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MODEL AND OPTIMIZATION OF ELECTROMAGNETIC FILTRATION OF METALS

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Electromagnetic buoyancy force causes the movement of non-conducive particles in a conducting liquid under electromagnetic field. The phenomenon allows filtration of small inclusions from molten metals. This paper presents a mathematical model of the filtration process under alternating electromagnetic field and the methodology for maximizing its efficiency.

Key words: electromagnetic filtration, magnetohydrodynamics, electromagnetic buoyancy

INTRODUCTION

The impurities like non-metal inclusions in the metal alloys used in automotive, aerospace and electronic industries may be the source of such problems as cracks, lower strength or surface quality and non-uniformity of some properties [1,2].

Electromagnetic separation is a method of moving the non-conductive particles in a molten metal by using the indirect action of the Lorentz force on the liquid metal. This force causes the electromagnetic buoyancy which affects the particles.

The electromagnetic force that acts on the liquid metal may be induced by the following methods: forcing the flow of direct current with the use of electrodes in the static magnetic field, forcing the flow of alternating electromagnetic field with the use of electrodes, and the most frequent one, that is using a coil generating the alternating or travelling electromagnetic field, which is a non-contact method.

This phenomenon is utilised mostly to remove the non-metal inclusions from the liquid metal, and on a laboratory scale the effects seem to be quite satisfying in the process of purifying of aluminum [3,4], Al-Si alloys [5] and zinc [6] and also in casting of functionally graded composites, where the aim is the segregation of the reinforcement so as to obtain a smooth spatial change in their properties [10].

However, the industrial application of electromagnetic separation to filter the liquid metals has its drawbacks, and the main problem is obtaining sufficient densities of electromagnetic forces, especially in the middle part of the channel through which the liquid metal is flowing [6]. Partially the cause of these difficulties is using simplified (particularly in the case of hydrodynamic phenomena) models, which makes it difficult both to fully understand the phenomena occurring during such a process and to use them in order to make the filtration process more efficient.

This paper presents a more complete mathematical model of this process and provides information about the trajectories of the particles flowing through the filter. It also shows the ways to increase the efficiency of the process.

RESEARCH OBJECT

The research was conducted on the example of filtration process of Al_2O_3 particles suspended in pure aluminum. The liquid metal flowing through the cylindrical channel 0,07 m in diameter was under influence of

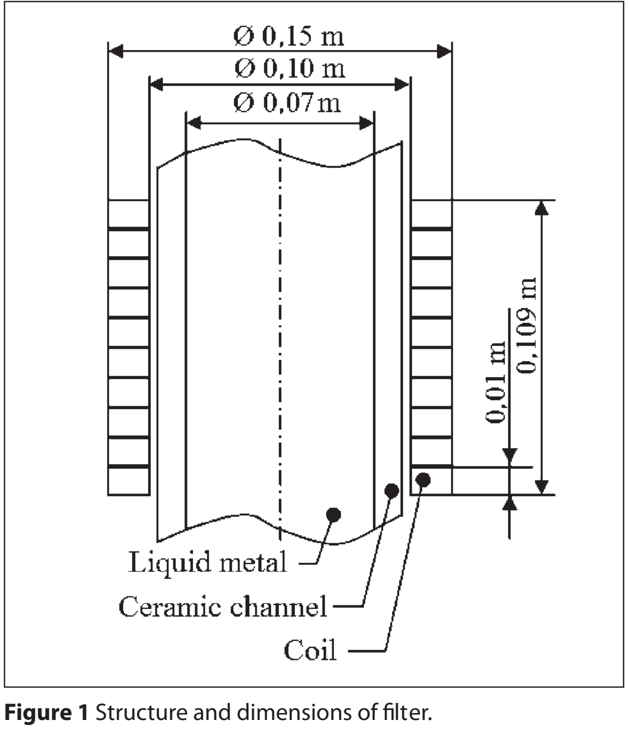

Figure 1 Structure and dimensions of filter.

S. Golak, R. Zagorski - Silesian University of Technology, Faculty of Materials Engineering and Metallurgy, Katowice, Poland alternating electromagnetic field produced by the coil wound around the channel (Figure 1). It was assumed that the flow speed, the frequency and the power of the current source can be controlled. Another assumption was the lack of slip of metal and particles on the channel wall.

MATHEMATICAL MODEL

The mathematical model of electromagnetic filter should take into account the coupling of the electromagnetic and flow fields. Since in the model situation the problem of free surface is non-existent [11] and because of low flow speeds, a weak one-way coupling of the fields was used. The knowledge of the fields distribution allowed determination of the trajectories of the particles suspended in the molten metal.

Electromagnetic field

The analysis of electromagnetic field was carried out based on Maxwell's equations and the generalized Ohm's law [12]. The calculations were simplified by the transition from time-domain analysis to the symbolic analysis. Electromagnetic field analysis was based on the expression using vector magnetic potential A (1) which is commonly used for steady-state electromagnetic problems [7,8,10-14].

$$\nabla\times\left(\frac{1}{\mu}\nabla\times \mathrm{A}\right)+\mathrm{j}\cdot\omega\cdot\sigma\cdot\mathrm{A}=\mathrm{J}_{\mathrm{s}} \tag{1}$$

where: μ, σ – magnetic permeability and conductivity of the matrix, ω – angular frequency, J_{s} – source current density.

In order to allow a one-way coupling of the electromagnetic model with the hydrodynamic model, the density of current caused by metal flow was not taken into account (because the magnetic Reynolds number for the problem is smaller then 10^{-1}).

Electromagnetic induction B and the eddy current density J were determined from equation (1) after taking into account the following dependences:

$$\mathrm{B}=\nabla\times\mathrm{A} \tag{2}$$

$$\mathrm{J}=-\mathrm{j}\cdot\omega\cdot\sigma\cdot\mathrm{A} \tag{3}$$

The above equations were solved by the finite element method in two-dimensional axisymmetric space. The volumetric density of the time-average electromagnetic force acting on the molten metal was determined from (4):

$$\mathrm{f}_{\mathrm{e}}=\frac{1}{2}\mathrm{Re}\,(\mathrm{J}\times\mathrm{B}^{*}) \tag{4}$$

where B^{*} is the complex conjugate of B.

Flow field

The analysis of electromagnetic field The flow is described by the Navier-Stokes and continuity equations:

$$\rho_f\left(\frac{\partial \mathrm{v}}{\partial t}+\mathrm{v}\cdot\nabla\mathrm{v}\right)=-\nabla p+\eta\cdot\nabla^2\mathrm{v}+\mathrm{f}_{\mathrm{e}}+\rho\mathrm{g} \tag{5}$$

$$\nabla\cdot\mathrm{v}=0 \tag{6}$$

where: v – velocity; η, ρ – dynamic viscosity and density of metal; p – pressure; g – gravitational acceleration.

The standard k-ε turbulence model was used. The flow equations were solved by the finite volume method.

Movement of particles

A reinforcement particle immersed in liquid metal in the electromagnetic field is affected by the resultant of the Stokes drag force F_{d}, gravitational force F_{g}, and electromagnetic buoyancy force F_{e}.

The Stokes drag force is equal:

$$\mathrm{F}_{\mathrm{d}}=3\cdot\pi\cdot\eta\cdot d\cdot(\mathrm{v}-\mathrm{v}_{\mathrm{p}}) \tag{7}$$

where: η – fluid dynamic viscosity, d – particle diameter, v – fluid velocity, v_{p} – particle velocity.

The action of gravity is the result of the difference between the densities of the metal ρ_m and the reinforcement particle ρ_p:

$$\mathrm{F}_{\mathrm{g}}=\pi\cdot d^3\mathrm{g}\,(\rho_p-\rho_m)/6 \tag{8}$$

Electromagnetic buoyancy force acting on a particle can be determined from the following dependence [9,10]:

$$\mathrm{F}_{\mathrm{e}}=-\pi\cdot d^3\mathrm{f}_{\mathrm{e}}/8 \tag{9}$$

The buoyancy force moves the particles opposite to the electromagnetic force acting on the metal, towards the channel wall.

The trajectory of the particle can be computed by integrating in time the force balance on the particle. It was assumed that if the particle reaches the wall it is stopped because of adhesion forces.

RESULTS

Structure of flow in the filter

From Figure 2a presenting the distribution of densities of electromagnetic forces acting on the liquid aluminium, there can be seen a strong non-uniformity of the distribution of its radial components on the length of the channel. This is a result of a short length of the inductor used, which caused significantly higher intensity of the electromagnetic field in the middle of the channel compared with its ends.

As a result of this non-uniformity there occur two toroidal vortexes bordering each other, and their border is located exactly in the middle of the inductor height (Figure 2b).

This disturbance of the flow, caused by the above-mentioned non-uniformity, solved the basic problem reported in the studies conducted so far on the electro-

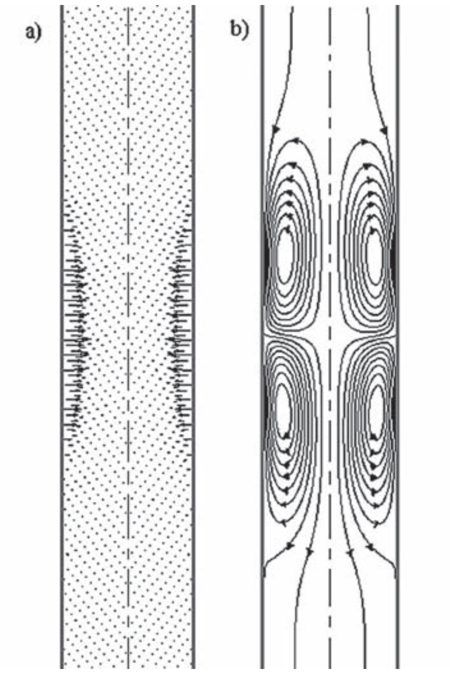

Figure 2 Distribution of densities of electromagnetic forces (a) and structure of liquid metal flows (b) in the middle part of the channel.

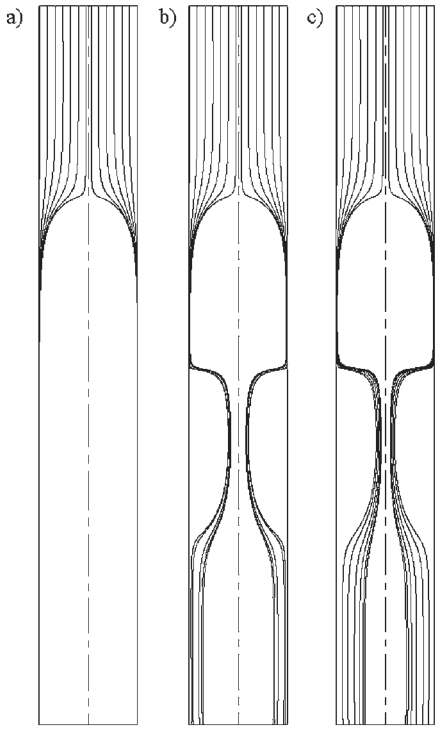

Figure 3 Trajectories of the particles flowing through the filter channel with diameters of: a – 30 µm, b – 20 µm, c – 10 µm.

magnetic filtration process with a uniform one-way flow along the channel axis. It was the fact that it was impossible to influence the particles in the middle of the channel. Owing to the first vortex these particles can be moved to the area of electromagnetic force action.

Figure 3 presents the trajectories of the particles suspended in liquid metal flowing at 0,02 m/s through the filter supplied by the current source of 1 000 Hz and 2 kW.

It can easily be seen that the particles were moved by the vortex toward the channel wall, which made it possible to trap the particles with diameters of 30 µm and larger.

The removal of the particles with smaller diameters (on which according to Formula (9) a weaker buoyancy force acts at the same density of electromagnetic forces) required an analysis of the influence of flow and the current source parameters, which, however, did not affect the structure of the metal flow and the filter operation.

The analysis of the influence of the filter operation parameters

The influence of the flow speed, the intensity and the frequency of current on the effectiveness of the filter was examined.

The effectiveness was determined from the following formula:

$$E = \frac{n_c}{n_i} \cdot 100\,\% \qquad (10)$$

where: n_c – number of particles trapped by filter, n_i – initial number of particles.

Figure 4 shows a significant influence of the metal flow speed through the filter on the effectiveness of filtration for different sizes of particles. At high speeds the filter is more efficient, but it can remove only big particles.

Figure 5 presents how the filter effectiveness depends on the particle diameters for various frequencies of the inductor. A relatively slight increase of the filter effectiveness at higher frequencies can be observed for the bigger particles (>15 µm). Since higher frequency causes lower flow speed [14] the particle remains longer in the area close to the wall, where it can be affected by the electromagnetic field.

Figure 6 shows the influence of the particles diameter on the effectiveness of filter operation for various levels of power of the current source. Each time the

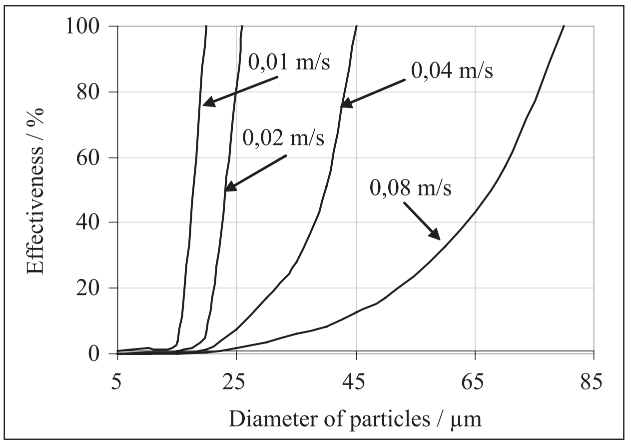

Figure 4 The dependence of the particles removal on their diameter for various flow speeds.

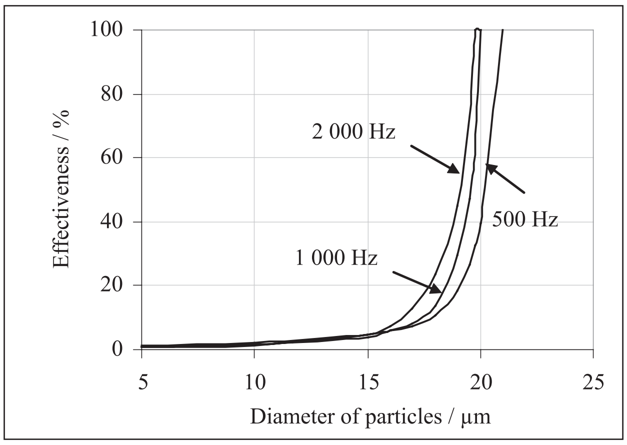

Figure 5 The dependence of the particles removal on their diameter for various frequencies of the current source.

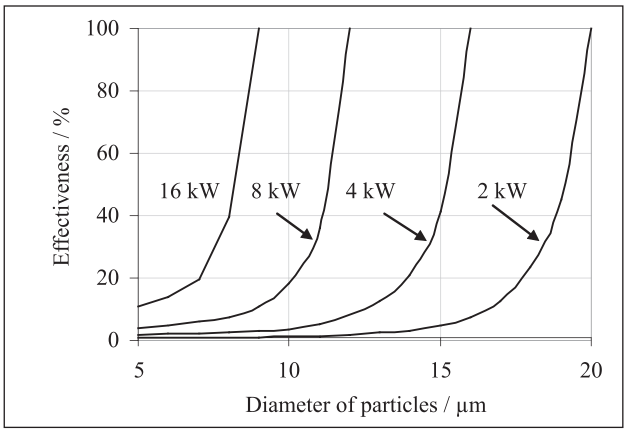

Figure 6 The dependence of the particles removal on their diameter for various powers of the current source.

power is doubled, the minimal diameter of the particles removed by the filter decreases by about 4 µm.

CONCLUSIONS

In the studies conducted so far it has been assumed that the flow of the liquid metal be parallel to the axis of the filter (in a case of long channel and coil). However, when a short inductor was used, the disturbance caused by non-uniformity of the densities of electromagnetic forces, manifesting itself as two toroidal vortexes, proved to be a surprising ally in the filtration process which allows the filtration of the particles in the middle of the channel. The analysis of the filter parameters indicated that its effectiveness increases slightly with the change of frequency and decreases significantly at higher flow speeds of the purified metal. The possibility of improving the effectiveness of particles removal through raising the inductor power, together with the limitation of the quantity of the metal filtered in a time unit, means growing costs of filtration. However, further multiple optimization of the power supply parameters, the flow speed and the geometry of both the channel and the inductor gives a chance to lower the costs considerably.

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Note: J. Piątek is responsible for English language, Katowice, Poland