new-solidified shell has no oxide on it, which is corresponding to $w_2$ as shown in Fig. 12. This explanation is well in conformity with the results of observing the billet surfaces as shown in Figs. 12 and 13, and thus it seems to be reasonable to assume that the liquid metal in touch with the mold wall exists between the meniscus and the solidified shell in case of the excessive coil current.

The above discussion on formation of wave marks provides some clues on the forming mechanism of the early-solidified shell in the EMC. Now, a solidification scheme or a working principle of the EMC by focusing on the Joule heating is suggested as illustrated in Fig. 15. In the Figure, the black arrow denotes the tip of solidified shell and the white arrow is for the location where the magnetic pressure becomes greater than the hydrostatic pressure of the melt.

Fig. 12. Wave marks of tin billet (a) appearance and (b) schematic figure.

Fig. 13. The wave mark parameters versus casting speed.

Fig. 14. Schematic figure of the wave mark formation at EMC.

Fig. 15. Schematic figure near the triple point at EMC (a) for lower than the optimal magnetic field, (b) for the optimal magnetic field, and (c) for higher than the optimal magnetic field. (The black arrow denotes the tip of solidified shell and the white arrow is for the point where the magnetic pressure becomes greater than the hydrostatic pressure of the melt.)
should denote the identical location as shown in Fig. 15(b) and solidification starts just at this point with no hook. Then, products with a flat and clean surface are obtained. It should be recognized that the billet surfaces do not show any effect of the magnetic pressure like curved oscillation marks until the magnetic field increases to the optimal magnitude. However, under an excessive magnetic field, the locations of these two arrows do not coincide since the Joule heat amount is larger than the heat as extracted by the mold. The liquid melt contacts to the mold wall in a curved line owing to the difference of the magnetic pressure in the width direction and the solidification starts where the Joule heat amount equals to the heat flux of the mold as shown in Fig. 15(c). Then, the billet surface shows the wavy patterns as shown in Fig. 12(a).

The above descriptions on the wave mark and the solidification scheme reveal that until the coil current is excessive, the magnetic pressure simply imposes a curvature on the meniscus to help the flux infiltrate well between the solid shell and the mold wall and it does not leave any trace on the billet surface where its magnitude does not seem big enough to deform the solidified shell tip of tin. When the coil current becomes excessive, the magnetic pressure leaves the wavy patterns since the liquid melt contacting to the mold wall can be easily deformed into a curved line according to the distribution of the magnetic pressure in the width direction. The billet surfaces shown in Fig. 5 well support this argument. Thus it can be said that the Joule heat rather than the magnetic heat directly determines the surface roughness of the billet. In this sense, the Joule heat rather than the magnetic pressure can be regarded as a dominant controlling parameter for the surface quality of the casting products in the high frequency electromagnetic casting process.

5. Conclusion

The casting experiments using tin as a simulating material for steel have been conducted to identify the effects of the high frequency electromagnetic field on the surface quality of billets. The following results are obtained.

Under the magnetic field in the mold, the method for using cold inserts was well established to lead a reliable numerical model. As for distribution of the magnetic field during casting, it was expected that it would be concentrated in the common part occupied by the coil and the melt, and its maximum value would be observed just below the melt level. It was also observed that the melt level had a significant effect on the maximum value of the electromagnetic field.

No oscillation mark was found in EMC billets because the early-solidified shell had no hook on its tip. Under the optimal condition, the surface roughness of the EMC billet was improved to 1/10 of that of the conventionally cast billet. The surface quality of the billet was heavily dependent on the melt level, the casting speed and the coil current. In an excessive magnetic field, wave marks other than oscillation marks were observed.

In the EMC billet, a thinner solid shell took place at the early stage of solidifying and a thicker shell took place at the mold bottom, compared with the shell in the conventional cast billet. Thus, a higher casting speed can be expected with the electromagnetic casting.

In the high frequency electromagnetic casting process, the Joule heat is a more dominant factor than the magnetic pressure in determining the surface quality of cast products.

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