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The influence of the supply parameters on the reinforcement distribution in a composite cast in the electromagnetic field

***Abstract**.. The basic problem in the process of graded composite casting is to obtain electromagnetic buoyancy that should move the particles, but at the same time to avoid stirring of the liquid metal caused by the field non-uniformity that thwarts the effect of reinforcement segregation. The research presented in the paper was focused on adjusting the supply current, its frequency and the dimensions of the inductor so that the liquid metal flow reduced.*

Streszczenie.** Podstawowym problemem utrudniającym proces odlewania kompozytu gradientowego jest uzyskanie działania wyporu elektromagnetycznego przemieszczającego cząstki, przy jednoczesnym uniknięciu, niweczącego efekt segregacji zbrojenia, mieszania ciekłego metalu spowodowanego niejednorodnością pola sił. Prezentowane badania dotyczyły doboru częstotliwości zasilania, natężenia prądu i rozmiarów wzbudnika w celu ograniczenia ruchu ciekłego metal. **(Wpływ parametrów zasilania na rozkład zbrojenia w kompozycie odlewanym w polu elektromagnetycznym.

Keywords: magnetohydrodynamics, functionally graded material, metal matrix composite, optimization
Słowa kluczowe: magnetohydrodynamika, materiały gradientowe, kompozyty metalowe, optymalizacja

Introduction

Functionally graded composites belong to the group of materials that have been developed extensively in many research centres around the world in the recent years. These composites yield the possibility of a smooth spatial change in the reinforcement distribution, which in turn allows to control the spatial distribution of some material properties (e.g. hardness); therefore both automotive and aerospace industries are greatly interested in them. Among many methods of manufacturing these materials that have been developed, there is one, relatively new, that offers interesting possibilities. It is casting the composite in the alternating electromagnetic field. The method utilises the electromagnetic buoyancy action on non-conductive particles of the reinforcement [1-3], and it may be used for popular composites with metal matrix (MMCs). The main problem with this technique is to obtain the desired direction of electromagnetic buoyancy that would move the particles, and simultaneously to minimise stirring the molten metal that hinders the expected segregation of the reinforcement. Since the cause of the flow of the liquid in the closed systems is a vorticity of the force field, the main way to minimise the stirring is to uniform the distribution of electrodynamic forces through special structure of the inductor and conductive elements of the mold [2]. Because in reality it is difficult to obtain a virtually uniform force field, some other mechanisms must be used that would hinder the flow of the matrix, first of all the effect of internal friction and inertial force. One of the ways to employ this mechanism is to control the supply current of the coil so that to use self-braking of the molten metal. This paper presents a magnetohydrodynamic model of the process of composite casting and the research methodology together with the analysis of the effect that the supply parameters have on the particles trajectories in the cast. The research was conducted on an aluminium cylindrical bush reinforced with SiC particles at the outer wall, but the conclusions may be generalised for the whole process of composite casting in alternating electromagnetic field.

Process principles

The concept of casting functionally graded composites in electromagnetic field is presented in Fig.1. The process starts with the preparation of a homogenous suspension of ceramic particles in the molten metal [4]. The suspension is poured into a non-conductive ceramic mold and exposed to the action of alternating electromagnetic field generated by a coil wound around the mold.

The interaction of the eddy currents $\boldsymbol{J}$ in the cast and the magnetic field $\boldsymbol{B}$ results in the occurrence of electromagnetic force compressing the metal towards the system axis (broad arrows). Its effect is the occurrence of electromagnetic buoyancy force (thin arrows) that moves the non-conductive ceramic particles of the reinforcement toward the outer wall.

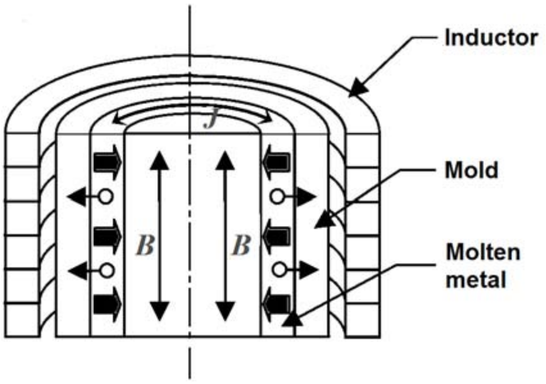

Fig. 1. Diagram of reinforcement segregation process

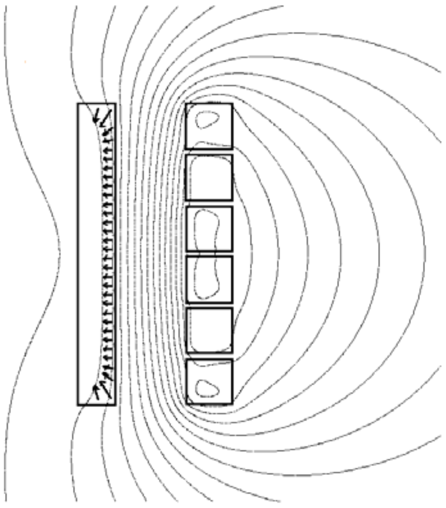

Fig. 2. Non-uniformity of electromagnetic field in a real cast

The electromagnetic buoyancy and electrodynamic forces presented in Fig.1 have only the radial component, and their value does not depend on the axial coordinate. Such situation can only occur in a theoretical case of an infinitely long inductor and charge.

In the case of real systems, at the ends of the charge occurs electromagnetic field deflection, which results in a non-uniform distribution of the force field (Fig. 2). In closed systems the vorticity of the field causes the flow of the molten metal which distorts the desired trajectories of the particles and destroys the expected spatial segregation of the reinforcement.

The way to make the casting system more similar to a theoretical system of infinite length is to lengthen the charge electromagnetically by the use of conductive elements of the mold whose conductivity is equal to the conductivity of the molten metal [2]. This solution yields the expected results, yet there arises a problem of the adequate material from which to make these elements, and some complications are also involved in the making the mold.

Another solution is to exploit internal friction and the inertial forces of the metal by means of intermittent action of electromagnetic field [5] or by controlling the supply current of the inductor, which is analysed in this paper.

Mathematical model of the process

The model of graded composite casting must allow for the coupling of electromagnetic field, molten metal flow field and reinforcement particles movement.

In order to use a weak one-way coupling between the electromagnetic model and the hydrodynamic model [6,7], and in this way to simplify the calculations, the following simplifications were assumed:

- Short time of the particle segregation process (it lasts for seconds) makes it possible to assume a constant temperature of the molten metal, which means its constant conductivity.
- Low magnetic Reynolds number (less than 10^{-2}) allows for disregard of the currents caused by the flow of the metal.
- Low concentrations of the reinforcement particles make it possible to ignore in the calculations its influence on the conductivity of the composite suspension and its effect on the molten metal momentum.

Owing to one-way coupling it was possible to carry out a sequence of independent calculations of the electromagnetic field, hydrodynamic field of the liquid metal and the trajectories of the particles.

The analysis of the electromagnetic field was based on Maxwell's equations completed with the generalized Ohm's law. The calculations were simplified by the transition from time domain analysis to symbolic analysis. The electromagnetic field analysis was based on the expression that makes use of magnetic vector potential $\boldsymbol{A}$ which is usually used in quasi-static electromagnetic problems[8-10].

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

where: μ, σ – magnetic permeability and conductivity of the matrix, ω – angular frequency, $\boldsymbol{J}_s$ – source current density.

Magnetic induction $\boldsymbol{B}$ and the eddy currents density $\boldsymbol{J}$ were determined from equation (1) after taking into account the following dependences:

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

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

The calculation of the magnetic induction and the eddy currents density from the above equations allows the determination of the distribution of time-averaged electromagnetic forces density $\boldsymbol{f}_e$ acting on the liquid metal:

$$\boldsymbol{f}_e=\frac{1}{2}\mathrm{Re}\left(\boldsymbol{J}\times\boldsymbol{B}^*\right) \tag{4}$$

where $\boldsymbol{B}^*$ – is the complex conjugate of $\boldsymbol{B}$.

In a closed system the condition that must be fulfilled for the molten metal to remain motionless is the absence of vortices in the electromagnetic field acting on it:

$$\nabla\times\boldsymbol{f}_e=0 \tag{5}$$

Since it is practically impossible to obtain a uniform distribution of electromagnetic forces in the case of finite length of the charge, the occurrence of the liquid metal flow is inevitable. It is described by Navier-Stockes equation and the continuity equation that takes the following form for incompressible liquid:

$$\rho_f\left(\frac{\partial\boldsymbol{v}}{\partial t}+\boldsymbol{v}\cdot\nabla\boldsymbol{v}\right)=-\nabla p+\mu_f\nabla^2\boldsymbol{v}+\boldsymbol{f}_e+\rho_f\boldsymbol{g} \tag{6}$$

$$\nabla\cdot\boldsymbol{v}=0 \tag{7}$$

where: $\boldsymbol{v}$ - velocity, μ_f – dynamic viscosity , ρ_f - density., $\boldsymbol{f}_e$ – electromagnetic force density, $\boldsymbol{g}$ – gravitational acceleration

The force that acts upon a reinforcement particle immersed a liquid matrix within the electromagnetic field is the resultant of gravitational force $\boldsymbol{F}_g$, Stokes drag force $\boldsymbol{F}_d$ and electrodynamic force $\boldsymbol{F}_e$.

The action of gravitation is the effect of the difference between the densities of the matrix and the reinforcement. For spherical particles it can be described by the following equation:

$$\boldsymbol{F}_g=\frac{\pi d_p^3\boldsymbol{g}\left(\rho_p-\rho_m\right)}{6} \tag{8}$$

Stokes drag force acting on a spherical particle for low Reynolds numbers is described by the equation:

$$\boldsymbol{F}_d=-3\pi\mu d_p\boldsymbol{v} \tag{9}$$

where: μ - dynamic viscosity, d_p – particle diameter, $\boldsymbol{v}$ – particle velocity relative to the fluid.

In the case of metal composites reinforced with ceramic particles, whose conductivity is so low compared with the matrix conductivity that it can be ignored, the electrodynamic force acting upon the particle can be determined from the following dependence [11]:

$$\boldsymbol{F}_e=-\frac{3}{4}\frac{\pi d_p^3}{6}\boldsymbol{f}_e \tag{10}$$

where: σ_f – liquid conductivity, d_p – particle diameter, $\boldsymbol{f}_e$ – volume density of electromagnetic force.

Knowing the forces and the particle mass, one can determine the particle trajectory through integration over time. It was assumed that after the particle reaches the outer wall it is stopped.

Optimisation

The basic condition for the molten metal to remain motionless is to ensure that the electromagnetic field acting on it is irrotational. The factors affecting the uniformity of the field are the geometry of the inductor and supply frequency, while the supply current determines only the values of these forces. For this reason it was possible to divide the optimisation process into two independent stages. The first stage involved the electromagnetic calculations and determining the optimal supply current frequency and dimensions of the inductor that would yield the greatest possible uniformity of the field. The minimisation criterion applied was the measure that expresses the ratio of the volume integral of the curl of the density forces field (according to the formula (5), a factor disturbing the process) to the volume integral of the electromagnetic force field component acting in the direction $\boldsymbol{n}$ that is opposite to the required direction of the particles movement. The value of this measure is independent of the value of the current supplied to the inductor.

$$T = \int_V \left|\nabla \times \boldsymbol{f_e}\right| dV \Big/ \int_V \left(\boldsymbol{f_e} \cdot \boldsymbol{n}\right) dV \tag{11}$$

The second stage of the optimisation process conducted for the geometry of the inductor and supply frequency determined in the first stage entailed the hydrodynamic calculations and aimed at an analysis of the influence of supply current on the particles trajectories. The change in the value of the current did not require the electromagnetic calculations to be repeated, but only simple rescaling the forces according to the formula below:

$$\boldsymbol{f_e^*} = \left(\frac{I^*}{I}\right)^2 \boldsymbol{f_e} \tag{12}$$

where: $\boldsymbol{f_e}$ – present force density value, $\boldsymbol{f_e}$* - original force density value, I* - present current, I – original current for which the original values were determined.

Experiment

The numerical experiment was carried out on an aluminium bush with a diameter of 65 mm and length of 65 mm, reinforced at the outer wall with SiC particles with a diameter of 50 μm.

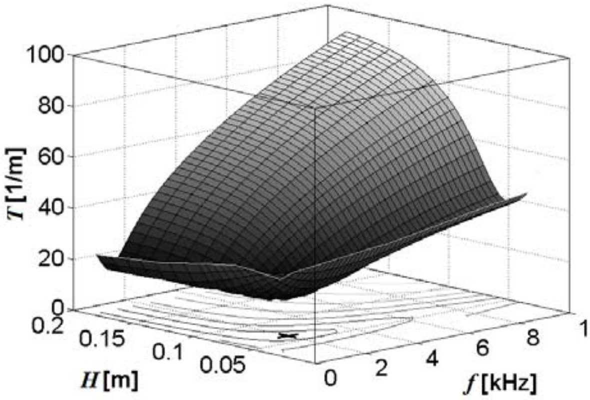

Fig. 3. The dependence of the field uniformity measure *T* on the height *H* and supply frequency *f*

The first stage of optimisation process was conducted for the supply current of 500 A. The influence of the inductor height and supply frequency were analysed. The lowest measure of the force field vorticity was obtained for the inductor whose height was equal to the height of the bush and for frequency of 2000 Hz (Fig. 3). The reason for a slight influence (as seen in the graph) of the inductor height on (for the optimal frequency) the measure *T* is the very mechanism of field disturbance that occurs at the interface between two media, one of high (aluminium) and the other of very low (air) conductivity. Deeper penetration of the field at the ends of the cast does not depend on the height of the inductor when the frequency of supply current is correctly adjusted.

In the second stage the influence of the supply current on the particles trajectory was analysed. Fig. 4 presents the change in the average velocity of metal over time for different supply currents. Velocity stabilizes in at the level which is approximately linearly dependent on the inductor current, which can be clearly seen in Fig. 5. It is quite interesting that according to formula (12) the electromagnetic forces are squarly dependent on the current. It is a consequence of the fact that inner friction forces within the metal grow squarly with velocity. The same linear dependence occurs in the case of maximum velocity. The flow structure presented in Fig. 6 changes subject to supply current. For values below 500A six separate vortices can be seen which then, with the increase of the current, join and make four paired vortices.

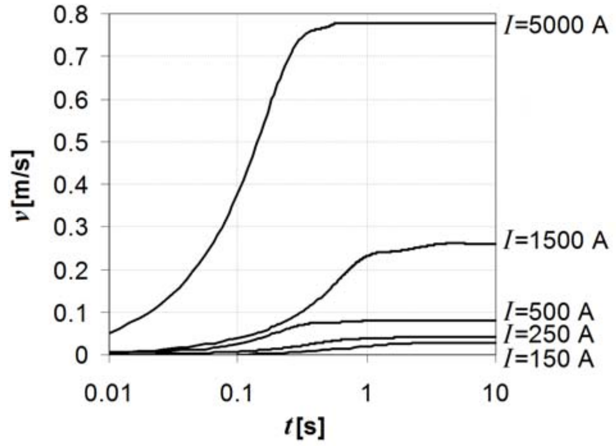

Fig.4. The dependence of the average velocity of metal *v* on time *t*

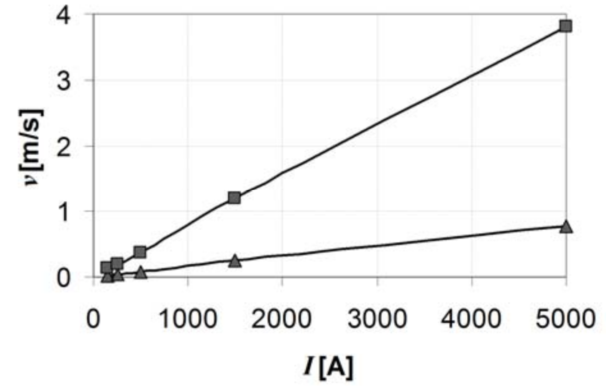

Fig. 5. The dependence of the average ▲ and maximum ■ velocity on the supply current value

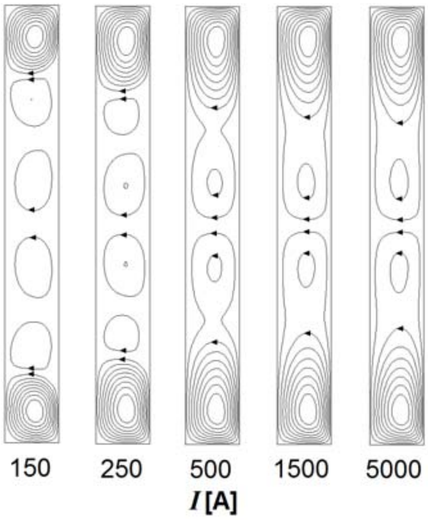

Fig. 6. Dependence of the flow structure on the supply current *I*

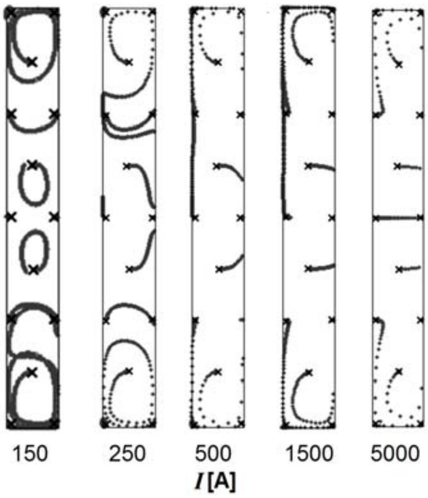

Fig. 7. Trajectories of particles-markers for different supply currents; x – starting point, ● – each 0.01 s (<500 A) or each 0.001 s (≥500 A)

As can be seen In Fig. 7, at 500 A the particles of 50μm reach the outer wall (the right side of cross-section) despite a significant disturbance of their trajectories. Moreover, the shape of the trajectory remains practically unchanged when the current is increased. It is only the particles velocity that grows. On the other hand, for low values of current it can be observed that some particles are trapped in the loops, which means that they will never reach the wall of the cast.

Conclusion

The possibility of avoiding conductive elements in the mold would significantly simplify the manufacturing process of functionally graded composites. The method of interrupted supply of the inductor proposed by Kanno [5] can be treated as a technique of decreasing the time-averaged current. However, the research proved that decreasing the current in a direct way has effects that are contrary to what is expected, increasing the disturbance of the particles trajectory, and at the same time preventing the particles from reaching the aimed position at the wall. An increase in current improves the situation to a certain extent, and at higher currents there is no change in the trajectory. This indicates that the process can be shortened in this way without any effect on the quality of segregation, which can be favourable for the obtained matrix microstructure and minimization of gravitational sedimentation of the reinforcement, which significantly differs from the matrix in density.

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