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Nippon Steel In-Mold Electro-Magnetic Stirrer "M-EMS" for Slab Caster

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Abstract

Japanese industries have been loudly demanding steel manufacturers to provide a stable supply of high quality steel sheet/plates. In order to satisfy customer need, slab surfaces have to be scarfed in large quantities. As the technique to solve such problem, Nippon Steel developed In-Mold Electro-Magnetic Stirrer (or "M-EMS") for slab casters which can improve the surface quality of slabs. In this paper, the features and effects of this system are outlined.

1. Introduction

Automotive, home appliance, construction, shipbuilding and other industries in Japan have required stable supplies of high quality steel sheet products that have excellent workability. To meet their requirements, the Japanese steel industry has expended efforts to develop various electromagnetic apparatuses for continuous slab casters and to use them commercially. Conventional measures for keeping cleanliness of slab surface layers have mainly been: (1) to prevent the contamination of molten steel; and (2) to control the molten steel flow in a mold making use of the steel flow from a submerged entry nozzle. Longitudinal cracks, which constitute one of the major problems of continuous casting, have been coped with through measures from outside the solidification shell of a cast slab such as the control of the characteristics of flux powder.

With respect to the above measures, Nippon Steel Corporation considered the following points. Since the final object was to improve the cleanliness not of molten steel but of the surface layers of a slab, it would be better to take measures directly at the stage in which non-metallic inclusions and other impurities are caught in the interface of solidification. With regard to the control of the molten steel flow in a mold, using a system independent from the steel flow from a submerged entry nozzle would be better than relying on the intrinsically unstable flow from the nozzle. As for the longitudinal cracks, since they are caused by the strain in an initial solidification shell resulting from its uneven thickness, they would be more effectively prevented from occurring by homogenizing the temperature distribution of the molten steel in a mold and thus eliminating the local delay in solidification. In line with the above, Nippon Steel began the development of an in-mold electromagnetic stirrer (M-EMS), wherein the liquid portion of a cast slab in a mold was made to flow by electromagnetic force during a solidification process; in due course, Nippon Steel installed the first unit of M-EMS for slab caster at Hirohata Works in 1980.

Through various trials and tests since then, it was confirmed that the stirring of molten steel in a mold using M-EMS significantly improved the surface quality of cast slabs and that this brought about a remarkable enhancement of product yield. The stirring also made the thickness of an initial solidification shell homogeneous and the breakout caused by longitudinal cracks was suppressed to stabilize casting operation. As a consequence, most of the continuous slab casters of Nippon Steel are now equipped with M-EMS[1,2].

This paper reports the yield improvement effects of the M-EMS for slab caster developed by Nippon Steel and the characteristics of the equipment.

2. Principle and Main Specification of M-EMS for Slab caster

2.1 Principle of M-EMS for Slab caster

Fig. 1 shows the principle of the molten steel stirring of M-EMS for slab caster. Linear inductors provided behind broad faces of a mold generate parallel shifting magnetic fields covering the entire mold width and the magnetic fields drive the molten steel in the mold near a meniscus to circulate horizontally[3]. This principle is the same as that of a linear motor taking advantage of the fact that, according to the Fleming's left-hand rule, when an electric current in a coil

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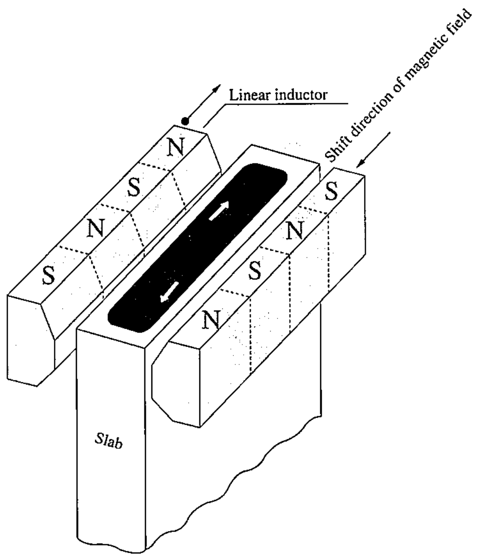

Fig. 1 Principle of molten steel stirring of M-EMS for slab caster

crosses a magnetic field of a permanent magnet, a force is generated in the coil.

2.2 Washing Effect of Stirring Flow of Molten Steel in Mold

The process in which a cast slab is made clean by the washing effect of the stirring flow of the molten steel in a mold is as follows:

(1) The stirring flow of the molten steel driven by the shifting magnetic fields washes off non-metallic inclusions caught between columnar crystals, as seen in **Fig. 2**, to prevent them from being entrapped in the initial solidification shell.

(2) The non-metallic inclusions washed off the solidification shell are carried to the center portion of the slab, hit each other, form large agglomerate and move up towards the surface.

(3) The agglomerate of the non-metallic inclusions having reached the meniscus is caught by flux powder and is removed from the cast slab.

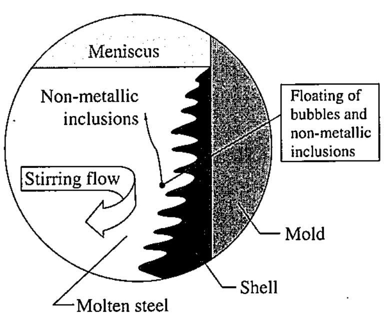

Fig. 2 Molten steel flow in mold

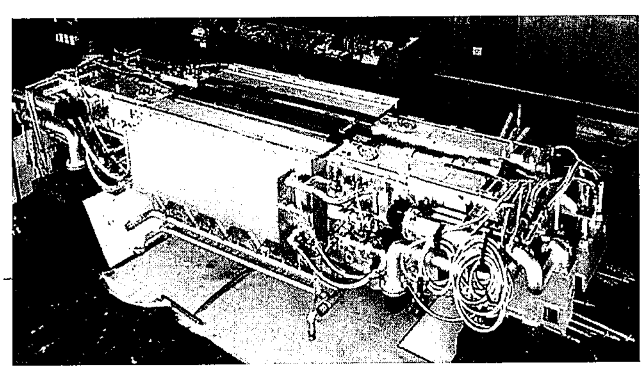

Fig. 3 Outside view of M-EMS installed in mold

Table 1 Main specification of M-EMS

General technical data

Casting radius		Curved/ vertical/ vertical-bend
Slab size	Thickness	150-400mm
	Width	600-1,600/ 900-2,360mm
Mold length		800-1,090mm
Casting speed		0.5-2.5m/min
Coil type		Linear induction motor type
Coil length		Pole pitch 420-972m/ number of pole 2/4
Capacity		300-600kVA
Thrust		Approx. $7\text{-}9\times10^3 kN/m^2$ (as measured along 15mm inside from the mold surface)
Coil weight		Approx. 2,500kgx2/st (slab size 250mmx1,680mm)
Cooling system for coil		Internal cooling by water
Sealing system for connector box		Purging by N_2 gas or dry air

The flow of the molten steel also homogenizes the temperature distribution of the molten steel in the mold, reduces the thickness fluctuation of the initial solidification shell, thus reduces the strain in the shell because of local delay in solidification, and thus prevents the longitudinal cracks of the cast slab from occurring.

2.3 Main Specification of M-EMS for Slabs

Fig. 3 shows typical structure of M-EMS for slabs and **Table 1** shows its main specification.

3. Effects of M-EMS on Quality of Cast Slab

Fig. 4 shows the relationships between the phenomena that the stirring flow of M-EMS causes at the meniscus, the effects on the quality of slabs and the cost advantages resulting from the phenomena. The effects of M-EMS on the slab quality are explained below individually.

3.1 Decrease of Pinholes

Fig. 5 shows the pinhole reduction effect of M-EMS. The index of pinhole density is significantly lowered by the application of M-EMS, and the effect is remarkable especially in a subsurface layer of

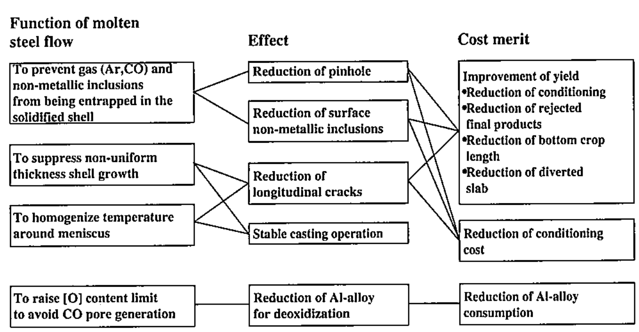

Fig. 4 Interrelations between quality effects and cost advantages of M-EMS

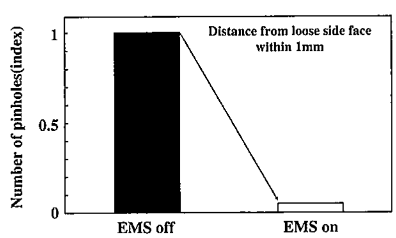

Fig. 5 Pinhole reduction effect of M-EMS

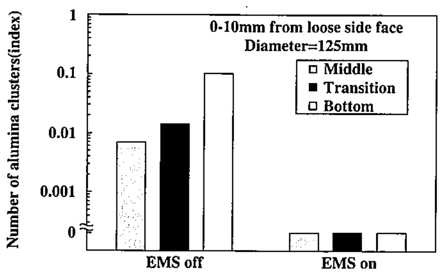

Fig. 6 Surface inclusion reduction effect of M-EMS

a cast slab.

3.2 Decrease of Non-metallic Inclusions

Fig. 6 shows the effect of M-EMS to reduce alumina cluster inclusions in the subsurface layer (down to 10 mm from the surface). When M-EMS is applied, large non-metallic inclusions 100 μm or more in size are prevented from being entrapped in the subsurface layer of a cast slab[4].

At the bottom and top of a heat and the joint between heats, the molten steel level in a tundish usually becomes low, the effect of the floatation of non-metallic inclusions in the tundish decreases and, as a result, the amount of the non-metallic inclusions brought from the tundish into the mold increases. What is more, since the casting speed is lower during the casting of these portions than in the steady state operation, the shell washing effect of the steel flow from the nozzle decreases. For these reasons, the slab surface defects caused by non-metallic inclusions tend to occur easily at these portions.

When M-EMS is applied, however, the number of non-metallic inclusions at the bottom of a heat and the joint between heats is made as low as that in the middle of heats as seen in Fig. 6. This fact indicates that the cleanliness of a cast slab depends more on the flow of the molten steel in the mold than the cleanliness of the molten steel coming into the mold. Because M-EMS forcibly drives the molten steel at the meniscus into a stirring flow at a constant speed independently from the unstable flow from the immersion nozzle, it is possible to continuously obtain slabs having small fluctuation of cleanliness. As a consequence, it is possible to reduce the length of the portions to be cropped off (for downgrading or scrapping) from the bottom slabs and the slabs at the joints between heats.

3.3 Decrease of Longitudinal Cracks at Cast Slab Surfaces

The molten steel tends to stagnate near the meniscus, which causes the shell thickness to become uneven because of uneven temperatures of the molten steel in the width direction, and this leads to the occurrence of longitudinal cracks. The longitudinal cracks caused by the uneven cooling are likely to occur especially with middle carbon steels (C = 0.1 to 0.15%).

Since the local delay in solidification is reduced and the shell thickness becomes homogeneous by the application of M-EMS, it is possible to reduce the occurrence of longitudinal cracks, as shown in **Fig. 7**[1].

3.4 Stable Operation

Fig. 8 shows the occurrence frequency of the breakout prediction alarm for detecting the mold surface anomaly possibly leading to a breakout[5]. With the application of M-EMS, the occurrence frequency of the breakout prediction alarm is drastically decreased and thus casting operation is rendered stable. This results from the stable initial solidification condition because of the molten steel flow by M-EMS at the interface of the solidification shell, decreased influence of the drift of the molten steel caused by the flow from the nozzle and restricted occurrence of dickel.

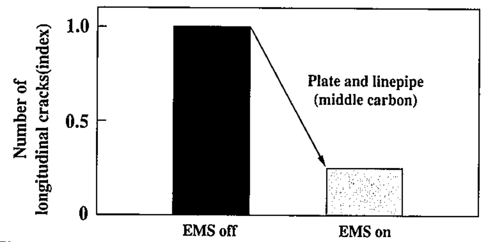

Fig. 7 Longitudinal crack reduction effect of M-EMS

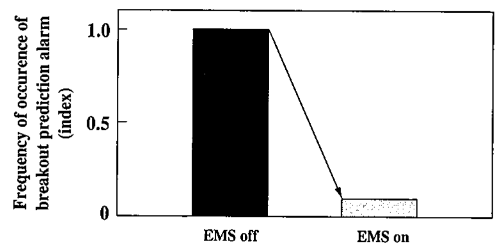

Fig. 8 Operation stabilization effect of M-EMS

3.5 Effects of M-EMS on Final Products

3.5.1 Ultra-low Carbon Steels for Car Body Sheets

Among ultra-low carbon steel sheets, high strength is required of the steel sheets for exposed car body panels in order to make the steel sheets thinner and thus to make the body lighter. Excellent workability is required, further, for materializing streamlined bodylines. M-EMS makes it possible to produce cast slabs with excellent surface cleanliness thereby meeting these requirements at a high yield.

As shown in **Fig. 9**, M-EMS is capable of decreasing the pinholes and non-metallic inclusions in the surface layer and reducing by 40% the number of the slabs to be subjected to hot scarfing and other conditioning at the steel-making stage. It also decreases the rejection at the final product stage caused by sliver by 50% and increases product yield thanks to the reduced crop length at the bottom (see **Fig. 10**). Furthermore, it decreases the range of steel sheets inapplicable to the exposed car body panels resulting from accidental abnormal casting operation and subsequent downgrading of the products (see **Fig. 11**)[1].

3.5.2 High-grade Steels for Heavy Plates and Pipes

Problems with the high-grade steels for heavy plates and pipes are that the change in casting speed during non-steady state operation causes the fluctuation of slab surface temperature, leading to surface defects such as corner cracks, and that the non-metallic inclusions increase during the non-steady state operation.

With the application of M-EMS, it becomes possible to control the occurrence of longitudinal cracks stably to a low level without relying on conventional countermeasures such as delicate control of

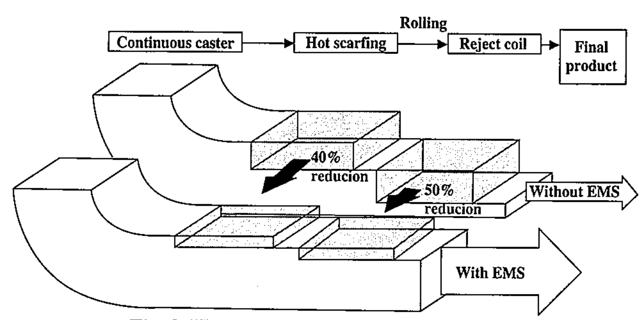

Fig. 9 Yield improvement effect of M-EMS

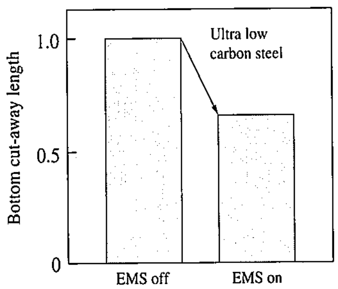

Fig. 10 Effect of M-EMS to decrease crop length of bottom slabs

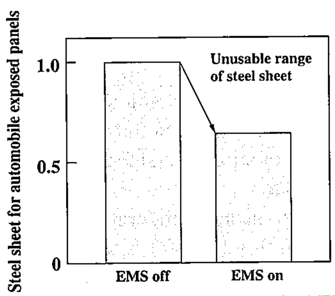

Fig. 11 Rejection reduction effect of M-EMS

Table 2 Decrease in length of crop cut of plate products caused by cracks

Portion	Crop cut length
Bottom end	Normal grades: 1.0 m Severely controlled grades: 1.5 m → Decreased to 0.6 m
Steel plate-inserted portion	Double pouring: ± 2 m or so → Decreased to ± 1 m or so (Portion of mixed chemical composition)
Top end	1.0 m → Decreased to 0.6 m

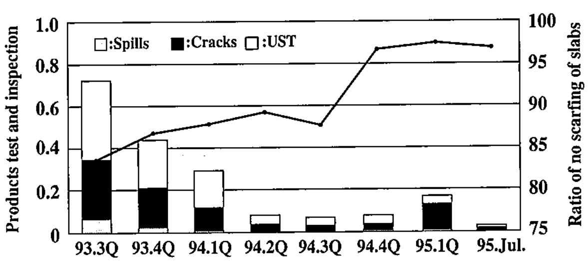

Fig. 12 Historical change of product test and inspection owing to problems in steel-making processes

mold cooling water temperature and the improvement of the characteristics of front powder[6]. The control of the initial solidification by M-EMS also significantly decreases the occurrence of longitudinal cracks at the cast slab surfaces and therefore, as shown in **Table 2**, the crop cut length of the slabs cast during the non-steady state operation can be greatly decreased. At the same time, M-EMS remarkably raises the ratio of the slabs not requiring machine scarfing, as seen in **Fig. 12**; in fact, the ratio has reached a level of 99% or so.

4. Characteristics of M-EMS Equipment

4.1 Construction of EMS Coils

In order that the coils for electromagnetic stirring (EMS) may fit into the limited space of a mold and exert strong stirring force on the molten steel, the EMS coil windings are designed to have the following features.

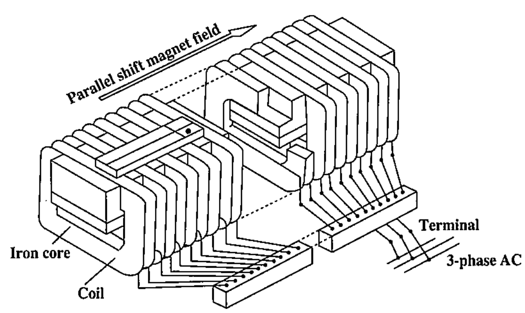

Fig. 13 Winding method of M-EMS coils

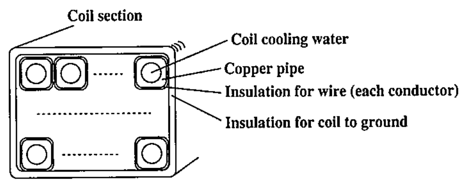

Fig. 14 Sectional shape of coil

4.1.1 Coil Winding Method of M-EMS

In the case of winding method usually employed for an induction motor, linear motor and the like, coil ends tend to be long and the height of the EMS coils becomes large as a consequence, which makes it difficult to accommodate the coils within the space of the mold. For this reason, the ring winding method, wherein the coil end space is small as seen in **Fig. 13**, was adopted for the coils of M-EMS. The method allows the coils to be installed at a position (height) near the meniscus for efficient stirring of the molten steel there.

4.1.2 Construction and Cooling Method of Coils

High current conduction is required of the coils in order to obtain strong stirring force. To meet the requirement, the direct water cooling method was adopted for the coils of M-EMS, wherein a coil strand (conductor) is made of a copper tube and the Joule's heat of the coil is carried away by cooling water circulating in the copper tube to obtain a high cooling capacity. With this method, the copper tube acting as an electric conductor directly contacts the cooling water and, in order to securely isolate it from the ground, non-conductive nylon tubes are used for the piping of the cooling water in the portions required for the purpose. Further, to make the coils compact, the copper tubes having a square section as seen in **Fig. 14** are used. This allows the arrangement of the coils in the slots of the core in high density, maximizing the utilization of space and realizing the high current conduction.

4.2 Optimum Equipment Configuration for Power Supply and Control

Fig. 15 shows the system configuration of the power supply and control equipment of M-EMS. The magnetic flux generated by an EMS coil passes through a copper plate of the mold and operates on

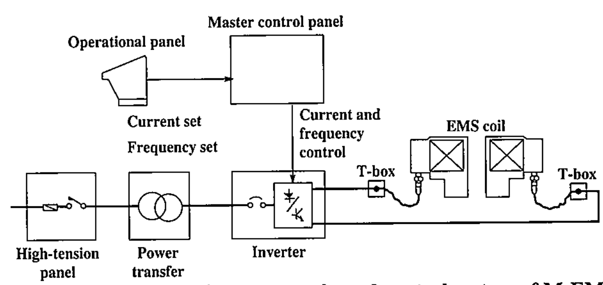

Fig. 15 Configuration of power supply and control system of M-EMS

the molten steel in the mold. However, in this process, it is attenuated by the eddy current generated in the copper plate. The higher the frequency, the larger the extent of the attenuation becomes and, therefore, the thrust force of EMS becomes the largest in a low frequency range of several Hz. In view of the above fact, an inverter is used in the power supply system of M-EMS so as to enable low frequency range operation. The frequency control and current control of the inverter work independently from each other based on the frequency and current values set through an operation panel. The operation of EMS is optimized by setting the frequency for obtaining the largest thrust force and the current for realizing required stirring intensity.

4.3 Engineering of Copper Plate for M-EMS

The design of the mold copper plate is very important in the design of the whole M-EMS mold. The copper plate has to be designed so as to (1) minimize the attenuation of the electromagnetic force by the copper plate, (2) maintain the fundamental function of the mold to cool molten steel, and (3) secure the same service life as that of a conventional mold.

A material having high thermal conductivity is chosen for the copper plate of a conventional mold so as to prevent its surface temperature from becoming too high in order to prevent a cast slab from sticking to it, extend its service life and make it reusable through remachining as many times as possible. The density of the magnetic flux of the EMS coils which generates the thrust force to stir the molten steel, on the other hand, is attenuated by the eddy current formed in the copper plate between the coil and the slab, as explained before. With the conventional copper plate material having high thermal conductivity, the attenuation of the magnetic flux density becomes large, since the electric conductivity of such a material is also high. To decrease the attenuation of the magnetic flux density by the copper plate, therefore, it is necessary to select a material having lower electric conductivity and thus minimize the eddy current generated in the copper plate.

Fig. 16 shows the relationships between the electric conductivity and temperature of the copper plate and the thrust force for stirring molten steel. It is clear from the figure that, in order to obtain sufficiently strong force to stir molten steel with coils fitting into the limited space of a mold, a material having electric conductivity of IACS 60% or less must be used for the copper plate. If a material having low electric conductivity is selected for the copper plate for decreasing the attenuation of the magnetic flux density and if its thickness is the same as that of a conventional mold, however, its surface temperature becomes too high, and this leads to problems such as frequent occurrence of sticking-induced breakout and short service life of the copper plate.

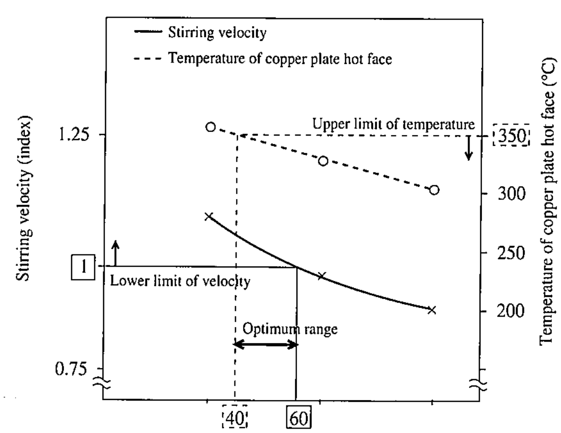

Fig. 16 Relationships between electric conductivity and temperature of copper plate and stirring velocity of molten steel

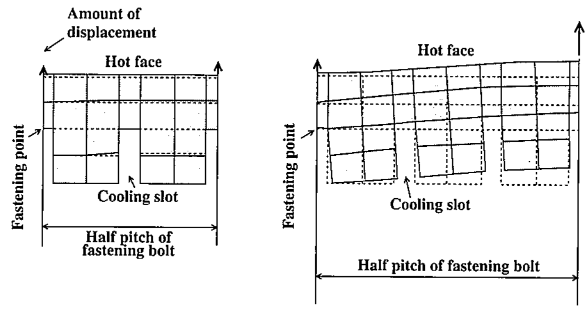

Fig. 17 Two-dimensional coupled analysis of temperature and deformation of copper plate

For lowering the surface temperature of the copper plate, it is necessary to make it thin but, if it is too thin, its rigidity becomes insufficient and the deformation during casting operation increases, leading to problems such as the deterioration of slab quality and the occurrence of breakout. From Fig. 16, it is understood that, in order to keep the surface temperature of the copper plate from exceeding 350°C, which is the upper limit not to cause the sticking with a cast slab and the shortening of its service life, a material having electric conductivity of IACS 40% or more must be used for the copper plate. Nippon Steel designs the copper plate based on the two-dimensional coupled analysis of the temperature and deformation of the copper plate using FEM. The optimum pitch of the copper plate fastening bolts for suppressing the deformation of the copper plate is obtained through the analysis of the copper plate deformation under different conditions of its thickness and temperature. **Fig. 17** shows the result of the deformation analysis. It is clear from the figure that, when the bolt pitch is large, the deformation of the copper plate becomes too large and that the deformation is controlled within an acceptable range by making the bolt pitch shorter.

The above design technique makes it possible to realize effective stirring of the molten steel, secure a service life of the copper plate comparable to that of a conventional mold and prevent the occurrence of troubles such as breakout from increasing.

4.4 Construction of M-EMS Mold

In M-EMS, in order to obtain high thrust force and effectively stir the molten steel at the meniscus, the coils for generating the parallel shifting magnetic fields are arranged in the cooling boxes of the broad faces of a mold and close to a cast slab. For this end, a coil chamber is formed at the upper part of cooling box a broad face, and the inlet and outlet chamber of mold cooling water is provided below the coil chamber. This construction allows the coils to be contained within the same outer dimension of a conventional mold and, therefore, it is not necessary to consider space limitations in the case of revamping from conventional mold to M-EMS. No interference occurs either with existing variable width and electromagnetic brake equipment, if any. **Fig. 18** shows the construction of an M-EMS mold.

4.4.1 Quick Coil change from Mold

The coils are fixed with bolts to a flange provided at the backside of the cooling box in order to allow easy detachment for the re-machining of the copper plate and the maintenance work of the mold. Quick coil change equipment is provided for easy detachment of the

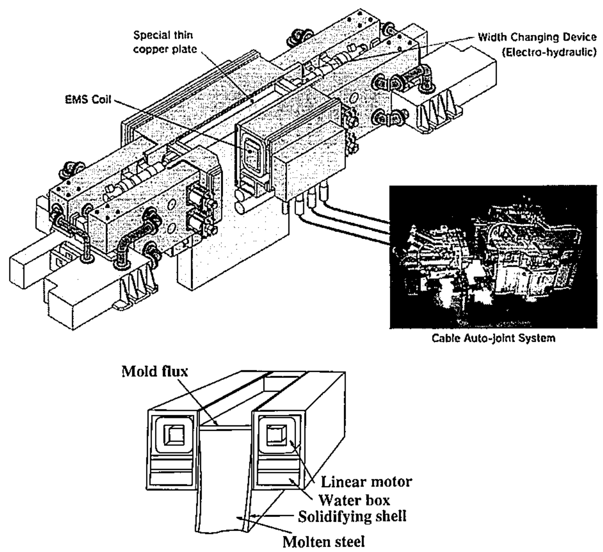

Fig. 18 Construction of M-EMS mold

coils from the mold so that the coils may be changed without disassembling the mold. This allows quick changes of the coils to a spare mold on the occasion of the mold change because of a breakout or an overflow, thus, the number of spare coils can be made smaller than the number of molds.

4.4.2 Automatic Cable Coupling equipment (Cable Auto-joint System)

The electric cables for the M-EMS coils have to be connected and disconnected at a mold change. Automatic cable coupling equipment make possible quick cable connection and disconnection at a mold change. This reduces mold changing time to nearly the same as required for the change of conventional molds.

5. Summary

Nippon Steel's M-EMS for slabs has the following advantages and features:

5.1 Quality Improvement Effects

The pinholes, surface non-metallic inclusions and longitudinal surface cracks of cast slabs are significantly decreased by the stirring flow of molten steel by M-EMS. The stirring flow also homogenizes the temperature distribution of the molten steel and the shell thickness in the mold, preventing breakout and other casting troubles.

5.2 Yield Improvement Effects

The application of M-EMS makes it possible to decrease the occurrence of the slabs for exposed car body panels requiring hot scarfing and other conditioning at the steel-making stage by 40%, as well as the rejection at the final product stage caused by sliver by 50%. It can also decrease the machine scarfing of the slabs for plate products to nearly zero.

5.3 Equipment Features

- Compact and highly efficient coil construction requiring small space for its installation.
- Power supply and control equipment to be able to control the stirring flow easily.
- Mold cooling box structure to allow the arrangement of coils close to the meniscus of the molten steel.
- Copper plate design to secure high stirring thrust force.
- Quick coil change from the mold.
- Automatic cable coupling for coil wiring.

References

1) Fukuda, J., Ohtani, Y., Kiyose, A., Kawase, T., Tsutsumi, K.: 3rd European Conference on Continuous Casting, 1998, p.437
2) Kittaka, S., Shukuri, K., Yamada, Y., Sawada, K., Soeda, Y.: Nippon Steel Technical Report. (55), 27 (1992)
3) Okazawa, K., Tou, T., Takeuchi, E., Umezu, K., Fujisaki, K.: CAMP-ISIJ. 7, 12 (1994)
4) Kiyose, K., Miyazawa, K., Goto, H., Fukuda, J., Ohtani Y., Nakashima, J.: CAMP-ISIJ. 7, 1195 (1994)
5) Fukuda, J., Kawase, T., Ohtani, Y., Iwata, S., Tsutsumi, K., Okumura, H., Watanabe, K.: CAMP-ISIJ. 7, 1193 (1994)
6) Ohtani, Y., Fukuda, J., Iwata, S., Ishiwata, N., Funato, K.: CAMP-ISIJ. 7, 1194 (1994)