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Electromagnetic Casting Technique for Slab Casting

Masahiro TANI*
Takehiko TOH
Kenji UMETSU
Kazuhisa TANAKA
Masafumi ZEZE
Keiji TSUNENARI
Kazunori HAYASHI
Shinichi FUKUNAGA

Abstract

In the electromagnetic casting (EMC) technique, an electromagnetic field is imposed by a solenoidal coil and a Lorentz force is generated at a meniscus. Consequently, a smooth cast surface without defects can be expected. So far concerning with EMC, the billet casting plant test, the slab casting bench scale test on pilot caster and the numerical simulation have been conducted. Finally the slab casting plant tests with the EMC technique were conducted. The castings were very stable and produced without any major difficulties. The qualities of slab cast were greatly improved by the EMC technique.

1. Introduction

Electromagnetic casting (EMC) is an improved version of continuous casting in which an electromagnetic field is applied to the initially solidified shell right under the meniscus of the molten steel within the mold. With this technology, it should become possible to control the phenomenon of initial solidification of molten steel and thereby improve the surface qualities of cast slab.[1)]

The Nippon Steel Corporation proposed pulsative electromagnetic casting (pulsative EMC) to further improve the surface qualities of cast slab through intermittent application of an electromagnetic field.[2, 3)] The company has already carried out a series of casting tests using an experimental continuous billet caster and a plant continuous billet caster and has demonstrated that EMC significantly improves the surface qualities of cast billet and makes it possible to omit the surface conditioning of billets before they are rolled into final products.[4-7)] In casting tests of small-section slabs using an experimental continuous slab caster, too, the company has demonstrated that EMC markedly improves the surface qualities of cast slabs.[7-10)] On the basis of the above test results, we carried out casting tests of large-section slabs using a plant continuous slab caster[11-13)] and developed EMC technology for large-section slabs.

In this report, we shall describe the principles of pulsative EMC technology, the circumstances leading up to development of the technology, and the results of large-section slab casting tests carried out using a plant continuous slab caster.

It should be noted that the contents of the report are partly the results of the "Development of Metal Manufacturing Processes for Rationalizing the Use of Energy" [5-10)] carried out by the Japan Research and Development Center for Metals (JRCM) under a subsidy of the former Ministry of International Trade and Industry and the results of the "Development of High-Efficiency Electromagnetic Slab Casting Technology for Saving Energy and Improving Slab Qualities" [11-13)] carried out jointly by the New Energy and Industrial Technology Development Organization (NEDO) and Nippon Steel Corporation.

2. Principles of Pulsative EMC and a Study of Basics

The main principles of EMC are illustrated in **Fig. 1**, and contrasted with that of the conventional continuous casting process. In the continuous casting process, it is necessary to oscillate the mold, with a frequency of several Hz, and an amplitude of several mm, in order to ensure adequate lubrication between the mold and the solidified shell/slab by fused flux. Therefore, in the conventional con-

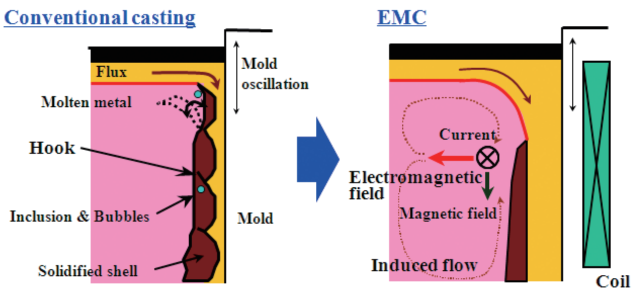


Fig. 1 Principle of EMC

* Senior Researcher, Yawata R&D Lab.
1-1 Tobihata-cho, Tobata-ku, Kitakyushu, Fukuoka 804-8501

tinuous casting process (left-hand diagram in Fig. 1), the pressure of the fused flux changes cyclically, causing tiny, periodic dents called oscillation marks (hundreds of μm in depth) to be formed on the slab surface at intervals of several mm in the casting direction. In addition, in the case of low carbon steel, a solidified shell tip called a hook (hook-shaped structure) is sometimes observed at the base of individual oscillation marks. Nonmetallic inclusions (hereinafter simply called inclusions) and bubbles entrapped in the hooks can become origins of defects in the slab or product.

On the other hand, in the EMC process (right-hand diagram in Fig. 1), an AC current is passed through a solenoid coil (a coil of wire spirally wound around a cylindrical or rectangular core) installed at a level very close to the surface of the molten steel to generate an induced magnetic field and an induced current in the molten steel and the solidifying shell. By means of the interaction between them (Fleming's left hand law), an electromagnetic field (Lorentz Force), which is always directed from the mold toward the molten steel, is generated. Then, the molten steel static pressure acting on the molten steel in the initially solidified portion and on the solidified shell decreases, thereby bringing about a "soft contact state" in which the layer of fused flux between the mold and the molten steel increases in thickness.

Under the soft contact state, the periodic change in pressure of the fused flux is restrained and the initially solidified portion is cooled slowly. In addition, as the solidified shell is cleaned by the molten steel flow induced by the electromagnetic field as shown in the right-hand diagram of Fig. 1, the oscillation marks and hooks disappear or decrease in depth markedly and the occurrence of defects is restrained. Thus, it can be expected that EMC will significantly improve the surface qualities of cast slab.[1)]

However, the original EMC technology had a number of drawbacks. One of them was that the molten steel flow induced by the electromagnetic field was so rapid that the meniscus of molten steel became unstable and irregular in terms of time and space, making it impossible to maintain a stable soft contact state in the casting direction or in the mold circumferential direction. Therefore, EMC did not always offer better surface qualities of cast slab.

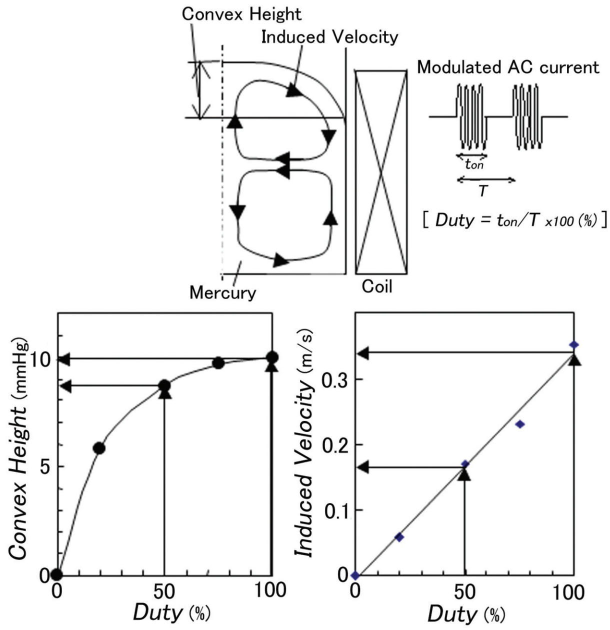
As a means of alleviating this drawback, the Nippon Steel Corporation developed a new technology named pulsative electromagnetic casting (pulsative EMC).[2, 3)] In pulsative EMC, an electromagnetic field is applied intermittently to the molten steel in the initially solidified portion and to the solidified shell by passing an AC current through a solenoid coil at a frequency of several to tens of Hz. By so doing, it is possible to control the velocity of the molten steel flow induced by the electromagnetic field.

Fig. 2 describes the results of a basic pulsative EMC experiment, carried out using mercury. A 200 Hz AC current was intermittently passed through a solenoid coil installed around a glass beaker filled with mercury.

In the experiment, the convex height of the meniscus of the mercury caused by the electromagnetic field—the index of "soft contact state"—and the magnitude of the velocity of mercury flow induced by the electromagnetic field were measured as a function of the parameter of intermittent current application, duty, defined by the following equation

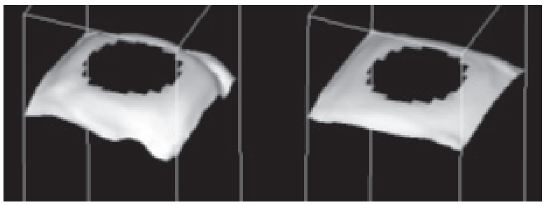
$$\text{Duty} = t_{on} \,/\, T \times 100\ (\%) \qquad (1)$$

where T is the intermittent current application period (conduction time + non-conduction time) and t_{on} is the conduction time. It can be seen from Fig. 2 that the relationship between induced velocity and duty is linear but that the relationship between convex height and



(a) Convex height vs. Duty (b) Induced velocity vs. Duty

Fig. 2 Pulsative imposition of electromagnetic field



(a) Continuous imposition (b) Pulsative imposition

Fig. 3 Free surface shape of molten steel

duty is nonlinear. The implication is that by intermittently applying an electromagnetic field at duty = 50%, it is possible to secure a convex height of approximately 90% while restraining the induced velocity to 50%. It is generally accepted that a stable soft contact state will be maintained when the surface profile (molten steel meniscus) is kept stable.[2, 3)]

Next, a numerical simulation of the flow of molten steel and the behavior of the molten steel meniscus, during pulsative EMC, was carried out through the coupling of an electromagnetic field analysis with a molten steel flow analysis, where the molten steel is treated as a free surface,[14)] on a system composed of a solenoid coil, molten steel, and mold. **Fig. 3** shows an example of the results of the simulation for the EMC of billet. It can be seen that the free surface shape of the molten steel in the mold circumferential direction is irregular when the electromagnetic field was applied continuously, whereas the free surface shape of the molten steel in the mold circumferential direction is regular when the electromagnetic field was applied intermittently (duty = 50%).[7)]

3. Casting Tests Using a Plant Continuous Billet Caster

Following preliminary studies based on the results of the basic experiments and numerical simulation described in the preceding section, and after the subsequent casting tests of low melting point alloy and steel using an experimental continuous billet caster,[4, 5] a pulsative EMC test was carried out using a plant continuous billet caster at Muroran Works of the Nippon Steel Corporation.[6, 7]

For test purposes, one of the streams of Muroran›s 6-stream continuous billet caster was provided with a solenoid coil and a specially constructed, 160-mm-square mold for use with pulsative EMC technology. The mold was fabricated from four pairs of copper plates and fashioned with a stainless steel back plate, which allowed for both mechanical rigidity and sufficient penetration of the electromagnetic field into the molten steel.

In pulsative EMC, a large induced magnetic field is generated near the meniscus of the molten steel, and the induced magnetic field interferes with proper functionality of the eddy current sensor that is commonly used in controlling the molten steel bath level (molten steel pouring rate). Therefore, we developed an eddy current bath level sensor that is synchronized with the pulsative electromagnetic field. The principle of operation of the sensor is shown in **Fig. 4**. With this system, molten steel bath levels are sampled using a signal from the eddy current sensor while the AC current is not passed through the solenoid coil, that is, while the electromagnetic field is not applied to the molten steel.

Using the solenoid coil, mold, and pulse-synchronized eddy current sensor developed for pulsative EMC, we carried out a pulsative EMC test on the plant continuous billet caster. With the exception of the intermittent application of an electromagnetic field, the same casting conditions were applied to all six streams of the continuous caster. It was found that the pulsative EMC operation could be performed stably for many hours without any adverse effect on the control of the molten steel bath level, etc.

Fig. 5 shows the difference in normalized mold flux consumption with and without pulsative EMC. It can be seen that pulsative EMC increases the consumption of mold flux. The observed increase is reasonably accounted for by assuming that the intermittent application of an electromagnetic field widens the gap between the mold and the solidified shell in the initially solidified portion. The implication is that pulsative EMC improves the lubrication between the mold and the solidified shell.

Fig. 6 shows the appearances of billets of 0.08% carbon steel obtained by the test. It was confirmed that the oscillation marks in the casting direction had almost disappeared for billets produced by the pulsative EMC process. **Fig. 7** shows the surface roughness of cast billets measured using a laser displacement meter. It can be seen from the figure that the pulsative EMC process reduced the surface roughness of cast billet.

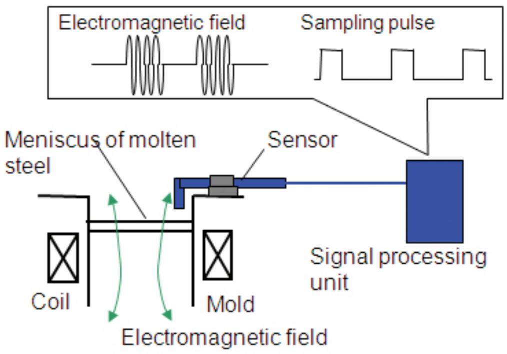


Fig. 4 Meniscus level sensing synchronized to pulsative electromagnetic field

Fig. 8 shows the incidence of defects in each of the products obtained by rolling a billet cast by pulsative EMC and a billet cast by the conventional casting process. The vertical axis represents the normalized incidence of defects in product obtained by rolling a billet cast by the conventional casting process without hot scarfing. It can be seen from the figure that, even without hot scarfing, the billet obtained by pulsative EMC offers a product quality equal or superior to that offered by the billet obtained by the conventional casting

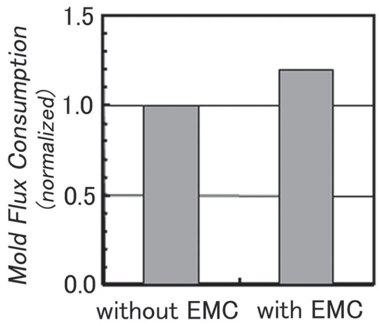


Fig. 5 Mold flux consumption

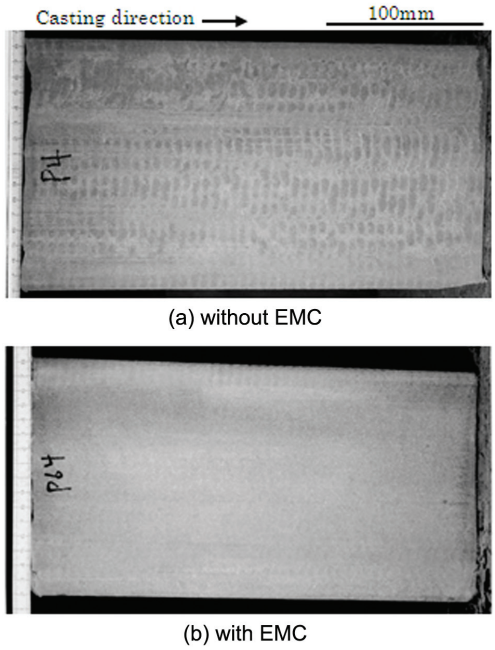


Fig. 6 Surface appearance of cast billet (0.08%C steel)

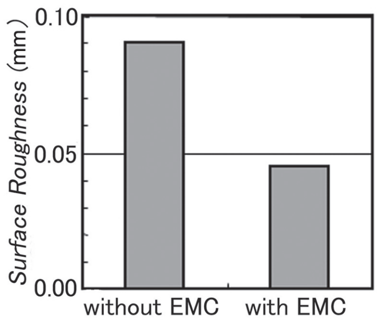


Fig. 7 Surface roughness of cast billet (0.08%C steel)

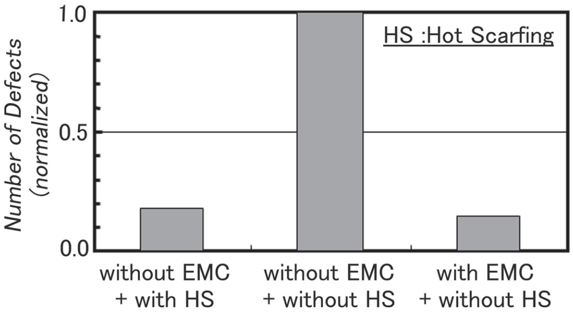


Fig. 8 Number of defects (0.1%C steel)

process with hot scarfing. Thus, it is evident from this data that hot scarfing of billets could possibly be omitted by employing pulsative EMC.

4. Casting Test of Small-Section Slab Using an Experimental Continuous Slab Caster

With the basic technology for pulsative EMC of billet established, development of pulsative EMC technology for slab was then pursued. A casting test of small-section slab was initially conducted using an experimental continuous slab caster within Kimitsu Works of the Nippon Steel Corporation.[7-10] For the purposes of the test, the 8 m-long experimental vertical type continuous caster was provided with a solenoid coil and specially constructed molds designed for use with pulsative EMC technology as shown in **Fig. 9**. The inside dimensions of the molds were 400 mm × 100 mm and 800 mm × 100 mm. Each of the molds was fabricated from four pairs of copper plates and fashioned with a stainless steel back plate that allowed for both mechanical rigidity and for sufficient penetration of the electromagnetic field into the molten steel. The molten steel bath level was controlled using the eddy current bath level sensor synchronized with the pulsative electromagnetic field described previously.

Fig. 10 shows the surface of a low-carbon Al-killed steel slab obtained by the pulsative EMC process. It was confirmed that the oscillation marks in the casting direction had almost disappeared for slab produced by this process. **Fig. 11** shows the under-skin solidified structures of slabs obtained with and without pulsative EMC. It can be seen that the pulsative EMC process markedly reduced the depths of oscillation marks on the slab surface and the depths of hooks under the skin. **Fig. 12** shows the surface roughness of slabs measured by a laser displacement meter. Consideration of Figs. 7 and 12 indicate that, even in the casting of small-section slab that uses a mold having a larger cross-sectional area than that for billets, the surface property of slab can be improved in almost the same de-

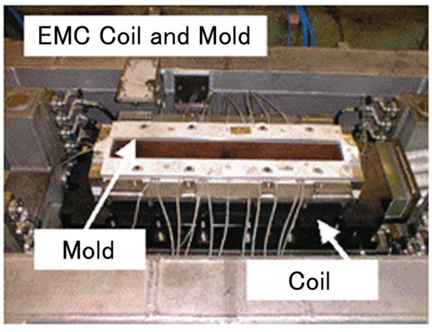


Fig. 9 Mold and coil for pulsative EMC

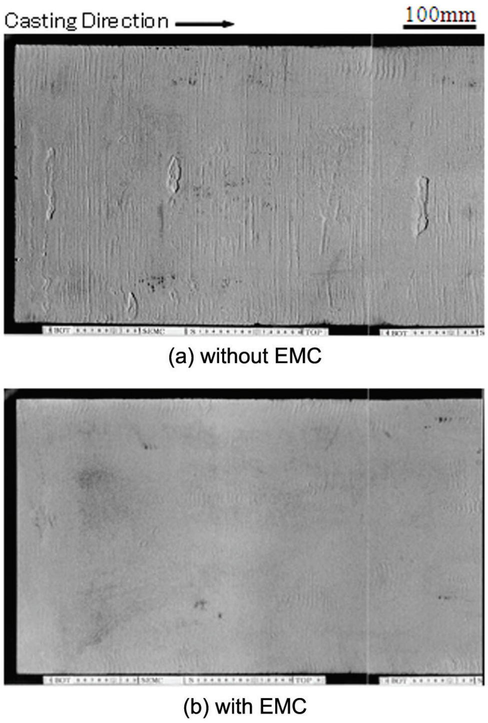


Fig. 10 Surface appearance of cast slab (0.2%C steel)

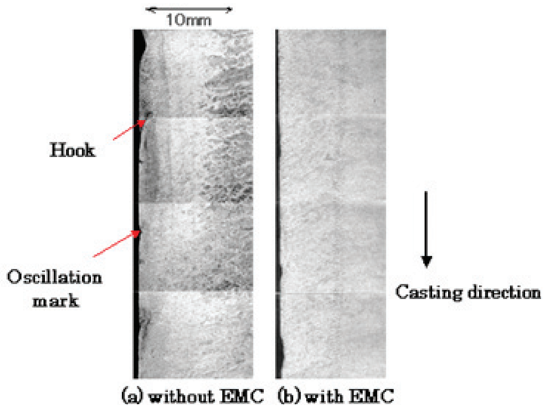


Fig. 11 Solidified structure of cast slab (0.2%C steel)

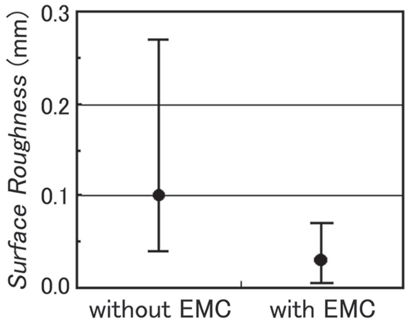


Fig. 12 Surface roughness of cast slab (0.2%C steel)

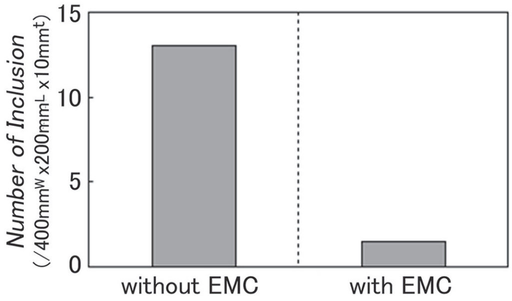


Fig. 13 Number of Inclusion at cast slab surface

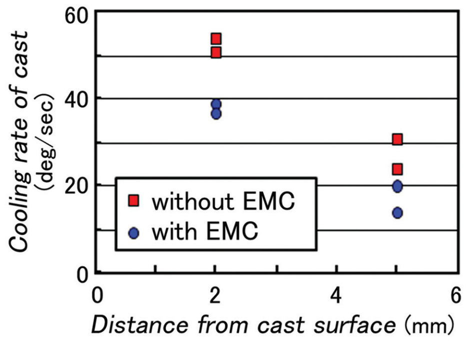


Fig. 14 Cooling rate at cast slab surface

gree as that for billet by intermittently applying an electromagnetic field to the molten steel.

Fig. 13 shows the number of inclusions 100 μm and more in size found in the cast slab by gradually cutting the slab to a depth of 10 mm from the surface. It can be seen that the pulsative EMC process markedly reduced the inclusions in the surface layer of the cast slab. There are two conceivable reasons for this observation. One is that the depth of hooks under the skin of the slab decreased, making it difficult for inclusions to be captured in the slab. The other is that the molten steel flow induced by the electromagnetic field had the effect of cleaning the solidified shell.

Fig. 14 shows the cooling rate of the initially solidified shell calculated from the spacing between dendrite arms under the skin of the slab. It can be seen that the pulsative EMC process reduced the cooling rate by 70% to 80%. The observed decrease is reasonably accounted for by assuming that the electromagnetic field widened the distance between the mold and the solidified shell and thereby caused the thermal resistance of the initially solidified shell to increase, bringing about a slow-cooling condition.

5. Casting Tests Using a Plant Continuous Slab Caster

In the experimental casting tests of small-section slabs described above, it was confirmed that pulsative EMC technology helped improve the surface qualities of cast slab. As an extension of this work, pulsative EMC tests were carried out using the plant continuous slab caster at Yawata Works of the Nippon Steel Corporation.[11-13]

Initially, to examine the proposed modifications to this casting process, an electromagnetic field analysis was conducted, taking into consideration the solenoid coil, molten steel, mold, and peripheral structure. In conjunction with the field analysis, a numerical simulation of the molten steel flow and meniscus in the mold was conducted, taking into consideration the fused flux and molten steel free surface, along with a structural analysis of the mold. In light of the above examination, a new power supply, solenoid coil, and a mold designed specially for pulsative EMC technology measuring 1,200 - 1,600 mm × 250 mm, were fabricated to implement pulsative EMC of full-sized slabs on the continuous caster.

Fig. 15 shows an example of results of the numerical simulation of the molten steel flow and meniscus in the mold described above. These results confirm that a uniform molten steel meniscus across the width of the mold and a uniform molten steel flow along the mold walls across the width of the mold can be obtained under the conditions of pulsative EMC even for a large cross section slab (1,280 mm × 250 mm). **Fig. 16** shows an example of the results of the mold structural analysis during the casting process. It can be seen that the amount of mold deformation for pulsative EMC during the casting operation is no more than that for an ordinary mold in a conventional casting process. **Fig. 17** shows an example of results of the calculation and measurement of the vertical magnetic flux density in the mold during pulsative EMC, where Cal refers to the calculated value, Exp to the measured value F, L to the mold wide face, and C to the mold center thickness. It can be confirmed from the figure that, for the pulsative EMC system designed for a slab

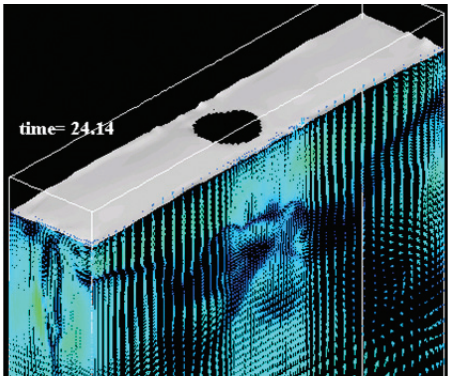


Fig. 15 Flow pattern of pulsative EMC

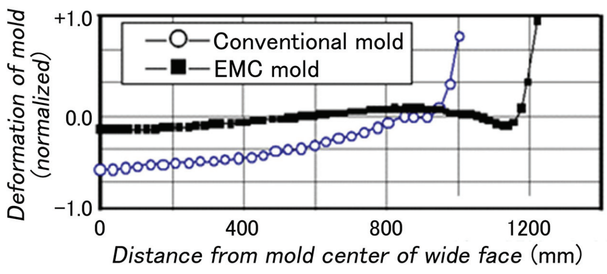


Fig. 16 Deformation of mold for pulsative EMC

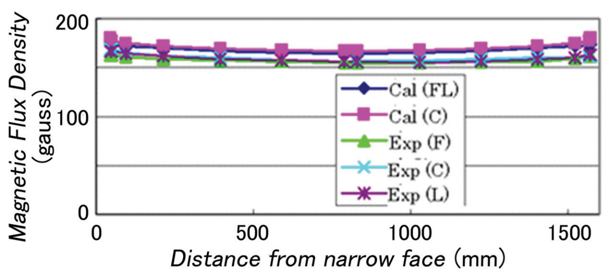


Fig. 17 Electromagnetic flux density in the mold for pulsative EMC

having a large cross section (1,600 mm × 250 mm), a uniform magnetic field distribution can be obtained along the wide face of the mold.

Next, to evaluate the stability of the meniscus of a molten Sn/Pb-based alloy of low melting point, the plant continuous slab caster was equipped with the power supply, solenoid coil, and the mold, developed specially for pulsative EMC, a stainless steel vessel was placed into the mold, the molten alloy poured into the vessel, and an electromagnetic field applied intermittently to the molten alloy. **Fig. 18** shows a photo of the meniscus of the alloy during intermittent application of an electromagnetic field. As shown in the figure, a stable, uniform meniscus could be observed across the width of the mold. At first, there was some concern that the induced electromagnetic field in the molten material would result in induction heating and an increase in the temperature of the mold and peripheral structure. However, no increase in temperature was observed.

Finally, using the above described power supply, solenoid coil, and mold for pulsative EMC, we cast low-carbon Al-killed steel slabs measuring 1,200 mm × 250 mm and 1,600 mm × 250 mm. During the casting, the bath level of molten steel was measured with a pulse-synchronized eddy current sensor to automatically control the molten steel pouring rate, and it was observed that the bath level and pouring rate of molten steel could be controlled stably. All in all, the pulsative EMC operation could be performed for many hours on a stable basis like that of the ordinary casting operation.

Concerning the surface qualities of the slabs obtained by the casting test, the depths of oscillation marks on the slab surface were evaluated across the entire slab width. **Fig. 19** shows the evaluation results together with those of small-section slabs obtained by the preceding tests, where plant test refers to samples derived from the plant continuous caster and bench-scale test refers to samples derived from the experimental continuous caster. These results confirm that pulsative EMC significantly improves the surface qualities of large-section slabs as effectively as it does for billets and small-section slabs.

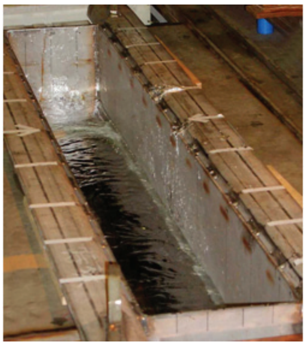


Fig. 18 Experiment with low-melting-point alloy

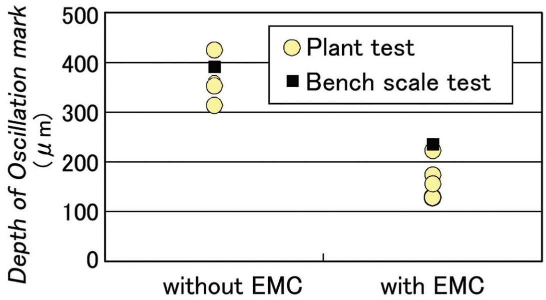


Fig. 19 Depth of oscillation mark

6. Conclusion

Through tests of the pulsative EMC processing of billets, using a plant continuous caster, and of small-section slabs, using an experimental continuous caster, we confirmed that EMC helped in improving the surface qualities of billets and small-section slabs and established the basic operational parameters for the pulsative EMC process.

We then developed a new power supply, solenoid coil, and mold for casting large-section slab using the pulsative EMC technology and carried out tests for the casting of large-section slab using a plant continuous caster. As a result, we confirmed that pulsative EMC could be applied even to large-section slabs, and that it improved the surface qualities of large-section slab as well as was done for the smaller products.

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Masahiro TANI
Senior Researcher
Yawata R&D Lab.
1-1 Tobihata-cho, Tobata-ku, Kitakyushu,
Fukuoka 804-8501

Masafumi ZEZE
Chief Researcher, Dr.Eng.
Yawata R&D Lab.

Takehiko TOH
Chief Researcher, Dr.
Mathematical Science & Technology Research Lab.
Advanced Technology Research Laboratories

Keiji TSUNENARI
Manager
Plant Engineering Div.
Plant Engineering and Facility Management Center

Kenji UMETSU
Manager
Systems & Control Engineering Div.
Plant Engineering and Facility Management Center

Kazunori HAYASHI
Senior Researcher, Dr.Eng.
Mechanical Engineering Div.
Plant Engineering and Facility Management Center

Kazuhisa TANAKA
Maneger
Steelmaking Div.
Yawata Works

Shinichi FUKUNAGA
Manager
Steelmaking Div.
Yawata Works