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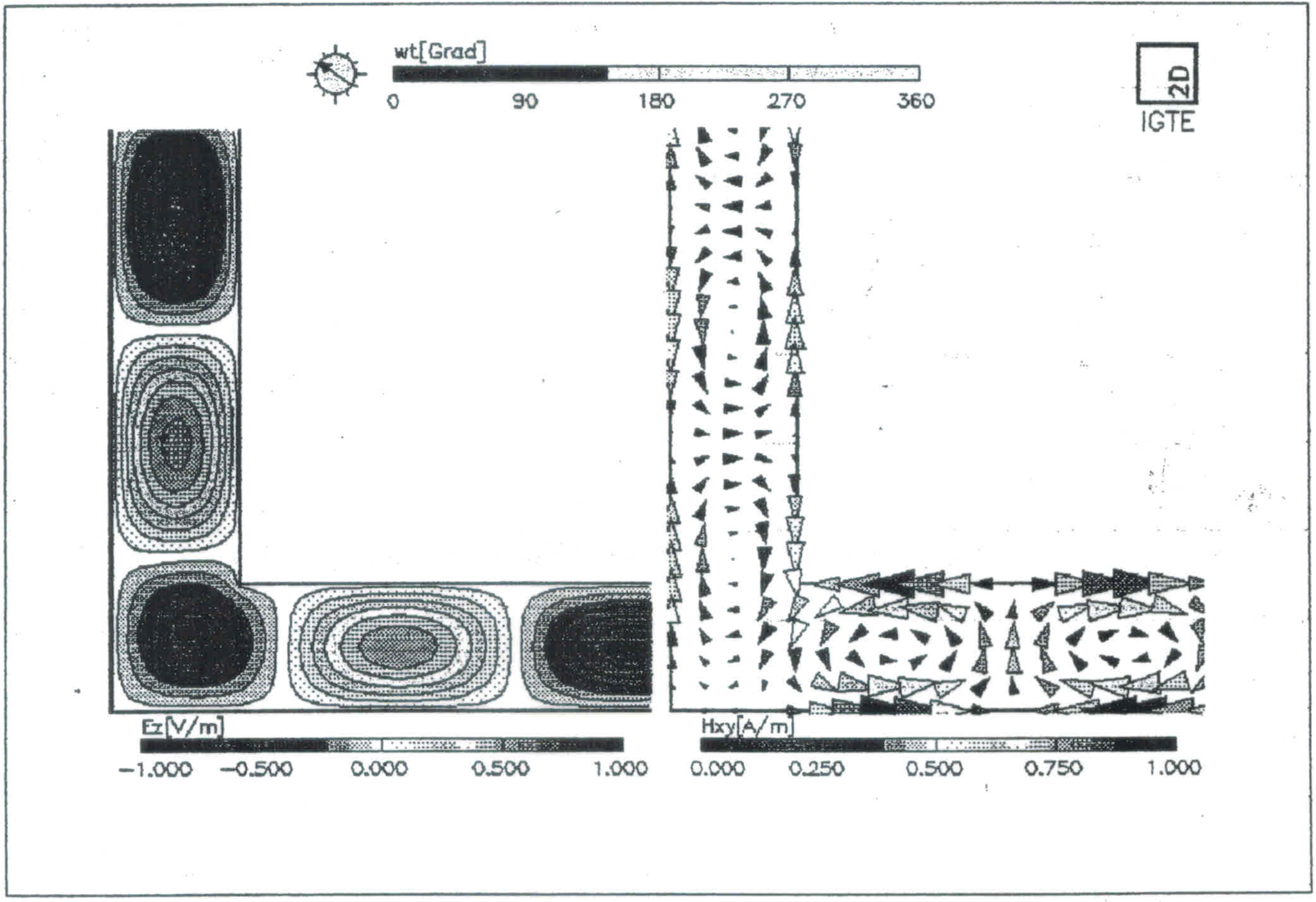
on
Numerical Field Calculation in Electrical Engineering

PROCEEDINGS



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FINITE ELEMENTS MODELING OF THE SHEETS LEVITATION IN THE HORIZONTAL ELECTROMAGNETIC CASTING

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Abstract. The work deals with the numerical modeling of the electromagnetic field in the levitated sheets continuous casting device, described in US Patent 4,678,024.

By means of the dedicated computing program, LEVITA, the influence of the physical structure, of the side guard configuration, and of the magnetic core properties are studied, on the transversal uniformity of the levitation electromagnetic force

The supply frequency choise and the liquid metal stability are analysed.

Introduction

Present steel mill practice typically produces thin steel sheets by pouring liquid steel into a mold. The solidified steel leaves the mold either as an ingot, or as a continuous slab; in either case, the solid steel is relatively thick and must be subsequently processed, to reduce the thickness to the desired value and to improve metallurgical properties.

Subsequent fabrication steps, such as rolling, extruding, forging and the like, usually require the scalping of the ingot or sheet prior to working to remove both the surface defects as well as the alloy deficient zone adjacent to its surface. These additional steps increase the complexity and expense of steel production. Steel sheet thickness reduction is accomplished by a rolling mill, which is very capital intensive and consumes large amount of energy.

Compared to current practice, a large reduction in steel sheet total cost and in energy required for its production could be achieved if the sheets could be cast in near-net shape, i.e., in a shape and size closely approximating the final desired product. Electromagnetic methods have been used commercially in metal casting mainly for mold stirring and containment of vertical ingots in the production of aluminium; the molten metal is cooled and solidified before it touches any mechanical suport.

Horizontal electromagnetic levitation concept and caster design

Horizontal electromagnetic casting offers several advantages over vertical casting. First, the entire casting system, including the post-solidification rollers can be on one floor of the factory. Second, the static pressure head, that the magnetic forces must support need not be much more than the thickness of the plate to be cast, and, consequently, relatively low magnetic field strength can be used for the levitation.

Electromagnetic levitation of an electrically conducting molten body occurs when an alternating magnetic field generates eddy currents in the material and produce a magnetic pressure acting normal to the surface. If a sufficient strong magnetic pressure is directed vertically upward, it can counteract the downward force of gravity on the body.

Assume a large, non-magnetic horizontal conducting plate of h - thickness in an horizontal alternating magnetic field. For the B_i amplitude at the bottom plate face and B_S respectively, at the top face, levitation is achieved when:

$$\frac{B_i^2 - B_s^2}{2\mu_0} = \rho g h \tag{1}$$

where ρ is the plate density and g is the acceleration of gravity.

The equation (1) shows that the horizontal levitation concept requires a uniform horizontal magnetic field below the liquid metal sheet and a much smaller field above it. A conceptual apparatus design to produce such a field, shown in Fig. 1, include a closed magnetic core, **1**, two a.c. conducting coils, **2**, a conductive shield, **3**, and two side guards, **4**.

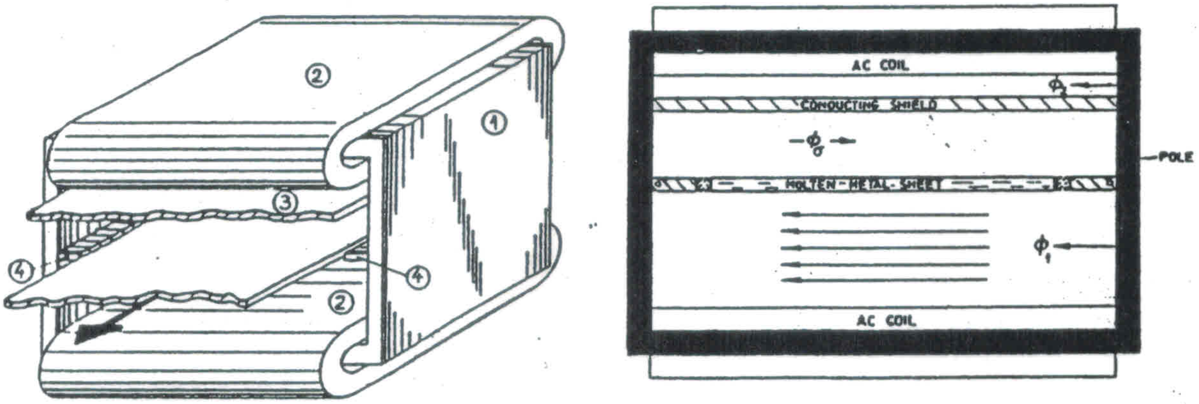


Fig. 1. Horizontal levitation apparatus design

In the inner side of the magnetic core the current has opposite direction in the top and bottom a.c. coils.

The conductive shield, preferably comprised of copper, in combination with the side guards and the molten metal sheet, excludes most of the magnetic flux from the region between the shield and the sheet.

Disposed between lateral edges of the sheet and the magnetic core, the side guards assist in shaping of the magnetic field and also serve to laterally confine the molten metal sheet.

The liquid steel and side guards provide parallel path for the eddy current, induced in them. They are connected to the copper shield at the ends of the magnet core and form a single - turn eddy current loop. The magnetic flux is excluded by the currents induced in the loop; hence, the magnetic field between the copper shield and the liquid metal, is small when compared with the field below the liquid steel and above the copper shield.

Finite elements modeling

The calculation domain of the bidimensional electromagnetic field structure, Fig. 2, include:

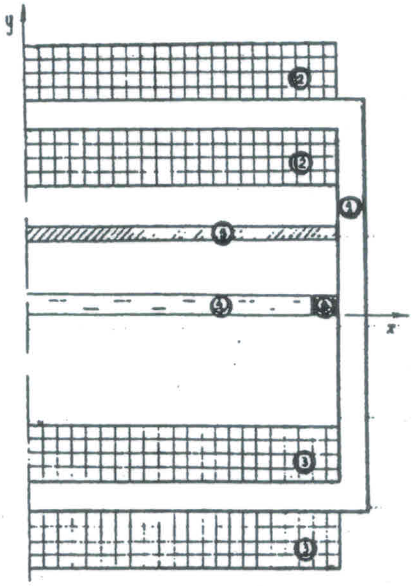


Fig. 2. The field calculation domain

- the magnetic core subdomain, 1, characterised by $\mu_1=\mu_0.\mu_{r1}$ permeability and σ_1 electrical conductivity (normally, a very low value);
- four subdomains, which represent the cross sections in the upper coil, 2, and in the inner one, 3, characterised by μ_0 permeability, zero conductivity and J_i primary current density, of $f=\omega/2\pi$ frequency;
- the levitated liquid metal subdomain, 4, nonmagnetic ($\mu_4=\mu_0$), with σ_4 conductivity;
- the shield subdomain, 5, nonmagnetic, with σ_5 conductivity;
- the side guard subdomain, 6, nonmagnetic, with σ_6 conductivity;
- the rest of the calculation domain, a nonmagnetic and nonconductive subdomain.

The computation model in cartesian coordinates (x,y,z) assumes that the primary current density vector has the structure $\mathbf{J_i}[0, 0, J_i]$; so, the electromagnetic field associated potential vector has the bidimensional structure, $\mathbf{A}[0, 0, A(x,y,t)]$.

The complex function $\underline{A}(x,y)$ complies with the general equation:

$$\mathrm{div}\,\mathrm{grad}\,A - j\omega\mu\sigma A + \mu J_i = 0 \qquad (2)$$

The midle term is zero in the nonconductive subdomains, the last term is nonnul only in the two-coils subdomains.

The electromagnetic field solution results through the minimization of the functional expression:

$$\Im = \frac{1}{2}\int_D (\mathrm{grad}^2 A + j\omega\mu\sigma A^2 - 2\mu J_i A)\, dS \qquad (3)$$

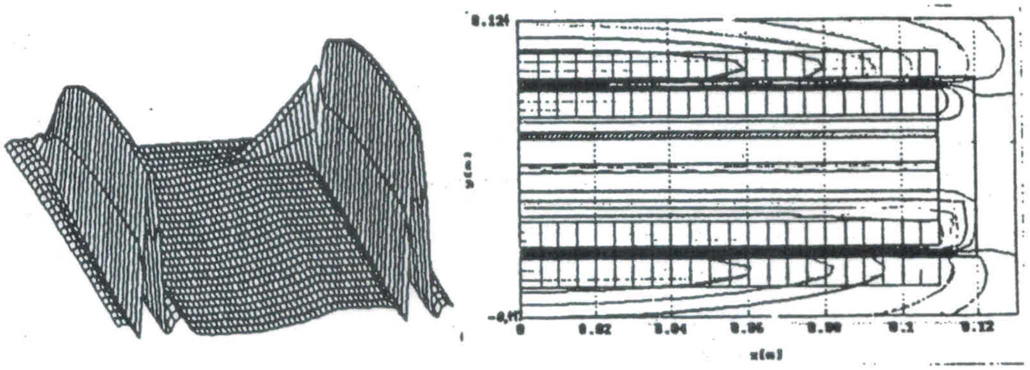
where D is the surface of the calculation domain. The Neuman homogene for A on the Oy symmetry axis, and A=0 in the rest, are the limit conditions of the computation model.

Numerical results. Discussions

The bidimensional image of the magnetic field, Fig. 3a, and the field lines, Fig. 3b, are the results of the dedicated computing program LEVITA.

These results corresponds to the input data:

- liquid metal band: width, 200 mm, thickness 10 mm, electrical conductivity, $\sigma_4 = 0.7$ S/m;
- coils: width, 200 mm, thickness, 20 mm, $J_i = 2$ A/mm^2, frequency, 30 kHz;
- magnetic core: thickness, 10 mm, permeability, $\mu_{r1} = 20$, conductivity, $\sigma_1 = 1$ S/m;
- shield: width, 200 mm, thickness, 5 mm, conductivity, $\sigma_5 = 50$ S/m;
- band - shield distance, 20 mm;
- shield - upper coil distance, 15 mm;
- band - lower coil distance, 40 mm.



a

b

Fig. 3. The bidimensional structure of the magnetic field

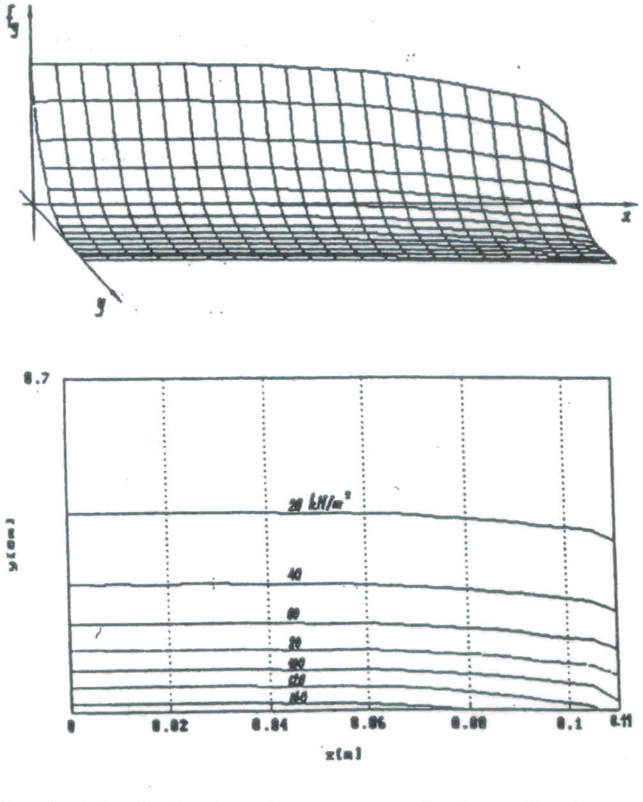


Fig. 4 The levitation electromagnetic force density

The influence of the side guards dimensions and properties on the levitation force is studied. The image of the levitation force density, f_y, in the liquid metal band, Fig. 4a, and the equivalues lines, Fig. 4b, proves a constant slowly decrease of the levitation effect from the center to the magnetic core limit, in the absence of the side guard apparatus components.

The dynamic stability of the band before solidification require a very good transversal uniformity of the levitation force density. For the same input data, but with side guard components of 10 mm width, and 180 mm band width, are represented in Fig. 5, for three cases: (a) - nonconductive side guards, (b) -copper side guards (very conductive, with $\sigma_6 = 50$ S/m), and, (c) - for $\sigma_6 = 0.4$ S/m electrical conductivity ones; the comparison stand out the importance of the correct side guard zone configuration on the dynamic stability of the molten sheet.

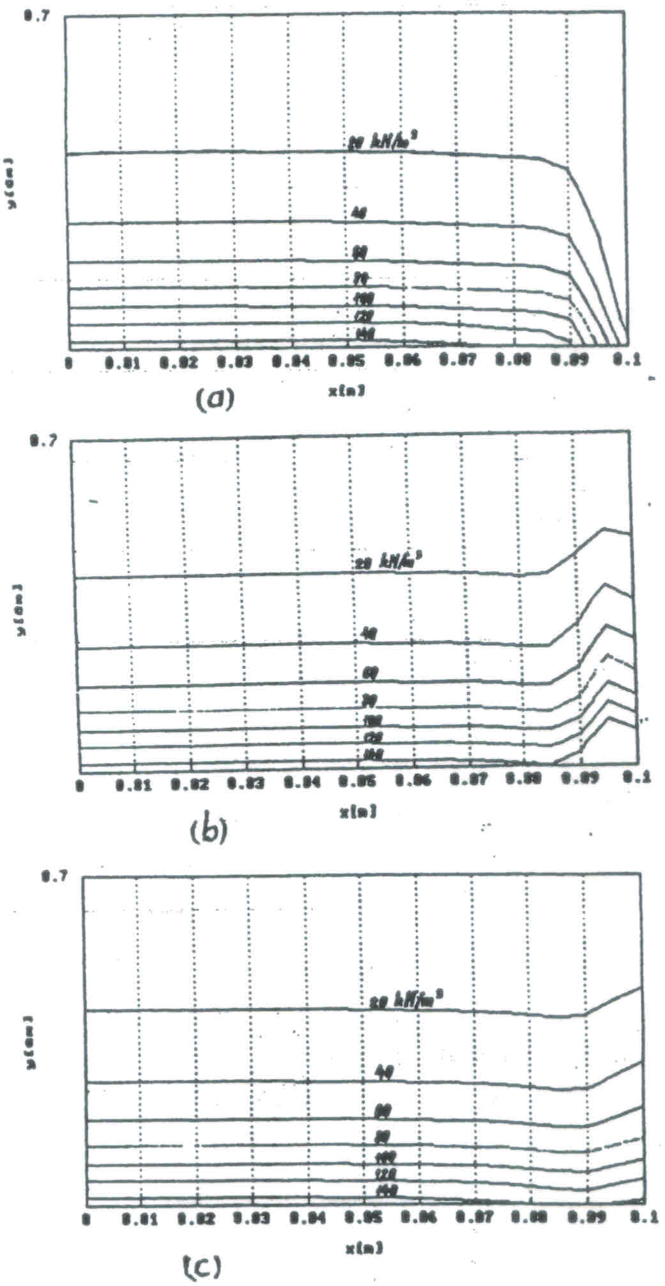


Fig. 5. The influence of the side guard conductivity

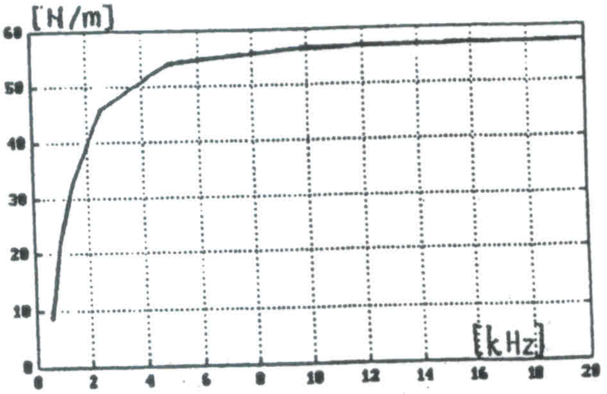


Fig. 6. The levitation force versus frequency

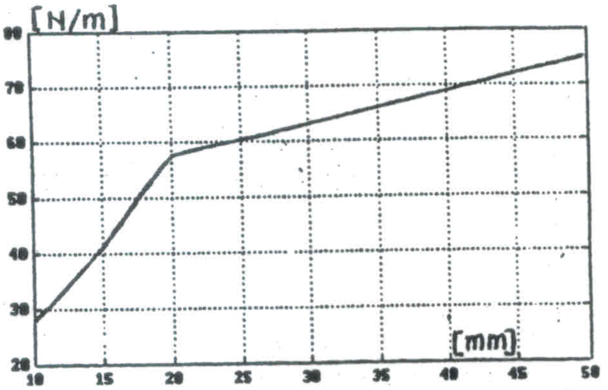


Fig. 7. The levitation force versus shield-band distance

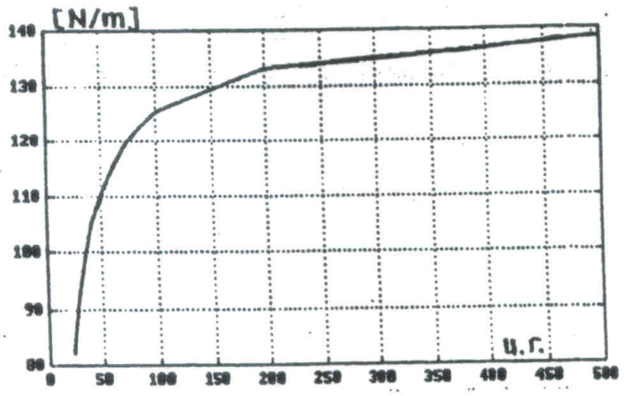


Fig. 8. The levitation force versus magnetic core permeability

Further on, somme global effects are regarded.

a. The supply frequency choise. The curves of the global levitation force versus frequency, Fig. 6, proves that is not necessary to work at a very high frequencies. The levitation force increase very slowly after un certain upper limit; for the presented input data, the domain (4 ... 10) kHz is recommended.

b. The dynamic band stability. The levitation force increase if the descendant tendency displacement of the metal band it exist, Fig. 7; the force increasing is very important for the reduced distances between the band and the upper conductive shield.

c. The increase of the shield thickness is favorable to the levitation force increase.

d. The selfstabilisation effect of the levitation force is proved, but is important to study external solutions to control the band position in the apparatus. One of this, is the control of the electrical supply, current intensity and/or the frequency. Another solution, showed by the levitation force curve versus permeability of the magnetic core, Fig. 8, is the control of the magnetic state of the apparatus magnetic core by, for exemple, a supplementary d.c. coil.

Acknowledgments

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