1. Introduction

Many defects, including an oscillation mark, a crack, etc., were formed on the surface of products during continuous casting. Such surface defects seriously affect productivity and workability in the continuous casting process.\(^1\)–\(^3\) If the cast has any surface defect, such defect has to be removed by scraping or grinding before it is passed on to the next process. Therefore, such surface defect results in a delay in production and labor and material loss. Steel industries, which have to reduce the amount of fossil fuel used in production, are striving to realize the hot direct-rolling process to eliminate having to reheat the cast. These factors demonstrate the need for extensive, technical study of the electromagnetic casting (EMC) process. This technology uses an electromagnetic force instead of a mold for casting of aluminum with a light specific gravity and a good electric conductivity.\(^4\)–\(^5\) However, the specific gravity of steel is relatively high, and its thermal and electric conductivity are low. Besides, its casting speed is high. Therefore, it was thought that moldless casting of steel was nearly impossible. For this reason, steel industries have turned their attention to the application of EMC in the soft contact casting form using the mold. There are two EMC methods. One is to use a high-frequency magnetic field of tens of kHz or higher,\(^6\)–\(^11\) and the other is to use a low-frequency magnetic field of 60 to 1 000 Hz.\(^12\) The former method results in a meniscus with good stability, but it requires a special mold and power device. On the other hand, the latter method’s shortcoming is that the meniscus is unstable.

This study has been conducted as part of a study to improve the surface quality of the billet by applying high-frequency magnetic field electromagnetic casting technology to the continuous casting of steel. In this study, the effect of the mold shape on the steel billet surface quality was examined by a continuous casting experiment. It also researched the effects of electromagnetic field on the surface quality of the billet by observing the shape of the early-solidified shell as well as measuring the meniscus shape and mold flux consumption.

Through the experiment, it was found that billet surface roughness was improved to 1/5 of the conventionally cast billets under an optimum condition. This study also discovered that a hook formed on the early-solidified shell and molten steel overflowed when an electromagnetic field was not applied. However, in the electromagnetic casting, a hook did not form in the meniscus and the early-solidified shell grew and became thin and even. The corner shape of the mold also had a great effect on the surface quality of billet’s corner. In addition, it was found that mold flux consumption is increased during electromagnetic casting.

KEY WORDS: electromagnetic casting; EMC; magnetic field; Joule heat; oscillation mark.

2. Concept of EMC

This is a brief introduction of the concept of soft contact EMC using a high-frequency magnetic field. As shown in Fig. 1, when the electric current is applied to the coil, the magnetic field is induced to the mold and therefore, the electric current is induced by the magnetic field. Again, this electric current generates through the mold segmented by slits a magnetic field and an electric current in the molten metal inside the mold. This induced current not only heats the molten metal but also generates an electromagnetic force in the molten metal, resulting in the induced magnetic field. This technology uses Joule heating and Lorentz force to produce the EMC principle using a high-frequency power.

Joule heating heats the meniscus and a thin early-solidi-
fied shell is formed in the lower part of the meniscus. This inhibits a hook, the root of the oscillation mark. The electromagnetic force enlarges the meniscus curvature of the molten metal in contact with the mold. This improves the inflow of the mold flux and, simultaneously, reduces the contact pressure between the shell and the mold. Also, since the Joule heating retards solidification of the flux existing between the billet and the mold, it is expected that heat transmission between the solidified shell and the mold is accelerated and any width directional deviation of the heat transmission decreases.

3. Experimental Apparatus and Method

As illustrated in Fig. 2, the effect of the EMC mold shape on the surface quality of the billet was examined by using 3 types of molds. Mold (a) consists of 20 segments (each segment size: 23×23×400 mm), where cooling water flows independently. Segments were assembled to form casting section dimensions of 102×102 mm, with a 4 mm corner curvature. This type is called a full-segment type mold. Mold (b) has one plate comprising its respective face, and each plate has slits at parts to which the electromagnetic field was applied, without curvature at its corners. This is called a partial-slit type of mold. Mold (c) is made by combining the full-segment and the partial-slit type molds so that two corners have a curvature and the other two corners have a right angle. This facilitates easy comparison of the effects of a mold's corner shapes on the surface quality of the billet. This is called a combination type of mold.

Experimental conditions are listed in Table 1. At the final stage of casting, the shape of the early-solidified shell was observed by adding FeS powder to the molten steel inside the mold. The EMC effect was evaluated by measuring the depth of the oscillation mark.

4. Experimental Results and Discussion

4.1. Effect of Mold Shape on the Billet Surface

4.1.1. Full-segment Type Mold

The number and length of slits existing in the mold have a great effect on the efficiency of the electromagnetic field. In this study, the casting experiment was conducted by using a mold in which respective manufactured segments were assembled as shown in Fig. 2(a).

The billet surface morphology of the face and corner and the billet surface roughness by measuring the depth of the oscillation marks, as obtained under varied electromagnetic conditions, are shown in Figs. 3, 4, and 5, respectively. Criteria for determining the effect of the electromagnetic field were the depth of the oscillation mark (OSM) and the latitude directional roughness of the billet. These were measured on the surfaces of the face, the corner and the off-corner (10 mm off the corner) of the billet. It can be seen from Figs. 3(a) and 4(a) that the OSM was clearly formed when the electromagnetic field was not applied. It was also noted that the surface shape of face was significantly improved in case (b), where a coil current of 670 A was applied, but the OSM still remained in the corner. In case (c), where a coil current of 830 A was applied, both the surface shape of the face and the corner were greatly improved so that the OSM was formed to a depth of 0.15 mm or more. It was observed in case (d), where a coil current of 1 100 A was applied, that the respective surface shapes of the face, corner and off-corner were greatly improved, but grooves formed along slits in the casting direction of the billet. These slits may be due to the electromagnetic field's high intensity, which acted on the molten steel through the slits where the magnetic flux density was relatively high, resulting in molten steel being pushed into the mold, thereby causing these grooves to form.8) These marks are about 1 mm deep—deeper than the OSM when the electromagnetic field was not applied. From this result, proper conditions and magnetic pressure are able to reduce the formation of the grooves. Experimentation revealed that an optimal electromagnetic condition minimized any grooving of the billet surface.

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![Fig. 1. The concept of electromagnetic casting of steel.](image1)

![Fig. 2. Schematic view of mold.](image2)

![Table 1. Experimental conditions.](image3)
Partial-slit Type Mold

The experiments described above revealed that using a full-segment type mold with magnetic field improved the billet surface morphology. However, when the EMC process is applied to actual work, errors may occur while respective segments are being manufactured and assembled into a mold. It is especially difficult to precisely assemble them into a mold so that the exact taper may be maintained.

Therefore, a mold with easy maintenance is required. For this reason, as shown in Fig. 2(b), a mold was manufactured by using one copper plate for its respective face and assembling this plate so that it has slits at parts through which the electromagnetic field was applied. This copper plate had its upper and lower parts connected. Then, the characteristics of the mold were evaluated by the casting experiment. The full-segment type of mold is perpendicular, but has a taper where the lower part is 0.4 mm narrower than its upper part. The partial-slit type of mold was manufactured with consideration being given to the solidification contraction and the thermal contraction of the molten steel.

The casting experimental conditions are listed in Table 1. The billet surface morphology and the billet surface roughness obtained under varied electromagnetic conditions are shown in Figs. 6 and 7, respectively. When the electromagnetic field was not applied, the OSM was clearly formed. On the other hand, when the coil current was 900 A, the billet had little OSM in its face but the OSM remained in the corner, as if it had been sucked in the direction of the casting. At 1100 A of coil current, the grooves, which take place when the magnetic field is excessive, began to appear in the casting direction. When the coil current was increased to 1300 A, the surface shape deteriorated and a wave mark, which is to shown as the distorted oscillation mark, was formed.

In the experiment using the partial-slit type mold, the surface morphology of the face was improved to a degree consistent with the full-segment type mold, while its corner morphology improved only slightly. As mentioned above, the major difference between the full-segment type of mold and the partial-slit type of mold is whether any curvature is present in the corner. Since the induced current, which flows from the charge surface in a latitudinal direction, has a tendency to flow along a short path, it fails to reach the molten steel surface of a right angle corner. It is believed that since the induced current was weaker on the corner surface than on the face surface, the electromagnetic force, acting as the pinch force, became weak. This meant that the electromagnetic force was uneven in the width direction, which might cause the molten steel to easily overflow due to any external factor such as oscillation of the mold. It may also explain the weak corner improvement.
4.1.3. Combination Type Mold

It is thought that the reason the corner surface shape was improved less in the partial-slit type mold than in the full-segment type mold was the difference in the mold corner shape. Therefore, as shown in Fig. 2(c), the combination mold was constructed so that two of its faces have a right-angle corner and the other two faces have a curved corner. The casting experiment was conducted to compare a right angle corner and a curved corner. The mold section dimensions were 107×111 mm.

The casting experiment was conducted under the same conditions as the previous experiment. After the experiment, the billet surface was observed in the 4th face (the curved corner) and the 2nd face (the right angle corner). Figure 8 shows the surface shape when a magnetic field was not applied. Figure 9 shows the 4th face (the curved corner) and the 2nd face (the right angle corner) when a coil current of 1,050 A was applied. Figure 10 shows the relationship between the OSM depth and the electromagnetic field. As shown in Fig. 8, the OSM was formed in both the 2nd face and the 4th face when a magnetic field was not applied. However, the formation of OSM was observed in a right angle like the full-segment type mold. In the curved corner, the OSM appeared to have been sucked along the casting direction similar to the partial-slit type mold. There was even evidence of an overflow of the molten steel. Figure 9, shows the effect when a coil current of 1,050 A was applied. The face shape was improved in both Figs. 9(a) and 9(c). In Fig. 9(b) the shape of the 1-4 corner (with the curvature) was similar to the shape of the full-segment type mold shown in Fig. 4(c). The shape of the 2-3 corner with a right angle in Fig. 9(d) has the same shape as shown in Fig. 7(c). In Fig. 10, it was identified that the billet surface shape, especially, the corner shape was dramatically improved in the mold with curved corners than that of the mold with right-angle corners.

4.2. Factors Effects on the Surface Quality

It is very important to understand the effect of the electromagnetic field on the shape of the early-solidified shell, since the forming position and the shape of the early-solidified shell have a great effect on the surface quality of the billet. In order to observe the early-solidified shell, 100 g of FeS powder was wrapped in the Al thin sheet, and it was added directly to the molten steel in the mold at the last stage of the casting. A sample was obtained from the molten steel along the casting direction of the billet, and the shape of the early-solidified shell was observed by the S-print method. In this experiment, partial slit type mold was used. Figure 11 shows the shape of the early-solidified shell without applying the electromagnetic field. A coil current of 830 A was found to provide the optimal results in this study. The black part in the photograph is where sulfur was intermixed. It is also the solidified part after the addition of FeS. When the electromagnetic field was not applied, the early-solidified shell was thick and uneven, and had a hook, which is the root of the OSM [see Fig. 11(a)]. Overflowed molten steel containing sulfur existed in the outer face of the early-solidified shell. On the other hand, when a coil current of 830 A was applied, the early-solidified shell was thin and even, without any hook formation. It is thought that a hook was not formed because the early-solidified shell was heated by the magnetic field and then cooled slowly. This prevented OSM and resulted in an improved surface shape.

Meniscus shape variations were determined when the electromagnetic field was applied by submerging a stainless plate (0.1 mm thick and 20 mm wide) in the mold face and the corner during casting. The measured results are shown in Fig. 12. When the electromagnetic field was not applied, both the face and the corner had a flat meniscus, as seen in Fig. 12(a). It can also be seen in Fig. 12(b) that a curvature
was formed in the meniscus by the electromagnetic pressure when the electromagnetic field was applied. From this measurement, it was determined that the magnetic pressure was generated when the electromagnetic field was applied, and therefore, the curvature was formed in the meniscus by the magnetic pressure.

Figure 13 is a photograph showing the shape of the submerged entry nozzle (SEN) after casting. Figure 13(a) reveals the results of casting without applying the magnetic field. It shows that the molten steel was solidified and clung to the part where the nozzle was in contact with the meniscus. It is thought that since a single-hole nozzle was used in this experiment, the flow of the molten steel ascending to the meniscus was weak. This allowed the temperature to drop at the meniscus to the point that the molten steel and flux were solidified and clung to the nozzle. However, when the casting was performed with an application of 1 100 A of coil current, there was no indication that the molten steel...
clung to the nozzle [Fig. 13(b)]. It was observed that the molten steel did not solidify because the meniscus temperature increased due to the Joule heating.

4.3. EMC without Mold Oscillation

In ordinary casting, the mold is oscillated to prevent any trouble between the mold and the billet as well as to increase the casting speed by accelerating the mold flux consumption. In EMC, it was thought that if the magnetic field was applied, the Joule heating would accelerate the melting of the mold flux resulting in increased consumption. The magnetic pressure made a curvature form in the meniscus, thus the inflow of the mold flux was improved. Therefore, it was found that EMC could be performed without mold oscillation. Figure 14 shows photographs of the billet surfaces made by casting steel without mold oscillation after the application of 1 050 A of coil current to the combination type mold. Under the same electromagnetic condition, both the 2nd face and 4th face had the better billet surface without mold oscillation than that with mold oscillation. It suggests that if the casting can be performed without mold oscillation, the casting plant could be dramatically simplified.

4.4. Mold Flux Consumption

Mold flux consumption has a great effect on the surface quality of the billet and the casting speed. When the magnetic field was not applied, about 300 g of mold flux was consumed during one test casting. Approximately 450–500 g of the mold flux was consumed with both the applied magnetic field and mold oscillation. When the magnetic field was applied but the mold was not oscillated, about 400 g was consumed. However, due to the short casting time, the exact cause of the difference in mold flux consumption could not be determined. It is thought that mold flux consumption increased when the magnetic field was applied, since the Joule heating expedited the melting of mold flux and the flux inflow channel became broader due to the electromagnetic field.
tromagnetic pressure. It is also observed that the consumption of mold flux increased with the application of a magnetic field and therefore, casting speed should increase. In addition, the application of a magnetic field, even without mold oscillation, produced more consumption of mold flux than ordinary casting where the mold was oscillated.

5. Conclusions

(1) EMC of molten steel can be achieved by using a full-segment type mold. The depth of the oscillation mark decreased from about 0.6 mm down to 0.15 mm. The billet surface morphology at the mold corner was greatly improved when the mold corner was curved.

(2) A hook formed at the meniscus and the early-solidified shell was thick and uneven when the magnetic field was not applied. However, when the magnetic field was applied, a hook was not formed in the meniscus and the early-solidified shell grew to be thin and even.

(3) In the EMC process, curvature was formed in the meniscus due to the force of the magnetic field, which was concurrent with Joule heating. There was also an increase in the consumption of mold flux.

(4) The new EMC technology without mold oscillation is applicable to industry because mold flux consumption was greater than in ordinary casting with mold oscillation.

REFERENCES