Biblio

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I. INTRODUCTION

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The stirring coil is supplied with alternative current and multiphase power source, and creates the traveling flux through the molten steel. Eddy current is induced in the molten steel, and the electromagnetic force is induced as the Lorentz's force. Since the molten metal becomes solid from liquid above the Curie temperature, it is non-magnetic but conductive.

Because of the electromagnetic force supplied by the in-mold electromagnetic stirring, the molten steel picks up some velocity. The rotating stirring mode is considered as the stirring direction, since a uniform velocity at the surface of the molten steel is obtained compared as with the parallel stirring mode. In this case, a clean slab surface and a low number of non-metallic inclusions are obtained.

To get the fundamental characteristics of in-mold electromagnetic stirring, magnetohydrodynamic calculation is important.

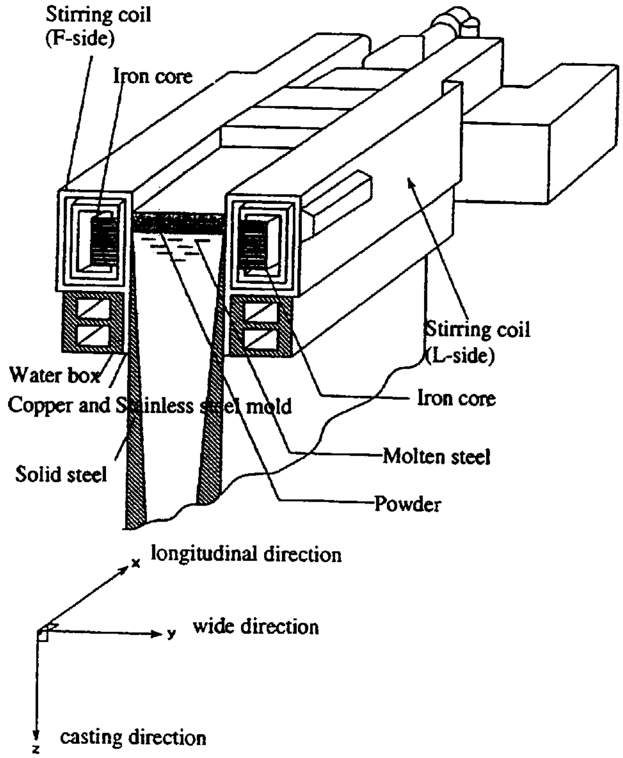

Fig. 1. In-mold electromagnetic stirring(schematic view).

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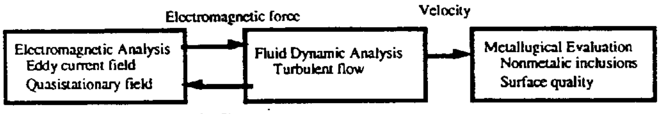
III. MAGNETOHYDRODYNAMIC CALCULATION

A. Calculation Method

The magnetohydrodynamic calculation is necessary for electromagnetic analysis and fluid dynamic analysis. The usual magnetohydrodynamic calculation needs the iteration between them as shown in Fig. 2(a). The electromagnetic force is transferred from the electromagnetic analysis to the fluid dynamic analysis. The electromagnetic force is treated as disturbance force of fluid dynamic. The velocity and surface are transferred from the fluid dynamic analysis to the electromagnetic analysis to take into account for the velocity electromagnetic motive force and the boundary condition of conductive material.

However, in case of the in-mold electromagnetic stirring, the surface is assumed to be fixed, and the velocity electromagnetic motive force is also assumed to be negligible. The synchronous speed of linear induction motor (traveling speed of electromagnetic flux, about 3m/s) is large enough as the maximum part velocity in the molten steel (about 0.2m/s).

Therefore, the magnetohydrodynamic calculation procedure of the in-mold electromagnetic stirring is that the electromagnetic force distribution is calculated first, and then the fluid dynamics is calculated second as shown in Fig. 2(b).



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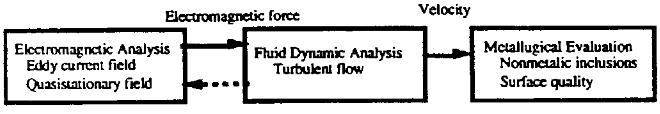

(b). In-mold-electromagnetic stirring calculation.

Fig. 2. Magnetohydrodynamic calculation.

B. Electromagnetic Analysis

The electromagnetic calculation method is finite elements using the A-ϕ method. The displacement current in Maxwell equation is ignored, and the quasistationary field is assumed (time partial differential is treated as j ω)[3]. The phase unbalance in power source, which occurs usually in linear induction motor, is ignored here. Studied model is shown in Fig. 3 and the material constants used here are shown in Table I.

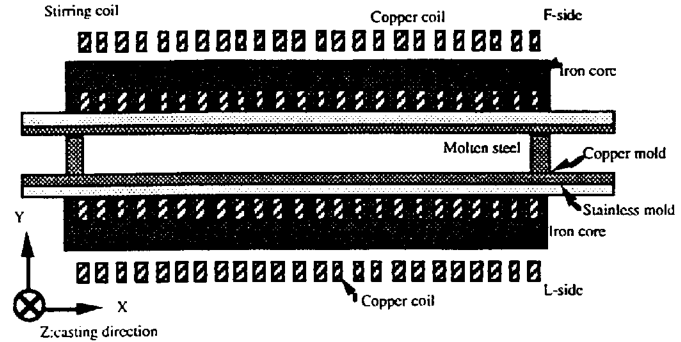

Fig. 3. Studied model of in-mold electromagnetic stirring.

TABLE I
MATERIAL CONSTANTS USED HERE

Materials	Relative permeability[-]	Conductivity[S/m]
Molten steel	1	$7.69*10^{6}$
Copper mold	1	1.7810^{7}
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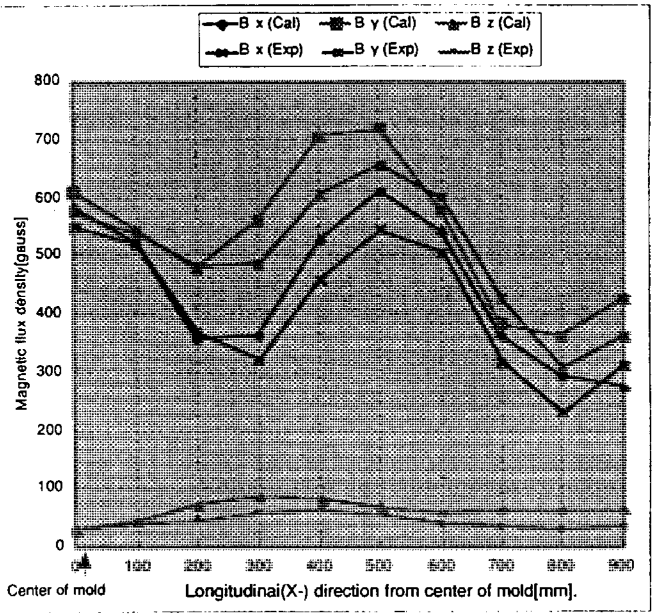
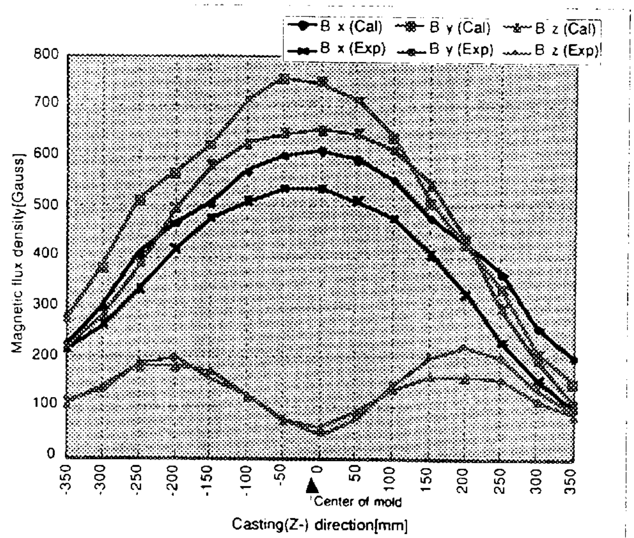


(a).Longitudinal direction distribution.



(b). Casting direction distribution.
Fig.4 . Magnetic flux density distribution.
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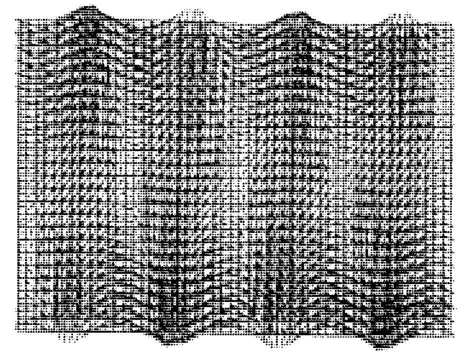
The magnetic flux density distribution in molten steel at the rotating stirring mode is shown in Fig. 5. There are some parts with no magnetic flux in the mold at the real part (a) as well as the imaginary part (b). These parts are considered to occur by the magnetic flux interaction between the F-side coil and the L-side coil[4]. Because these parts have no magnetic flux at all time, they also have no electromagnetic force.

Electromagnetic force distribution in the molten metal is shown in Fig. 6. The rotating force along the longitudinal wall and the normal force vertical to the wall are obtained. Then the eddy distribution of the electromagnetic force appears. The eddy position of the electromagnetic force is the same as the position of no magnetic flux in Fig. 5. The eddy distribution of electromagnetic force is considered to be caused from the magnetic interaction between the coils. The eddy distribution of the electromagnetic force makes the normal force of the electromagnetic force.

The normal component of the molten steel velocity makes no influence on the metallurgical characteristics, because the surface of the solid steel has some parts with no velocity. Then it is said that the normal component of the electromagnetic force usually has a bad influence on it.

To consider the mechanism of the eddy distribution of the electromagnetic force, the parallel stirring mode is also shown for comparison. The rotating stirring mode is caused when the directions of the traveling flux of each coil are different, and the parallel stirring mode is caused when the directions of the traveling flux of each coil are the same. The electromagnetic force distribution in rotating stirring mode has eddy distributions, though the one in the parallel stirring mode has no eddy distribution. Then, it is found that the eddy distribution of the electromagnetic force is a characteristic of the rotating stirring mode.



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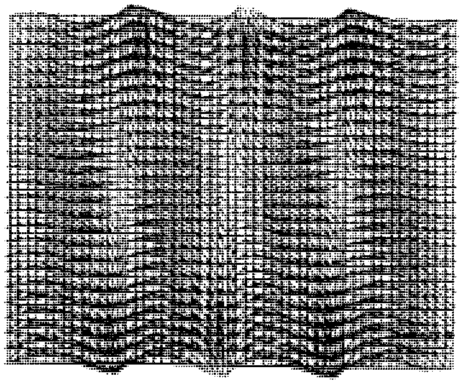
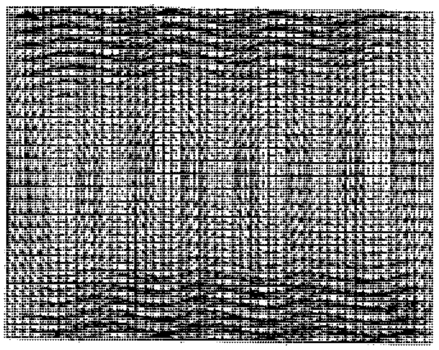
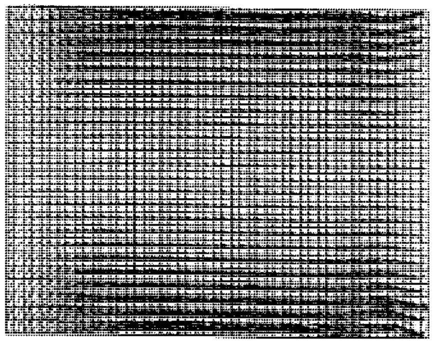


(b). Imaginary part.
Fig. 5. Magnetic flux density distribution.
(rotating stirring mode, 2Hz, 4 pole)



(a). Rotating stirring mode.



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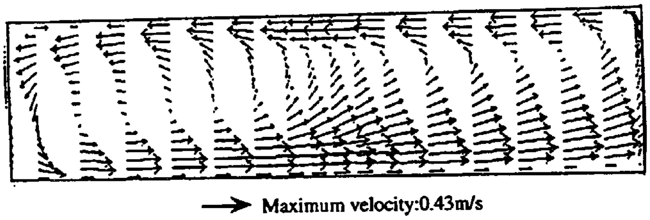

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NUMERICAL METHOD

approximation of partial difference	finite difference method
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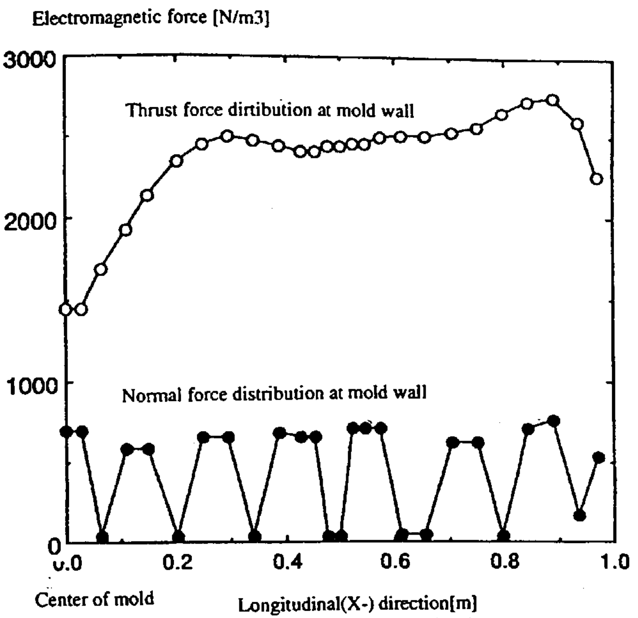

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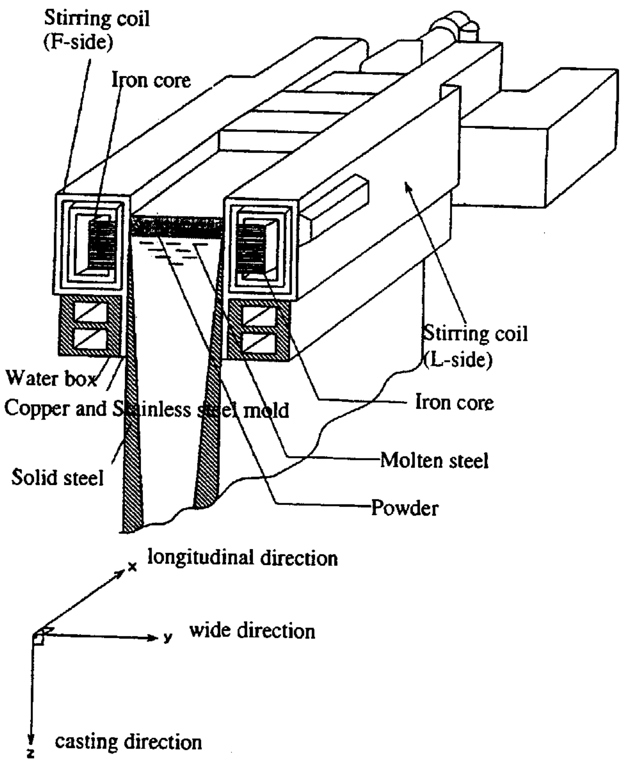

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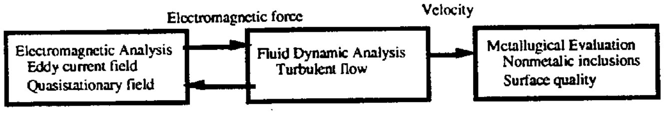

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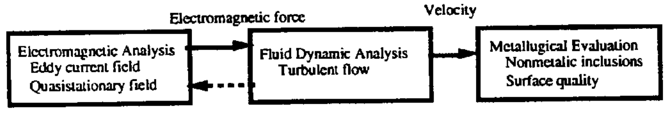

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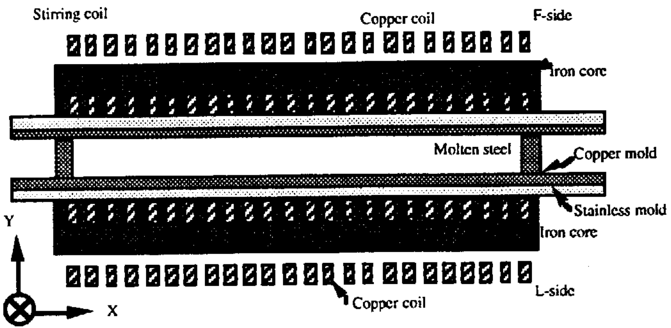

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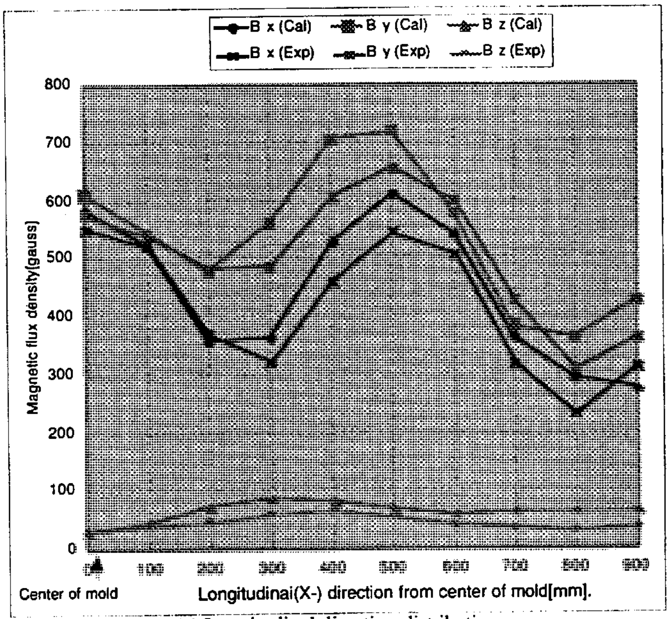

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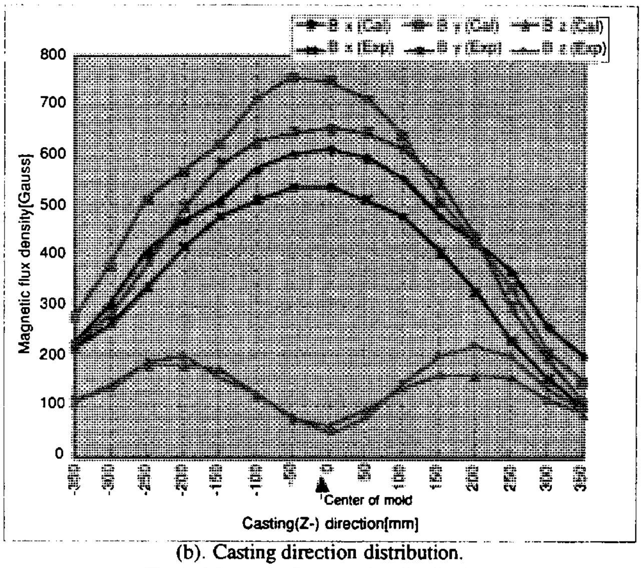

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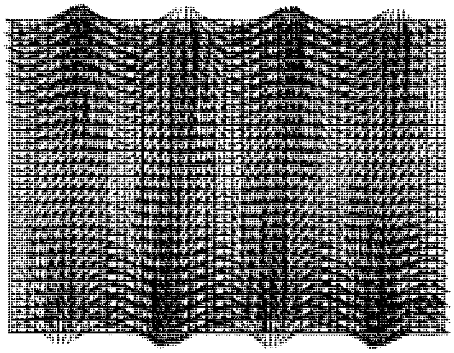

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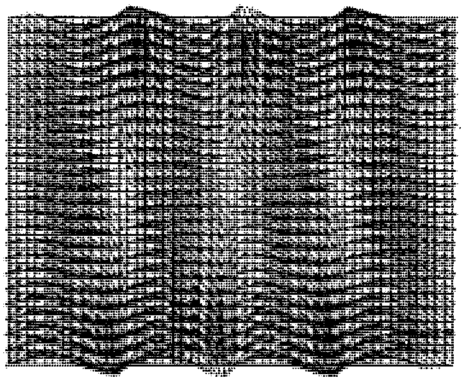

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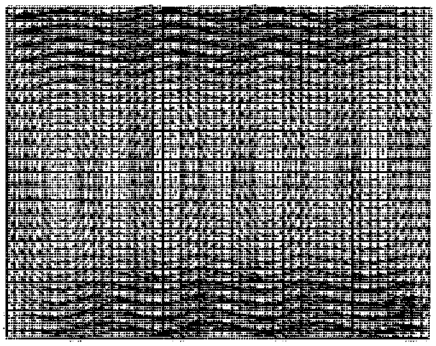
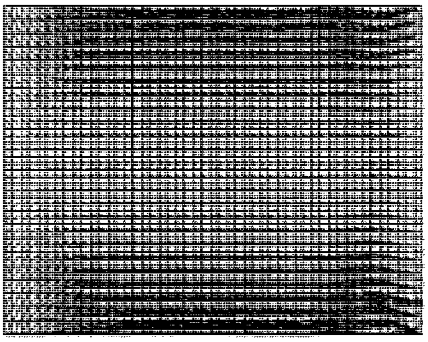


(a). Rotating stirring mode.



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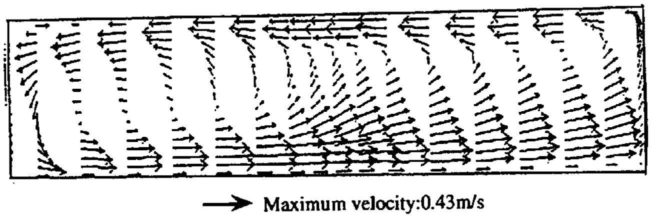

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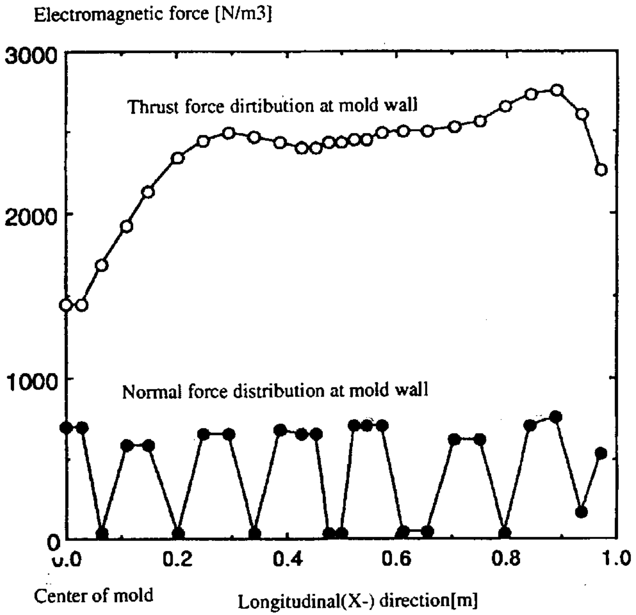

Fig. 8. Electromagnetic force distribution.

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