Features of modeling multiphase media in problems of electromagnetic generation of flows

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Abstract.
The study of the electromagnetic force acting on a medium with inhomogeneous electrical conductivity has been carried out. The electrical conductivity changes abruptly which simulates the liquid-solid interface during the crystallization of a pure metal. The electromagnetic force is created by a traveling field inductor with one of the most demanded in metallurgy construction. The results showed a significant dependence of the electromagnetic force on the position of the interface with respect to the inductor. Consequently in the mathematical modeling of the directional crystallization process under the influence of an electromagnetic force created by an inductor of this type it is necessary during the movement of the interface, either to do the calculation of the electrodynamic part of the problem anew or to use the method of canonical domains.

1. Introduction
It is well known that the characteristics of metal products depend on the conditions of its transition from liquid to solid state (thermodynamic, physical, etc.). The best properties of metals are achieved when the crystallization rate is fast enough and the crystallization front is as flat as possible.

A practical solution of this problem is mixing the liquid metal during crystallization. This helps to homogenize the distribution of temperature and impurities in the volume of the liquid phase, to reduce the size of the crystal grain and to increase the strength properties of the casting [1–4].

Due to the high temperatures and chemical activity of most liquid metals, mechanical stirring presents great difficulties. At the same time, the electromagnetic impact allows the generation of mixing vortex flows in a conductive liquid medium in a non-contact manner [5–8].

For the reasons mentioned above, it is difficult to experimental study the structure and influence of such flows on the thermophysical properties of phase transition processes and, as a consequence, the mechanical properties of the final products. Nevertheless, numerical modeling allows us to obtain detailed information about the fields of all physical quantities that determine the processes [9].

In turn, numerical modeling requires verification data to check the predictive accuracy of the models and take into account the governing physical mechanisms. This work is devoted to the development and verification of a numerical model for calculating the field of forces arising in a two-phase conductive medium with different conductivities of individual phases under the action
of an external alternating electromagnetic field. Such a physical model simulates a two-phase "liquid metal–solid metal" medium, in which the electrical conductivity of the phases can differ from 2 to 5 times, depending on the chemical nature of the working medium.

2. Numerical model

The main elements of the traveling field inductor are copper ring windings and steel ferromagnetic cores. The windings are connected to a three-phase AC power, so their number is a multiple of 3. The number of windings determines the number of core teeth. Simulations have been carried out for a pump with six windings. Mathematical model for solving a three-dimensional electrodynamic problem is based on the following subset of Maxwell’s equations (1):

\[ \nabla \times \mathbf{H} = j, \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \quad \nabla \cdot \mathbf{B} = 0, \tag{1} \]

where \( j = j_s + \sigma \mathbf{E} \) is sum of applied source current density vector and induced current density vector, \( \mathbf{B} = \mu \mu_0 \mathbf{H} \) is magnetic flux density vector. In this formulation the magnetic permeability \( \mu \) is constant.

In the calculations, apart from the above volumes, the surrounding nonmagnetic space is considered as well. To take into account the saturation of ferromagnetic media, we calculate the dependence of the magnetic field \( \mathbf{B} \) on the current in the windings \( j_s \). In this case the mathematical model is based on the following subset of Maxwell’s equations (2):

\[ \nabla \times \mathbf{H} = j_s, \quad \nabla \cdot \mathbf{B} = 0, \tag{2} \]

where \( j_s \) is applied source current density vector, \( \mathbf{B} = \mu_H \mu_0 \mathbf{H} \) is magnetic flux density vector. In this formulation the magnetic permeability \( \mu_H \) is derived from the \( \mathbf{B} \) versus \( \mathbf{H} \) curve.

The problem is solved with the finite element package ”ANSYS” [10]. The model has been verified using data of our previous experiment with traveling magnetic field inductor [11]. In the model, the geometry of cells with non-ferrous metal is specified, their electrical conductivity is indicated, and the electromagnetic force acting on these cells is determined.

3. Experimental setup

Experimental setup (figure 1) was assembled to measure the magnitude of electromagnetic forces acting on a bimetallic plate placed above the traveling magnetic field inductor to verify the numerical model. The bimetallic plate simulates a two-phase electrically conductive medium (for example, partially crystallized liquid metal in a mold). The plate consists of copper and gallium layers brought into electrical contact by soldering with gallium in the contact area. Copper plate sizes are \( 298 \times 19 \times 76 \text{ mm}^3 \) and gallium plate sizes \( 302 \times 19 \times 76 \text{ mm}^3 \). Copper electric conductivity is \( 58.5 \cdot 10^6 \text{ S/m} \) and gallium conductivity is \( 7.1 \cdot 10^6 \text{ S/m} \) [12].

The plate is placed in the enclosure made of fiberglass with a thickness of 5 mm. The tightness of this enclosure is ensured by gluing with epoxy resin. To ensure the accuracy of the geometric sizes, the copper part of plate was milled. Then one of the copper plate’s narrow ends was tinned with molten gallium. The gallium plate was cast in the enclosure after installation of the copper plate. To reduce the influence of thermal deformations effects during the phase transition the gallium layer was filled in several stages in small portions. The next batch was poured only after the previous batch has been completely crystallized. In the course of crystallization the metal was also stirred to increase the homogeneity of the phase transition process.

The resulting bimetallic plate was suspended above the inductor of a linear induction machine (LIM) on inextensible metal threads. The dynamometer was mounted on an outer frame above the LIM. The distance from the LIM plane to the plate enclosure was 3.0 mm.
The planar dimensions of LIM are $480 \times 350$ mm$^2$. The magnetic field is created by six coils each with 170 turns of a copper bus. The coils are powered by a Pacific Smart Source 360 ASX-UPC3. This source allows to set the shape of the output signal, control the shifts between the phases of currents as well as modulate a magnetic field with a low frequency. The carrier frequency of the current source was 50 Hz and the supply current was 4.0 A. The power supply was controlled remotely from a PC using the IEEE-488 BUS interface.

The end face of the bimetallic plate is brought into mechanical contact with an electronic dynamometer as shown in figure 1. In the diagram shown in figure 1 the $d$ parameter displays the shift of the phase separation axis of the bimetallic plate relative to the LIM center. Two configurations of the plate orientation relative to LIM were considered. In the first case the sequence of metallic phases along the $OX$ axis (and, accordingly, along the direction of the traveling magnetic field) was Cu–Ga; offset $d = 0$ mm. In the second case, the plate was turned $180^\circ$, so that the sequence of metallic phases along the $OX$ axis was Ga–Cu; offset $d = 5$ mm. The appearance of displacement $d$ in the second case is due to the balancing of the plate on the suspension and the rigidity of the non-separable outer frame with attached elements of the measuring system.

4. Results

The dependencies of the $x$-component of the electromagnetic force value on the supply current of the LIM switched on in the traveling magnetic field mode with two orientations of the bimetallic plate relative to the LIM were obtained as a result of experiment measurements. The difference in electrical conductivity is characterized by the parameter $k = \sigma_{Me}/\sigma_{Ga}$, where $\sigma_{Ga}$ is electrical conductivity of pure gallium, $\sigma_{Me}$ is electrical conductivity of another metal and $k \sim 8$ was in experiment. The corresponding dependencies are shown in figure 3. The average error in determining the forces is $\Delta F_x(I)|_{Cu-Ga} = 4.2$ mN for configuration Cu–Ga and $\Delta F_x(I)|_{Ga-Cu} = 3.6$ mN for configuration Ga–Cu. Thus, the relative measurement error does not exceed 2%. Attention is drawn to the asymmetry of the electromagnetic force value, which also manifests itself in the calculations, and there this asymmetry was also confirmed by
Figure 3. Dependence of the planar component of the electromagnetic force on the LIM supply current in measuring configurations Ga–Cu and Cu–Ga (calculated and experimental data).

a change in the corresponding direction of the traveling wave propagation.

For the Cu–Ga configuration, the dependence of the electromagnetic force on the strength of the LIM supply current (in the traveling magnetic field mode) was obtained at various displacements \( d \) of the metal phase boundary relative to the LIM center. The corresponding dependencies are shown in figure 4 and in the normalized version in figure 5. Calculations and experiments demonstrate qualitative agreement – the maximum force is achieved at the central position of the interface, the force decreases with distance from the center. A small quantitative difference can be explained by the imperfect design of the inductor. When the electrical conductivity of the cells is equal, the force practically does not change. The normalized version of the dependencies allows us to reveal better the nature of the dependencies and confirms the asymmetry of the electromagnetic force from the order of the cells position. Figure 6 shows the dependence of the electromagnetic force on the position of the interface at a greater length relative to LIM, while the boundaries are fixed, which distinguishes these data from those obtained in the experiment (shown in figure 3–5). Both last figures (figure 5 and figure 6) show that the greatest change in the value of the electromagnetic force is achieved when the boundary moves near the area between the LIM windings, and the smallest in the area of the ferromagnetic tooth.
5. Conclusion
The study of the electromagnetic force acting on a medium with inhomogeneous electrical conductivity has been carried out. In our model the electrical conductivity changes abruptly, which simulates the liquid–solid interface during the crystallization of a pure metal. The electromagnetic force is created by a traveling field inductor with one of the most demanded in
metallurgy construction.

The results of calculations and experiments are in qualitative agreement and show a decrease in the electromagnetic force when the interface between the media moves relative to the LIM plane of symmetry, while the difference between the results does not exceed 12%. The results showed that the force changes significantly with a change in the position of the interface relative to the inductor coils.

The results of calculations and experiments showed the asymmetry of an inductor of this type: the force significantly depends on the order in which the plates with different electrical conductivity will be located.

On this basis the following general conclusion can be formed: in the mathematical modeling of the process of directional crystallization under the influence of an electromagnetic force created by an inductor of this type it is necessary during the movement of the interface either to do the calculation of the electrodynamic part of the problem anew or to use the method of canonical domains.

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