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Nippon Steel Strand Electro-Magnetic Stirrer "S-EMS" for Slab Caster

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Abstract

Japanese industries have been severely requesting steel manufacturers to stably provide high quality steel sheet/plates. As the technique to cope with these demands, Nippon Steel developed Strand Electro-Magnetic Stirrer "S-EMS" for slab caster which can improve internal quality of slab with Yaskawa Electric Corporation. In this paper, the features and effects of this system are outlined.

1. Introduction

In view of ever increasing requirements for higher product performance and quality, Japanese steel-consuming sectors such as shipbuilding, construction, home appliance and electric equipment industries have requested steel industry to supply heavy plates with good welding workability, stainless steel sheets with excellent surface quality and electrical sheets with excellent surface quality and magnetic properties. These industries are presently expanding their production sites to outside of Japan. As a result, the stringent demands for high quality steel products characteristic of Japanese steel consumers have spread over the world, especially in China, which forms a vast, expanding market for their products. To sustain the overseas manufacturing of the Japanese steel-consuming industries, steel makers in China, South America and other parts of the world are endeavoring to establish mass production systems for steel products of the same quality level to which the Japanese steel users have become accustomed.

In consideration of the required quality of the steel products and the needs of steel makers, Nippon Steel Corporation, in cooperation with Yaskawa Electric Corporation, developed the Strand Electro-Magnetic Stirrer (S-EMS) for stirring molten steel inside a cast slab at the secondary cooling zone of a continuous caster with electromagnetic force. The first S-EMS for slabs was introduced in 1973 at Kimitsu Works and as its effects to improve slab internal quality and enhance productivity have been verified, its use has expanded to the other works of the company and widely varied steel products.

This paper describes the effects of Nippon Steel's S-EMS for slabs and the characteristics of its equipment.

2. Principle and main specification of S-EMS for slabs

2.1 Principle of S-EMS for slabs

Fig. 1 shows the principle of the molten steel stirring by S-EMS. A pair of linear inductors provided at the upper secondary cooling zone of a slab caster on both sides of a slab along broad faces generate parallel shifting magnetic fields, which drive molten steel in the cast slab to circulate horizontally. This is based on an application of the principle of a linear motor that, when a magnetic flux shifts in a conductor, a force is generated in the conductor toward the flux shifting direction.

2.2 Main specification of S-EMS for slabs

Fig. 2 shows a typical appearance of a S-EMS coil for slabs and **Table 1** shows the main specification of S-EMS.

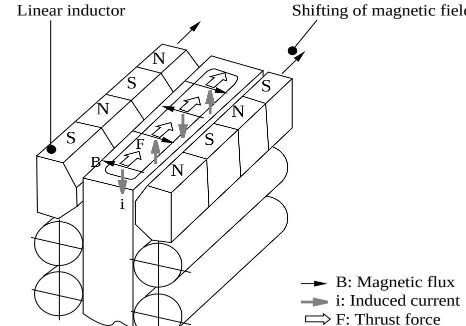

Fig. 1 S-EMS working principle for slabs

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Fig. 2 Appearance of S-EMS coil for slabs

Table 1 Main specification of S-EMS for slabs

General technical data

Casting radius	Curved/ vertical/ vertical-bend
Slab size	Typical thickness: Approx. 140-300mm (no restriction from width)
Coil type	Linear induction motor type
Typical capacity	Approx. 800-1,300kVA/ 400-500kW for typical slab size (250mm×2,000mm)
Coil weight	Approx. 4,000kg/ set for typical slab size (250mm×2,000mm)
Cooling system for coil	Internally cooling by water
Sealing system for connector box	Purging by N_2 gas or dry air

3. Enhancement of slab quality and productivity with S-EMS

The effects of S-EMS to improve slab internal quality, the principle behind the effects, the quality improvement effects by kind of steel to which S-EMS is applied and the productivity enhancement effect are explained hereafter.

3.1 Slab internal quality improvement

The principle of improving the slab internal quality by molten steel flow inside a slab is as follows.

The molten steel flow induced by S-EMS separates dendrites forming during solidification and has them suspended in molten steel, thus creating solidification nuclei. The molten steel flow also raises the temperature of molten steel at solidification interfaces and accelerates re-melting of the dendrites and, thus, makes it possible to cast slabs at lower temperatures compared with in conventional practice. By this mechanism, S-EMS contributes to improving the equi-axed crystal zone ratio and center porosity[1]. The stirring flow of molten steel disperses condensed molten steel between dendrites and homogenizes the density of molten steel chemical contents, to decrease centerline segregation. Further, it inhibits internal cracking of slabs by promoting the formation of equi-axed crystals, homogenizing molten steel temperature inside a solidification shell and the solidification shell thickness and thus, relaxing strain inside the solidification shell.

3.2 Effects of S-EMS on final products

The effects of S-EMS are explained below regarding electrical sheets, heavy plates and stainless steels, the kinds of steel in which the application of S-EMS is effective.

3.2.1 Electrical steel sheet

A type of surface defect called ridging occurs to final electrical sheet products when the solidification structure inside a slab is not homogeneous. The ridging means crinkles running in the direction of rolling, and it not only deteriorates product appearance but also lowers the space factor when the sheets are piled into lamination layers, causing poor performance of a motor or a transformer. The molten steel flow by S-EMS promotes the formation of equi-axed crystals and secures a fine and homogeneous solidification structure.

Fig. 3 shows a method of evaluating the equi-axed crystal zone ratio. The equi-axed crystal zone ratio is defined as the ratio of the thickness of equi-axed crystal area to the whole slab thickness. **Fig. 4** shows the relationship between the superheat temperature of molten steel and the equi-axed crystal zone ratio, with and without S-EMS. With a superheat temperature of 30 to 40°C, a sufficiently high equi-axed crystal zone ratio is realized through the application of S-EMS installed near the mold. Thus, S-EMS makes it possible to stably produce high performance electrical sheets excellent in surface quality[2].

3.2.2 High grade steels for heavy plates

Stringent control of centerline segregation is required of high grade steels for heavy plates in order to secure a high strength of welded joints in the applications such as ships and line pipes. **Fig. 5** shows the relationship between the equi-axed crystal zone ratio and an index of centerline segregation with and without S-EMS, and **Fig. 6** shows the relationship between an index of sulfur bands, which is an indicator for evaluating centerline segregation of plate products, and thermal stress cracking of heat affected zones (HAZ) of welded joints. It is clear from the figures that the application of S-EMS significantly improves the centerline segregation index, and that the

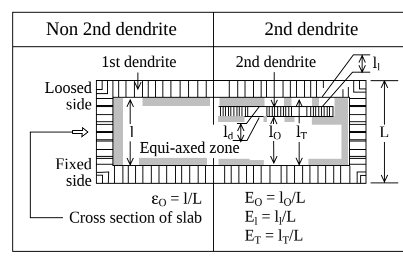


Fig. 3 Evaluation method of equi-axed crystal zone ratio[2]

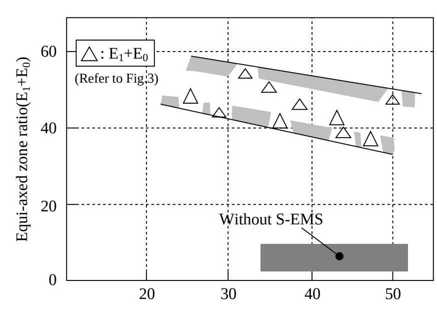


Fig. 4 Relationship between molten steel superheat and equi-axed crystal zone ratio, with and without S-EMS[2]

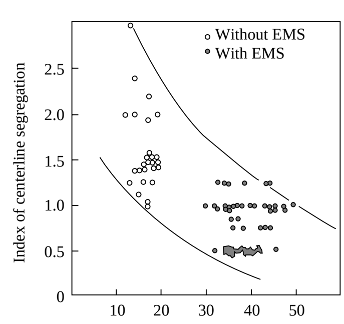


Fig. 5 Relationship between equi-axed crystal zone ratio and centerline segregation index, with and without S-EMS[3]

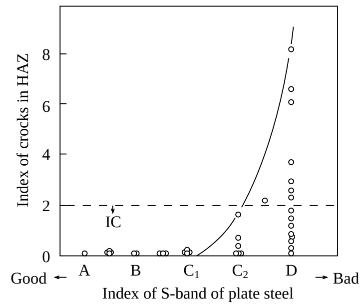


Fig. 6 Relationship between sulfur band index of plate products and thermal stress cracking of HAZ[3)]

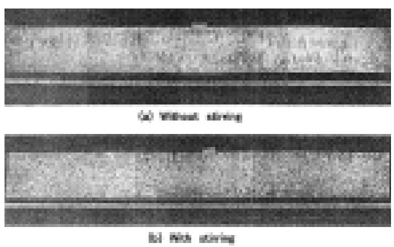


Fig. 7 Solidification structures of SUS 430 cast slabs, with and without S-EMS[4)]

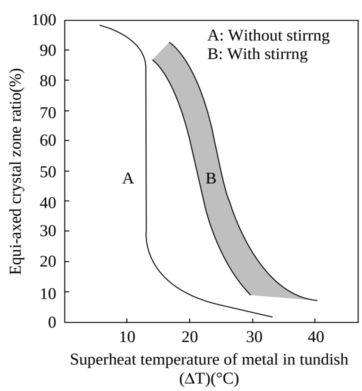


Fig. 8 Relationship between superheat temperature and equi-axed crystal zone ratio, with and without S-EMS[4)]

decrease in the centerline segregation is effective for enhancing welding quality[3)]. The improvement in the centerline segregation and sulfur bands makes it possible to shorten the soaking time before the subsequent rolling process and thus, enhance productivity.

3.2.3 Stainless steel sheets

In SUS 430 (a high-Cr steel), there is a strong correlation between the equi-axed crystal zone ratio and the occurrence of the ridging; it is known that securing an equi-axed zone ratio of 50% or more is effective for inhibiting the occurrence of the ridging. This is achieved with the application of S-EMS[1)]. **Fig. 7** shows solidification structures of SUS 430 cast slabs with and without S-EMS[4)]. **Fig. 8** shows the relationship between the superheat temperature and the equi-axed crystal zone ratio, with and without S-EMS. It is seen in the figure that S-EMS substantially relaxes the restriction on casting temperature[4)].

3.3 Productivity improvement

Due to the quality improvement effects explained above, the allowable range of casting temperature is expanded and as a result, the freedom of operation is remarkably increased. By the application of S-EMS, the equi-axed crystal zone ratio and the centerline segregation are improved and, as a result of these quality enhancement, higher casting speeds and lower reduction ratios at plate rolling are made viable, leading to enhanced productivity. For instance, an improvement in productivity by approx 10% is brought about when the equi-axed crystal zone ratio is increased. Further, when the reduction ratio at rolling is lowered by 10% through the improvement of slab quality, restrictions on rolling conditions can be relaxed.

4. Characteristics of S-EMS equipment

4.1 Coil arrangement and stirring method

Fig. 9 shows an S-EMS coil unit installed in a guide roll segment, and **Fig. 10** schematically shows the molten steel flow induced by S-EMS[3)].

For improving slab internal quality by means of stirring molten steel, it is necessary to stir molten steel sufficiently and strongly. And for obtaining a strong molten steel flow with a small energy input, the S-EMS coils are arranged close to the slab on both the sides. The S-EMS equipment is installed at a position where the high temperature molten steel flow from the tundish through the immersion nozzle does not significantly interfere with an upward flow induced by the stirring of S-EMS. The location of S-EMS coils is designed as close to the mold as possible while minimizing the interference with the steel flow from the tundish, taking advantage of the method of controlling the molten steel flow established through accumulation of operation experience, and this secures a high equi-axed crystal zone ratio.

Table 2 shows the arrangement of the S-EMS coils and the char-

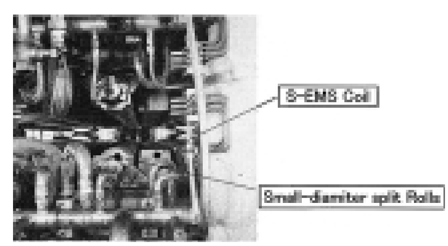


Fig. 9 S-EMS coil in position

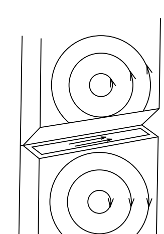
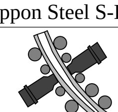
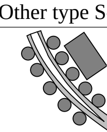


Fig. 10 Schematic illustration of molten steel flow induced by S-EMS

Table 2 Comparison between Nippon Steel S-EMS and other type S-EMS

	Nippon Steel S-EMS	Other type S-EMS
Composition layout		
Thrust force	Large: 10 (facing to slab directly)	Small: 1 (base) (behind guide rolls)
Flow pattern	Intermittent (forward and reverse)	Continuous
Affecting area	Narrow	Wide

acteristics of the molten steel stirring by S-EMS.

4.2 Construction of EMS coils

In order that the S-EMS coils may fit into the narrow space between guide rolls and exert strong stirring force on the molten steel, the S-EMS coils are structured as follows.

4.2.1 Coil winding method

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 narrow space between guide rolls. For this reason, the deep slot ring winding method, wherein the coil end space is small as seen in **Fig. 11**, was adopted in the EMS coils. The method, together with the use of small diameter rolls (to be explained later), allows the S-EMS coils to be installed close to the slab in the strand for efficient stirring of the molten steel there, without having to widen the pitch of guide rolls.

4.2.2 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 S-EMS coils, wherein a coil wiring (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 high cooling efficiency. 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 tubes are used for the piping of the cooling water at the connections with the coils. Further, for making the coils compact, the core and windings are integrated by the vacuum pressure impregnation method. This allows packing of the windings in the slots of the core in high density, maximizing the utilization of space and realizing the high current conduction.

4.2.3 High durability jackets

Since the S-EMS coils are installed in high temperature and high humidity environment near a hot cast slab, high durability and reliability are required of the jackets that protect the coils from the heat radiation of the slab and water vapor. For this reason, the jackets are fabricated of stiff stainless steel sheets, and their portions close to the slab and those subjected to the induction heating of the S-EMS coils are internally cooled with water. An independent circulation system with stainless steel pipes is provided for the cooling water for preventing corrosion and maintaining the quality of the water.

4.3 Optimum configuration of power supply and control equipment

So that the thrust force of the S-EMS coils works as effectively as possible and in an ideal operating condition, the power supply and control equipment of S-EMS is constructed as follows.

4.3.1 Characteristics of power supply equipment

Fig. 12 shows the configuration of the power supply and control equipment of S-EMS. The shifting magnetic fields of S-EMS coils induce induction currents in the molten steel inside the solidification shell to generate the thrust force. The strength of the thrust is proportionate to the square of the magnetic flux in the molten steel and the speed of the shifting. The flux in the molten steel is attenuated by an eddy current forming in the shell and the molten steel, and the higher the frequency is, the larger becomes the degree of the attenuation. On the other hand, the shifting speed of the flux is proportionate to the frequency and for this reason, there is a peak in the frequency characteristics of the thrust force generated by S-EMS, and the peak lies in a low frequency range from several Hz to several tens of Hz. The power supply equipment uses a compact inverter excellent in controllability on low frequency ranges.

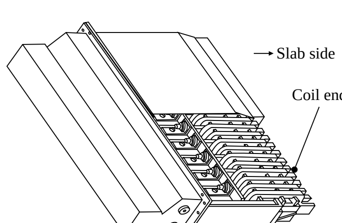


Fig. 11 Internal structure of S-EMS coil for slabs

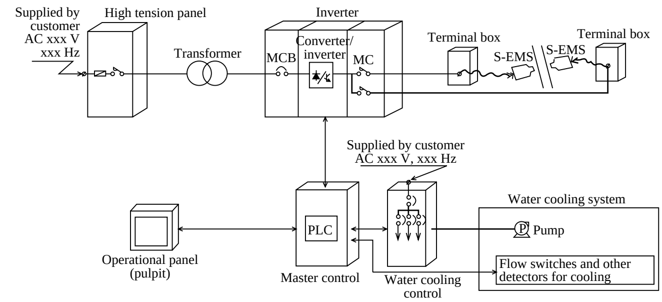


Fig. 12 Power supply and control system of S-EMS

4.3.2 Easy operation, high reliability and safety

S-EMS system is designed to work in an optimum condition under simple operation. The power supply equipment forms a highly reliable system incorporating the latest hardware and software technologies to realize high reliability and safety.

(1) From an operation desk, an operator can easily set the values of frequency and current required for obtaining a prescribed stirring strength, and the frequency and the current of the inverter can be controlled independently from each other based on the set values. In the automatic operation mode, S-EMS can be easily put on and off based on a cast length signal, which starts to count at the casting start of the caster.

(2) The elements of the inverter consist of IGBT transistors, the waveform is controlled by the PWM method, and the control functions are totally digitized. At the time of the inverter troubles or an equipment failure, an alarm message is given to the operator and the system is stopped without causing damage to the equipments.

(3) The operation of S-EMS is stopped automatically, if necessary, based on the detections of the coil cooling water flow rate, the temperature at typical point of the coils, coil grounding, power supply equipment failure, etc. By this, the equipment, operator and maintenance personnel are well safeguarded.

4.4 Segment structure of S-EMS

4.4.1 Optimum roll pitch structure

The coils are installed between small diameter rolls due to position them as close to the slab as possible to stir the molten steel efficiently, while maintaining an optimum roll profile. **Fig. 13** shows the structure of the small diameter rolls. Split rolls are used for securing sufficient rigidity, and they are cooled from outside for maintaining roll stiffness under a high thermal load.

4.4.2 Structure for high stirring efficiency

The amount of leakage flux of the S-EMS coils depends on the materials of the structures surrounding them; when the structures surrounding them are of ferromagnetic material such as ordinary steel, the leakage flux increases. An increase in the leakage flux causes the stirring thrust to weaken and the structures surrounding the coils to heat up. For preventing these problems, non-magnetic materials

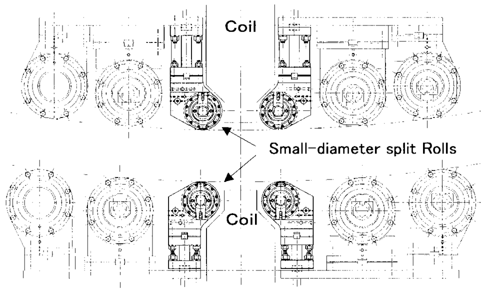


Fig. 13 Structure of small diameter split rolls

are used for the structures near the coils.

4.4.3 Good maintainability

The S-EMS segment is as maintainable as normal guide roll segments. The coil can be attached to the segment from the back side of its frame without dismantling the segment. The power cable of the coil has couplers for quick connection/disconnection and protection against dust and water.

Owing to compact construction, Nippon Steel's S-EMS can be fitted to guide roll segments of the slab caster builders and, thus, it can be easily fitted to existing slab casters.

5. Summary

Nippon Steel's S-EMS for slabs is characterized by the following.

5.1 Quality improvement with S-EMS

S-EMS improves slab internal quality through decrease of centerline segregation, increase in the equi-axed crystal zone ratio and so forth by the molten steel flow inside a slab in continuous casting, especially with slabs for electrical sheets, stainless steel sheets and heavy plate products.

5.2 Productivity improvement with S-EMS

S-EMS expands the allowable casting temperature range through the quality improvement effects. Through the improvement of the centerline segregation and increase in the equi-axed crystal zone ratio, S-EMS makes it possible to cast in high speed, thus, enhance the productivity.

5.3 Characteristics of S-EMS equipment

The equipment of S-EMS has the following characteristics:

· Compact coil design excellent in efficiency and durability;
· A structure of coil and guide roll segment frame to realize strong stirring thrust force with small energy consumption;
· A structure of small diameter rolls suitable for an optimum roll profile;
· A segment structure for easy attachment/detachment of the coils;
· A compact power supply and control system excellent in the control of molten steel flow.

References

1) Takeuchi, H., Mori, H., Ikehara, Y., Komano, T., Yanai, T.: Tetsu-to-Hagané: 66(6), 38 (1980)
2) Okimori, M., Tuchida, M., Inaoka, K.: Tetsu-to-Hagané: 80, T25 (1994)
3) Ujiie, Y., Maede, H., Itoh, Y., Ogibayashi, S., Seki, H., Wada, K., Itoh, Y.: Tetsu-to-Hagané: 67(8), 257 (1981)
4) Takeda, M., Komano, T., Yanai, T., Hino, T.: Nippon Steel Technical Report. (13), 36 (1979)