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Application of Electromagnetic Field Techniques to Steelmaking Processes

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Abstract:

Nippon Steel is expanding the application of electromagnetic field techniques in steelmaking processes by making the most of numerical analysis techniques based on the general-purpose electromagnetic field analysis software "FLEDY" they have developed. They have developed models concerning each problem of electromagnetic stirring, electromagnetic breaking and free-surface shaping. These are the basic magnetohydrodynamic analysis techniques to be applied to the molten steel process. The models are based on the models which were developed in magnetohydrodynamics and fluid dynamics. Next, electromagnetic stirring for continuous slab and billet casters, electromagnetic braking, and electromagnetic stirring in consideration of free surface shape in billet casters were developed as techniques to be applied to molten steel, and the magnetohydrodynamic characteristics involved were clarified. Furthermore, a DC electromagnetic force hot strip mill runout table and a strip center positioning unit were efficiently developed as techniques to be applied to strip. Lastly, the magnetizer of a magnetic particle tester for billets was optimally designed as an example of electromagnetic field technology application to sensors. Some of these techniques are already employed at steel plants as important tools for quality improvement and cost reduction.

1. Introduction

Great environmental changes in Japan and abroad in recent years have demanded greater quality improvement and cost reduction of steelmaking processes and have consequently brought electromagnetic field application techniques into the spotlight more than ever as new seed techniques to meet these challenges. We are developing such electromagnetic field techniques by making the most of numerical analysis, an important research and development tool substituting for experimentation, and particularly the general-purpose electromagnetic field analysis software FLEDY developed by Nippon Steel.

First, coupled magnetohydrodynamic-fluid dynamic models for such problems as electromagnetic stirring, electromagnetic braking, and free surface shape were developed as basic magnetohydrodynamic techniques to be applied to molten steel. Then, electromag-

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netic stirring and braking techniques were developed for continuous slab and billet casters, an electromagnetic stirring technique was developed for continuous billet casters by considering the shape of the free surface concerned; and the magnetohydrodynamic characteristics of these techniques were clarified. A DC electromagnetic force hot strip mill runout table and a strip center positioning unit were efficiently developed as examples of application to strip. Lastly, the magnetizer of a magnetic particle tester for billets was optimally designed as an example of application to sensors[1-3].

2. Magnetohydrodynamic Analysis

Magnetohydrodynamic analysis is used when an electromagnetic field is to be applied to molten metal such as molten steel. It takes too much computing time to perform magnetohydrodynamic analysis together with fluid dynamic analysis by coupling the four Maxwell's equations and related equations with the Navier-Stokes equations and the equations of energy conservation and momentum conservation, among other equations. Such coupled magnetohydrodynamic-fluid dynamic problems should be analyzed by some modeling.

An example of conventional magnetohydrodynamic analysis is shown in **Fig. 1**(a). This analysis is performed by the following procedure. The distribution of electromagnetic forces in a given shape of molten metal is obtained by the analysis of the electromagnetic field applied to the molten metal. Next, the flow of the molten metal is analyzed by taking the electromagnetic force distribution as an external force term for the fluid dynamic analysis. The electromagnetic field is then analyzed by taking the velocity distribution and the free surface shape as the speed electromotive force and the boundary condition for the electromagnetic field analysis. This series of calculations is repeated to a certain degree of convergence. Given the enormous time taken by individual calculations, it is considerably difficult to apply this technique to practical problems.

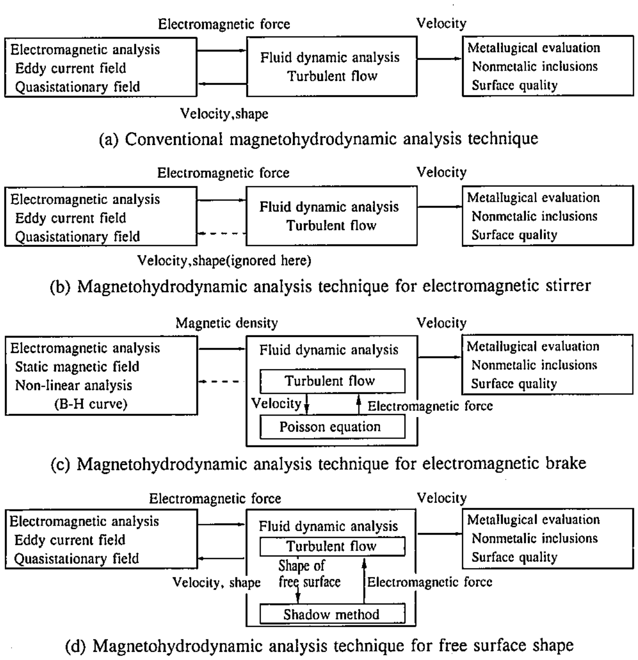


Fig. 1 Magnetohydrodynamic analysis techniques for specific purposes

It is deemed necessary to first model each magnetohydrodynamic application problem to suit its characteristics and then to develop a practical numerical analysis technique for the problem.

Take an electromagnetic stirrer (EMS) as the first problem. The synchronous speed of the magnetic field of the EMS is a small 4-6 m/s as compared with the molten steel velocity of about 0.5 m/s or less, so that the effect of the speed electromotive force in the electromagnetic field is negligibly small. Since the surface of the molten steel in the mold of a continuous slab caster is relatively flat, the effects of the velocity and surface shape on the electromagnetic field can be ignored in the fluid dynamic analysis. The magnetohydrodynamic analysis technique to be employed in this case is shown in **Fig. 1**(b).

The next problem is that of an electromagnetic brake. The magnetic Reynolds number, or the ratio of the DC magnetic field applied to the molten steel to the magnetic field induced by the eddy current produced by the velocity of the molten steel, is small at 0.1 or less. The electromagnetic field can be thus represented by the Poisson equation. If the Poisson equation is incorporated into the fluid dynamic analysis and if the magnetic field distribution to be applied is determined by the electromagnetic field analysis, the magnetohydrodynamic analysis is performed as shown in **Fig. 1**(c).

Lastly, the R projection method[4] was devised for modeling the free surface whose shape is changed by electromagnetic force[5]. When the free surface of a fluid is deformed by electromagnetic force, the electromagnetic force is projected on the basis of the distance R from some reference. The R projection method was developed, based on the multiple-rigid body dynamic model of magnetically levitated vehicles[6]. The magnetohydrodynamic analysis technique to be used in this case is shown in **Fig. 1**(d). The electromagnetic field is recalculated only when the free surface is deformed to a great extent.

The magnetohydrodynamic analysis techniques developed as described above can simultaneously analyze the electromagnetic field by partly incorporating an electromagnetic field analysis model into the fluid dynamic analysis. This enables process development with attention focused on the characteristics of electromagnetic coils.

3. Application to Continuous Casters

3.1 In-mold electromagnetic stirring for continuous slab caster

In-mold electromagnetic stirrers (EMSs) are practically applied in the molds of continuous slab casters at the works of Nippon Steel for improving the surface quality of continuously cast slabs. Here the basic characteristics of the in-mold EMS are studied by numerical analysis[7,8].

Fig. 2 shows a bird's-eye view of the EMS installed in the mold of a continuous slab caster. The molten steel is cooled and gradually solidified by the copper plate mold. The mold is encircled by the EMS coil. **Fig. 3** shows the EMS coil seen from the casting direction (z). The magnetic shielding effect of the copper plates interposed between the molten steel and the coil limits the operating frequency to an extremely low level of a few kilohertz. The coil is wound into a low enough volume to be installed in the mold.

To verify the validity of the electromagnetic field analysis, the calculated values are compared with the experimental values. The results are shown in **Fig. 4**. The calculated values of three-dimen-

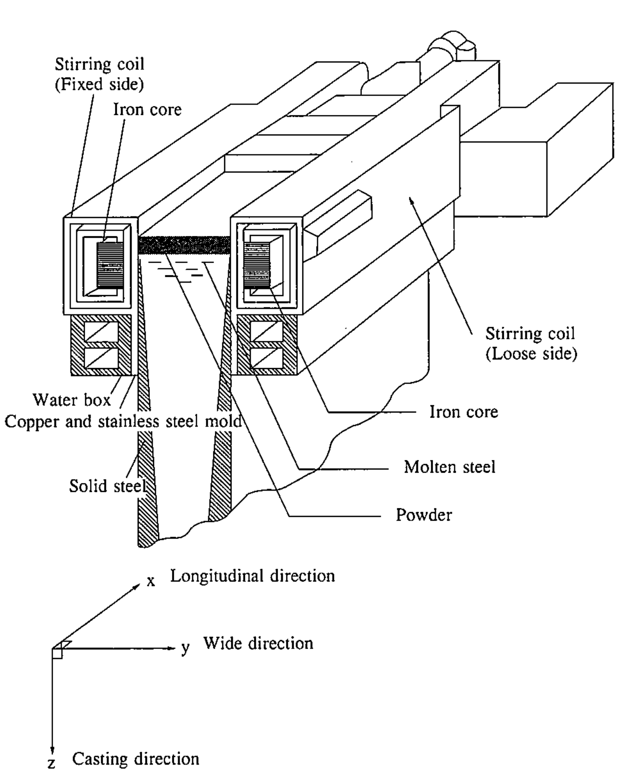


Fig. 2 Bird's-eye view of in-mold electromagnetic stirrer

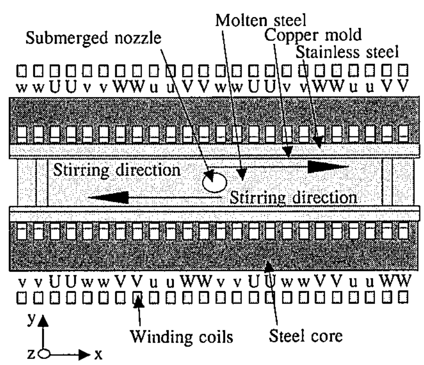
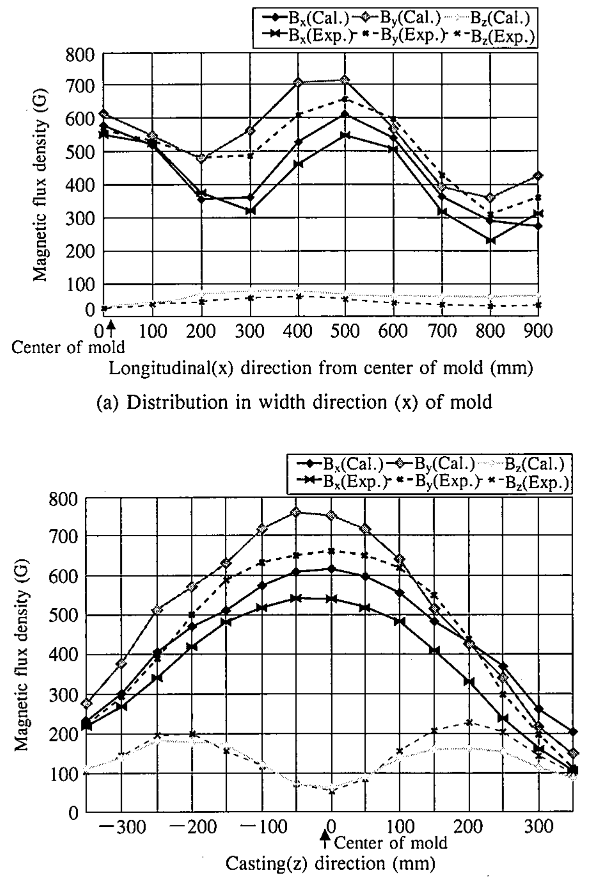


Fig. 3 In-mold electromagnetic stirrer for continuous slab caster



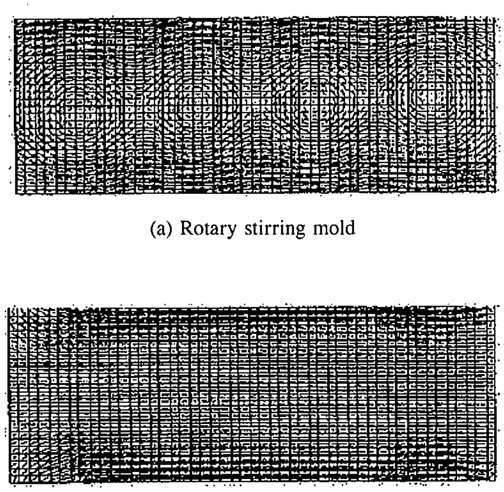
(a) Distribution in width direction (x) of mold

(b) Distribution in casting direction (z) of mold

Fig. 4 Comparison of experimental and calculated three-dimensional magnetic flux density distributions

sional magnetic flux density distribution agree well with the experimental values in both the longitudinal direction (x) and the casting direction (z).

The electromagnetic force distribution is shown in **Fig. 5**. In the rotary stirring mode in present use, vortices are produced in the same number as the poles, as shown in **Fig. 5**(a). The vortices are caused by the interaction between the magnetic field of the fixed-side coil and the magnetic field of the loose-face coil and are absent in the horizontal stirring mode as shown in **Fig. 5**(b). The effect of these electromagnetic force vortices was evaluated by fluid dynamic analysis. As shown in **Fig. 6**, the velocity distribution represents an almost neat rotary stirring stream. The effect of the electromagnetic force vortex distribution is masked by the inertia and continuity of the fluid.



(a) Rotary stirring mold

(b) Horizontal stirring mold

Fig. 5 Electromagnetic force distributions

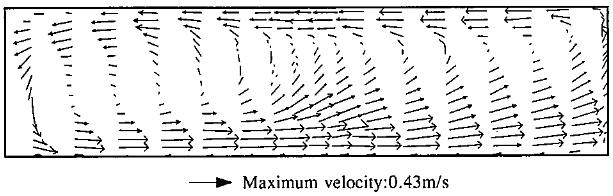


Fig. 6 Velocity distribution (rotary stirring, 2 Hz, 4 poles)

3.2 In-mold electromagnetic stirring for continuous billet caster

The in-mold electromagnetic stirring characteristics of a continuous billet caster are reviewed next. Usually, one electromagnetic stirrer (EMS) is installed for each mold on multiple-strand billet caster. When a slab caster is used to cast three billet strands as one measure for equipment consolidation, one EMS coil electromagnetically stirs the molten steel in the three billet casting molds as shown in **Fig. 7**. In this case the EMS coil must be arranged so that the electromagnetic force can be uniformly applied to the three molds. The optimum value of relative phase difference between the fixed-side and loose-side coils[9] is studied here.

The relative phase characteristics are shown in **Fig. 8** by reference to the electric connections of **Fig. 7**. The electromagnetic torque T is given by

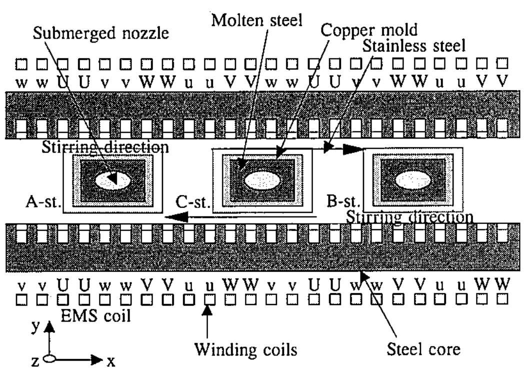


Fig. 7 Reuse of continuous slab caster electromagnetic stirrer on continuous billet caster

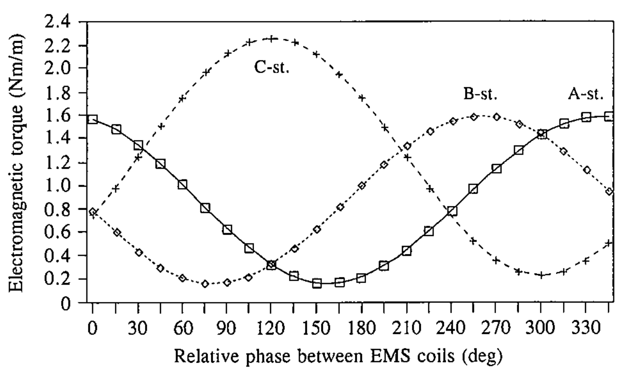


Fig. 8 Phase characteristics of electromagnetic stirrer as applied to three-strand billet caster

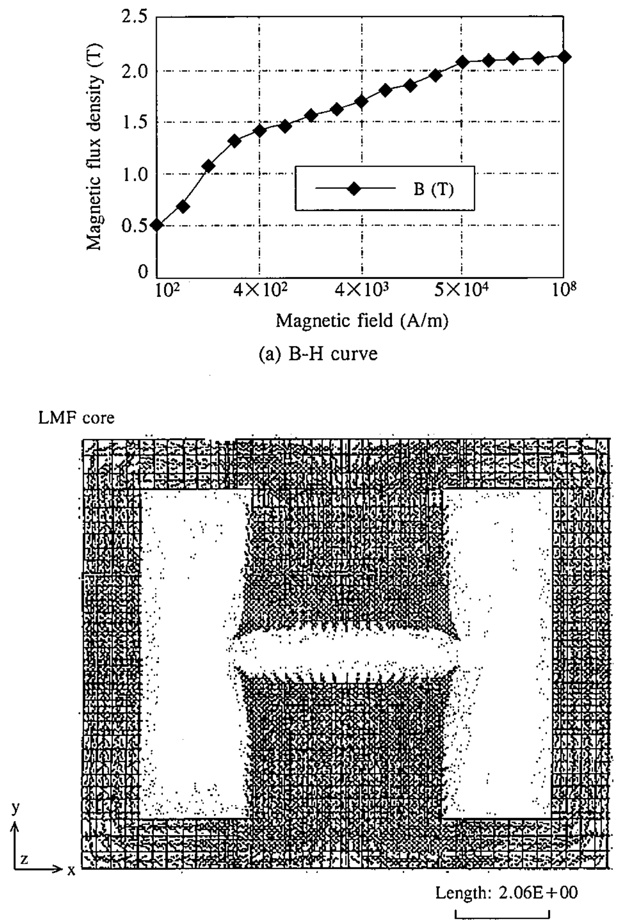
$$T=\sum_{i=1}^{All}\frac{f_i V_i r_i}{z_i}\,(\mathrm{Nm/m})$$

where f_i is the electromagnetic force of the i-th element (N/m^3); V_i is the volume of the i-th element (m^3); r_i is the distance from the mold center to the i-th element (m); and z_i is the thickness of the i-th element in the z-direction (m). As can be seen from **Fig. 8**, the electromagnetic torque changes into a beautiful sinusoidal pattern as the relative phase changes. There are no phases at which the electromagnetic torque becomes the same for all three molds. Relatively good agreement is observed at the phase angles of 0 and 240°.

3.3 Electromagnetic braking

Fluid flow control by electromagnetic braking is well known. Many magnetohydrodynamic analyses are performed for electromagnetic braking. Here is described the magnetic saturation of the electromagnetic brake core.

The electromagnetic coil core of the electromagnetic brake is used in the magnetic saturation region because it is necessary to provide as high a magnetic flux density as possible in the narrow space around the mold. The magnetic flux density distribution of the core on the B-H curve of **Fig. 9**(a) is shown in **Fig. 9**(b). It is seen that magnetic saturation is caused at the core teeth and their roots.



(a) B-H curve

(b) Magnetic flux density distribution of electromagnetic coil

Fig. 9 Electromagnetic brake characteristics

3.4 Free surface problem

When electromagnetic stirring is applied to a continuous billet caster, it is known that the surface of the molten steel in the mold rises as observed with the water in a clothes washer and adversely affects the quality of the cast steel. The shape of the molten steel surface was evaluated by the R projection method. The analytical results are shown in **Fig. 10**. The surface of the molten steel surface is seen standing up in the same way as the surface of water in the clothes washer.

3.5 Development of linear motor nozzle[10)]

The electromagnetic stirrer is one type of linear motor (induction type). An EMS application to a nozzle for the purpose of flow control is described below.

The linear motor as applied to the nozzle is shown in **Fig. 11**. The linear motor decreases the flow rate through the nozzle when its traveling magnetic field is applied to the nozzle in the upward direction and increases the flow rate through the nozzle when its traveling magnetic field is applied to the nozzle in the downward direction. If the linear motor is driven by an inverter-based power source, the magnitude of the electromagnetic force can be changed by changing the voltage or frequency, and the linear motor can be used as a nozzle flow rate controller.

This characteristic of the linear motor as experimentally confirmed is shown in **Fig. 12**. A vertical nozzle is used in this example. When the current of the double-sided linear induction motor (DLIM) is 60 A, the flow of molten metal would be completely stopped or would be reversed for a horizontal nozzle or solid secondary conductor. With the vertical nozzle and with molten metal as secondary conductor, the molten metal started to leak at the nozzle edges where no electromagnetic force was applied, and could not be completely stopped. The DLIM can completely stop the flow of molten metal through the horizontal nozzle and is expected to act as a valve.

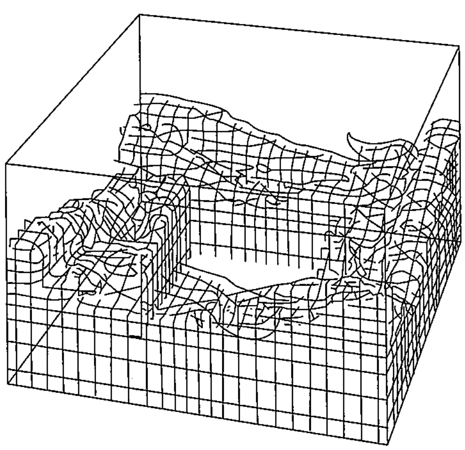


Fig. 10 Shape of free surface with electromagnetic stirring

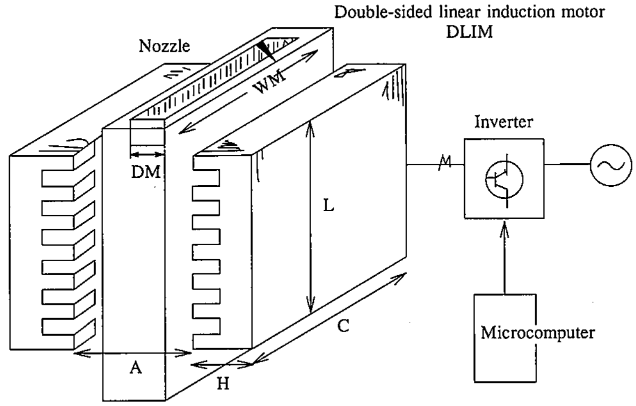


Fig. 11 General view of linear motor nozzle

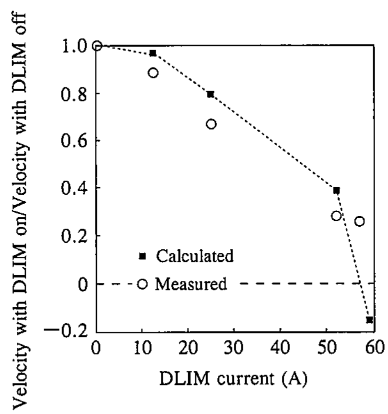


Fig. 12 Flow rate through vertical nozzle

4. Application to Strip

4.1 Development of electromagnetic force runout table[11)]

As the first electromagnetic force application to strip, here is described an electromagnetic force runout table or a hot strip mill runout table having rolls equipped with electromagnetic coils to prevent the head end of strip from flying as it is threaded through the runout table.

The electromagnetic force runout table with rolls retrofitted with electromagnetic coils is schematically illustrated in **Fig. 13**. When DC current is supplied to the electromagnetic coil, the roll doubles as the core of an electromagnet and attracts the flying strip to increase the threading speed of the strip on the runout table.

The results of electromagnetic field numerical analysis conducted by considering the magnetic saturation of the strip show that most of the electromagnetic force is concentrated over about 20 mm across the contact point of the roll and the strip where the gap between them is smallest, as shown in **Fig. 14**. The contact between the strip and the roll increases the attractive force between the strip and the roll and reduces the frictional force between the strip and the roll. As a result, the roll driving force is directly

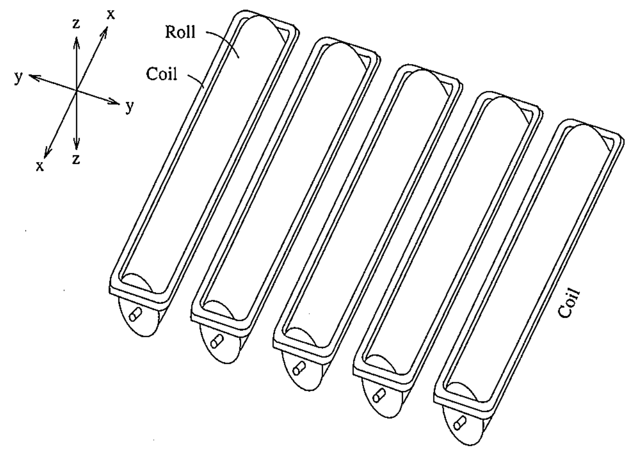


Fig. 13 Schematic of electromagnetic force runout table

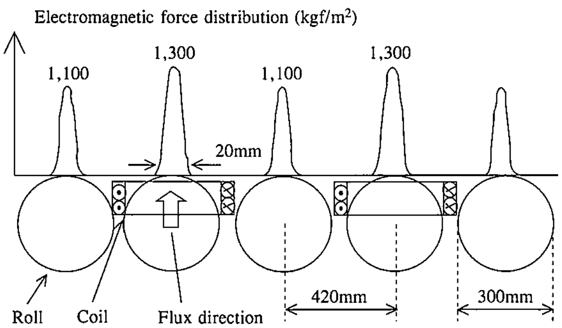


Fig. 14 Electromagnetic force distribution of electromagnetic force runout table

transmitted to the strip and is expected to increase the threading speed of the strip on the runout table.

The magnetic flux produced by the electromagnetic coil perpendicularly crosses the rotating roll in some portions. A speed electromotive force is generated in the axial direction (x) of the roll. If the roll is grounded, eddy current flows in the roll. Since the energy to drive the eddy current is supplied from the roll drive motor, the flow of the eddy current increases the motor current. This characteristic was evaluated in detail by off-line experimentation. It was found that the motor current increased with the electromagnetic force runout table but was not high enough to pose any practical problems.

4.2 Development of strip center positioning unit[12]

The development of an electromagnetic strip center positioning unit is discussed as the next example of electromagnetic field application to strip.

In **Fig. 15** two electromagnets are installed opposite one another above and below a 0.5-mm thick steel strip. The voltage of each electromagnet is changed to control the strip center position. When the strip is displaced upward, for example, a downward electromagnetic force is applied to the strip to bring back the strip to the center of the line by decreasing the voltage of the top electromagnet and increasing the voltage of the bottom electromagnet. In this way the strip is controlled to run through the center of the line.

The current in the two electromagnets flows in one of two configurations or the homopolar and heteropolar configurations as shown in **Fig. 16**. The question is which configuration provides superior electromagnetic force characteristics. The results of numerical analysis conducted to answer this question are given in **Fig. 17**. The electromagnetic force almost varies linearly with the current due to the magnetic saturation of the strip. The heteropolar configuration is shown to generate a larger electromagnetic force.

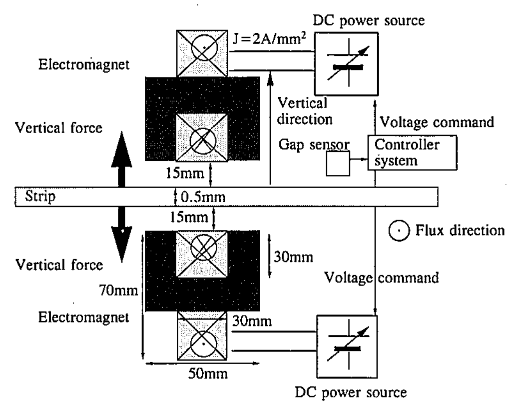
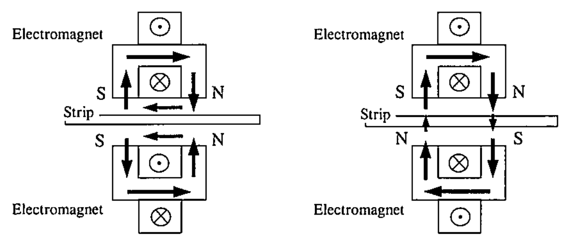


Fig. 15 Strip center positioning unit with electromagnets



(a) Homopolar configuration (b) Heteropolar configuration

Fig. 16 Magnetic flux path

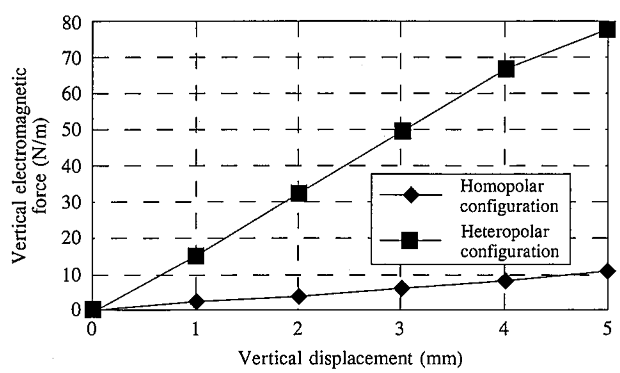


Fig. 17 Electromagnetic force characteristics of homopolar and heteropolar configurations

5. Application to Electromagnetic Sensor

Besides the above-mentioned applications centering on electromagnetic forces, electromagnetic field technology is also being developed rapidly in electromagnetic sensor applications. Following an example of electromagnetic field application in which the magnetizing coil of a magnetic particle tester was optimally designed[13].

A steel billet magnetic particle tester is schematically illustrated in **Fig. 18**. Magnetic particles (fine iron particles suspended in alcohol) are applied to the billet. When the billet is magnetized, surface defects form magnetic particle patterns different from those observed on the normal portions of the billet. These magnetic particle patterns are detected by the inspector to locate the corresponding surface defects of the billet. It is important that the magnetizer should generate only those magnetic flux components that are parallel with the surface of the billet. Magnetic flux components normal to the billet surface cause magnetic particle patterns similar to those created by defects and result in detection errors. The magnetizer must be designed to produce as large parallel components as possible.

The tangential and normal components of the magnetic flux density produced by this analysis are shown in **Fig. 19**. A magnetizer by far superior to a conventional one was successfully designed by changing the coil shape and arranging electromagnetic shields.

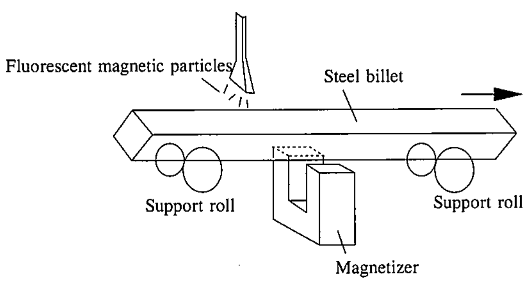


Fig. 18 Schematic construction of magnetic particle tester

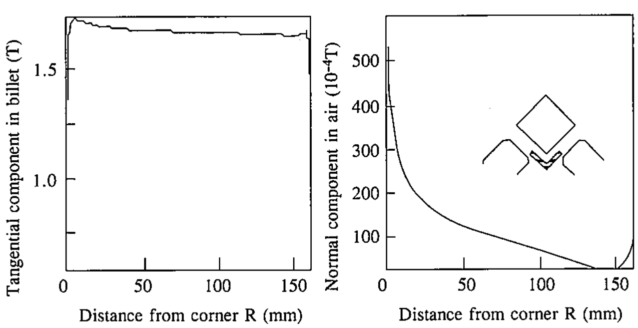


Fig. 19 Magnetic flux density distribution of magnetizer in magnetic particle tester

6. Conclusions

As discussed previously, electromagnetic fields are finding steadily increasing applications in steelmaking processes. Not only electromagnetic force applications, but also electromagnetic sensors are widely developed. Some of these techniques are already employed as important tools for quality improvement and cost reduction at steel plants. Further advancements of the electromagnetic field techniques are expected.

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