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COMPOSITES THEORY AND PRACTICE

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MODEL OF CASTING PROCESS OF COMPOSITES REINFORCED LOCALLY AT INNER WALL OF BUSH IN ELECTROMAGNETIC FIELD

The methods of manufacturing composites with spatial variation in the reinforcement distribution which exploit reinforcement segregation in the liquid matrix are among the most effective ones. However, methods based on density differences such as gravitational casting and centrifugal casting have their limitations in the range of reinforcement configurations that are possible to obtain. An alternative is to exploit the phenomenon of electromagnetic buoyancy occurring in situations where the particles and the matrix have different electric conductivities. This paper presents some possibilities of exploiting this phenomenon to obtain the local reinforcement of a bush made of aluminum alloy AK12 with SiC particles at its inner wall. The paper discusses the model of such a process and the effect of its parameters on the trajectories of the particles moving in the molten matrix.

Keywords: electromagnetic buoyancy, magnetohydrodynamics, functionally graded materials, metal matrix composites

MODEL PROCESU ODLEWANIA W POLU ELEKTROMAGNETYCZNYM KOMPOZYTÓW ZBROJONYCH STREFOWO PRZY WEWNĘTRZNEJ ŚCIANIE TULEI

Techniki wytwarzania kompozytów o przestrzennej zmianie rozkładu zbrojenia poprzez jego segregację w ciekłej osnowie są jednym z bardziej efektywnych sposobów otrzymywania tego rodzaju materiałów. Jednakże metody oparte o różnice gęstości materiałów, takie jak odlewanie z segregacją grawitacyjną lub odlewanie odśrodkowe, mają pewne ograniczenia w zakresie możliwych do uzyskania konfiguracji zbrojenia. Alternatywą jest wykorzystanie zjawiska wyporu elektromagnetycznego występującego w przypadku cząstek różniących się konduktywnością elektryczną od osnowy. Artykuł przedstawia modyfikację tej metody opartą o zastosowanie wzbudnika wewnętrznego, której celem jest uzyskanie strefowego zbrojenia cząstkami odlewu ścianie wewnętrznej. Badania prowadzono na przykładzie tulei ze stopu aluminium AK12 zbrojonej cząstkami SiC. W pracy omówiono model takiego procesu oraz wpływ jego parametrów na trajektorie ruch cząstek zbrojenia w ciekłej osnowie.

Słowa kluczowe: wypór elektromagnetyczny, magnetohydrodynamika, materiały gradientowe, kompozyty metalowe

INTRODUCTION

Metal matrix composites in which non-uniform distribution of the reinforcement is deliberately obtained have many applications in automotive, airspace and engineering industries. This is owing to the fact that the spatial distribution of properties such as hardness and thermal conductivity can be controlled in these materials. As a result, the obtained products are lighter, more durable and have better operational properties. Various methods of manufacturing metal matrix composites have been developed so far. However, it is believed that one of the most effective and cost-efficient methods is a casting technique in which various physical forces are used to move the reinforcement particles in a liquid matrix in the desired direction. The most popular techniques are those exploiting the density differences between the materials of the reinforcement and matrix, and first of all gravitational segregation and centrifugal casting [1-4]. When the density of the reinforcement particles is higher than that of the matrix, they move in the direction of the gravitational force or centrifugal force. In the opposite case, the particles are moved in the direction of the upward buoyancy force. With light metal matrix composites, which are the most popular, this latter situation is relatively rare, occurring for example, when graphite or glassy carbon particles are used as reinforcement [5, 6]. In popular technical solutions such as cylinders in car engines and compressors, plain bearings and tubes, a desirable feature would be to have a higher concentration of reinforcement at their inner surfaces, however, this is impossible to achieve by centrifugal casting for most of the combinations of matrix and reinforcement materials.

At the beginning of this century Xu [7] suggested that electromagnetic buoyancy should be used in the process of casting functionally graded composites. The method consisted in a forced current flow through a liquid cast under a static magnetic field. As a result of the Lorentz force (in the direction orthogonal to the direction of the current flow and induction) acting on the liquid metal matrix, an opposite electromagnetic buoyancy force occurred that acted on the non-conductive ceramic particles. This method, improved in subsequent studies [8-11], ensured a functionality that can be compared to that of the gravitational reinforcement segregation method. Here the density difference was replaced with the difference in the conductivity of the two materials.

Another interesting method of manufacturing functionally graded composites is the use of a rotating magnetic field [12,13]. However, this method uses angular acceleration and density difference to segregate the particles, therefore its range of functionality and limitations are similar to centrifugal casting.

Taniguchi with his team also based their method on the electromagnetic buoyancy [14]. However, they used a high frequency electromagnetic field generated by a cylindrical inductor wound around the mold. This allowed non-contact forcing of eddy currents to flow in the molten metal, whose interaction with the alternating electromagnetic field resulted in the Lorentz force squeezing the matrix towards the axis of the mold, and causing electromagnetic buoyancy that moved the particles toward the inner wall of the cast. This method yields a functionality to be compared with that obtained by the centrifugal methods for a composite in which the density of the reinforcement is higher than the density of the matrix. However, the high frequencies limited the thickness of the obtained reinforced layer to a few micrometers. It was caused by the small penetration depth of such a field. Decreasing the frequency, on the other hand, was not possible since it caused intensive stirring of the molten metal, which ruined the reinforcement segregation obtained before. The paper [15] presents a modification of this technique which allowed for a low-frequency field to be applied, which in turn resulted in the whole cast being affected by the field action, and in this way a thicker layer of higher concentration of the reinforcement was obtained at the outer wall. The solution presented below is based on the above-mentioned method. It employs an internal inductor, owing to which it is possible to obtain a reinforced zone at the inner walls of a cylindrical bush. This extends the range of functionally graded composites applications to products that have been difficult to obtain by the casting methods used so far.

PROBLEM DESCRIPTION

The concept of the solution is presented in Figure 1 on the example of the manufacturing process of a bush reinforced at the inner wall. The inductor placed in the interior channel of the mold generates an alternating electromagnetic field that induces eddy currents in the molten metal. The interaction between these currents ***J*** and the magnetic field ***B*** results in the Lorentz force acting towards the outer wall of the bush.

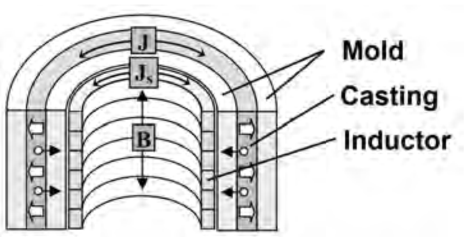

Fig. 1. Schematic diagram of process: **B** - induction, $\mathbf{J_s}$ - source current of inductor supply, **J** - eddy currents in casting, white arrows - Lorentz force, black arrows - electromagnetic buoyancy

Rys. 1. Schemat procesu: **B** - indukcja, $\mathbf{J_s}$ - prąd źródłowy wzbudnika, **J** - prądy wirowe w odlewie, białe strzałki - siła Lorentza, czarne strzałki - wypór elektromagnetyczny

Thanks to the buoyancy caused by the Lorentz force, the reinforcement particles are pushed toward the inner wall, and as a result, a reinforced layer forms at this very wall. In the diagram of the process, the direction of the electromagnetic forces has only one radial component, and its value is constant along the whole length of the bush. In such a case, Condition (1) that the liquid metal remains motionless would be fulfilled, which means that no vorticity occurs in the field of electromagnetic density forces

$$\nabla \times \boldsymbol{f_e} = 0 \tag{1}$$

Such a situation could be observed only in the theoretical case of an infinite cast, while in the real system with a cast of a finite length, a strong distortion of the electromagnetic field occurs at the ends of the cast (Fig. 2), which results in a non-uniform distribution of the electromagnetic forces.

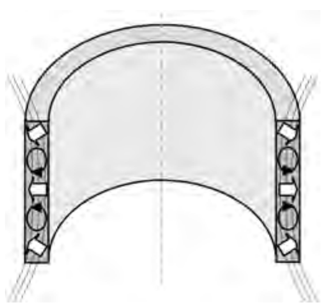

Fig. 2. Distortion of electromagnetic field in casting of finite length: thin lines - magnetic field lines, white arrows - Lorentz force, black arrows - flow of metal

Rys. 2. Zburzenie pola elektromagnetycznego w odlewie skończonej długości: cienkie linie - linie pola magnetycznego, białe strzałki - siła Lorentza, czarne strzałki - przepływ metalu

Apart from the undesirable direction of electromagnetic buoyancy acting on the reinforcement particles at the ends of the bush, the main problem is the vorticity of the force field, which is the reason why Condition (1) is not satisfied. As a result, a forced flow of the composite suspension occurs, significantly distorting the desired trajectory of the reinforcement particles, which makes it impossible to obtain the desired spatial distribution of the reinforcement concentration.

Paper [15] presents a solution to the problem. The idea is to make the cast more electromagnetically similar to a theoretical, infinitely long cast. It was done by introducing to the mold some conductive elements with conductivity similar to that of the liquid matrix but with a relatively higher melting point. In the case of aluminium alloy matrix casts, they may be made of cupronickel CuNi25 (75% Cu, 25% Ni). This material at the temperature of 500°C (assuming mold preheating) has an electrical resistivity conductivity equal to $3 \cdot 10^{-7}$ Ω·m (similar to that of the liquid alloy AK12). Its relative magnetic permeability is 1.

This solution makes it possible to move the field distortion away from the liquid metal. The same solution can also be used in the process of concentrating the reinforcement at the inner wall as described in this paper.

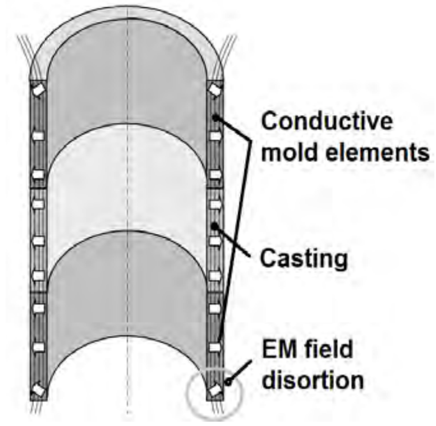

Fig. 3. Moving electromagnetic field distortion away from cast by conductive elements of mold. Non-conductive parts of mold are not shown

Rys. 3. Wyprowadzenie zaburzenia pola elektromagnetycznego z odlewy przez przewodzące elementy formy. Nieprzewodzące elementy formy zostały pominięte

MATHEMATICAL MODEL OF PROCESS

The mathematical model of the process encompasses the electromagnetic field, liquid metal flow field and reinforcement particles movement. The calculations were based on one-way coupling between the electromagnetic and hydrodynamic fields, frequently used in magnetohydrodynamic problems. It means that the distribution of the electromagnetic forces density field is determined for a given geometry of the metal and inductor and given supply parameters, and this distribution becomes the input data for the flow model. With this type of coupling, the flow field does not affect the electromagnetic field, which is true for low flow velocities occurring in the analysed process.

The analysis of the electromagnetic field was carried out based on Maxwell's equations supplemented by the generalized Ohm's law. It was based on the expression using vector magnetic potential $\boldsymbol{A}$:

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \boldsymbol{A} \right) + j\omega\sigma\boldsymbol{A} = \boldsymbol{J}_s \tag{2}$$

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

Electromagnetic induction $\boldsymbol{B}$ and eddy current density $\boldsymbol{J}$ were determined from Equation (2) after taking into account the following dependences:

$$\boldsymbol{B} = \nabla \times \boldsymbol{A} \tag{3}$$

$$\boldsymbol{J} = -\, j\omega\sigma\boldsymbol{A} \tag{4}$$

The above equations were solved in a two-dimensional axisymmetric space. The volumetric density of the time-average electromagnetic force acting on the molten metal was determined from:

$$\boldsymbol{f}_e = \frac{1}{2} \mathrm{Re}\left(\boldsymbol{J} \times \boldsymbol{B} \right) \tag{5}$$

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

The electromagnetic calculations based on the finite element method were done by the computer program Cedrat Flux2D.

The flow is described by the Navier-Stokes and continuity equations for incompressible fluid:

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

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

where: $\boldsymbol{v}$ - velocity; η, ρ - dynamic viscosity and density of the matrix; p - pressure; $\boldsymbol{g}$ - gravitational acceleration.

A reinforcement particle immersed in the molten metal in the electromagnetic field is affected by the resultant of the Stokes drag force $\boldsymbol{F}_d$, gravitational force $\boldsymbol{F}_g$, and electromagnetic force $\boldsymbol{F}_e$:

$$\boldsymbol{F}_p = \boldsymbol{F}_d + \boldsymbol{F}_g + \boldsymbol{F}_e \tag{8}$$

The Stokes drag force acting on a spherical particle of diameter d in a fluid of dynamic viscosity η for small Reynolds numbers is described by the following equation:

$$\boldsymbol{F}_d = 3\pi\eta d \left(\boldsymbol{v} - \boldsymbol{v}_p \right) \tag{9}$$

where: $\boldsymbol{v}$ - fluid velocity, $\boldsymbol{v}_p$ - particle velocity.

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

$$\boldsymbol{F}_g = \pi d^3 \boldsymbol{g} \left(\rho_p - \rho_m \right) / 6 \tag{10}$$

In the cases of metal matrix composites reinforced with ceramic particles, whose conductivity is negligibly small relative to the conductivity of the matrix, the electromagnetic force acting on a particle can be determined from the following dependence [16]:

$$\boldsymbol{F}_e = -\pi d^3 \boldsymbol{f}_e / 8 \tag{11}$$

The trajectory of a particle can be computed by integrating in time the force balance on the particle:

$$\frac{d\boldsymbol{v}_p}{dt} = \frac{1}{\rho_p}\left(\frac{18\eta(\boldsymbol{v}-\boldsymbol{v}_p)}{d^2} + \boldsymbol{g}(\rho_p - \rho_m) - \frac{3}{4}\boldsymbol{f}_e\right) \tag{12}$$

Calculations of the flow fields and the particles trajectories were done by the commercial software application Ansys Fluent.

SIMULATION RESULTS

Numerical simulations were conducted on the example of a bush made of aluminum alloy AK12 with an outer diameter of 100 mm, length of 100 mm and wall thickness of 8 mm, reinforced at the inner wall with SiC particles. The primary reason for this choice of popular combination of components was their similar density, which helped reduce the impact of gravitational sedimentation on the results and facilitated their analysis. A 62 mm inductor in the outer diameter was supplied with a frequency of 1000 Hz that ensured penetration depth of the electromagnetic field close to the thickness of the cast wall. Earlier studies [17] showed that segregation effectiveness increases with an increased current but only at low intensities. In the case of higher intensities it does not change. Higher values of current reduce the adverse effect of gravitational sedimentation of the reinforcement. For this reason, a relatively high value of supply current was chosen for the inductor at the initial casting setup, that is 1 kA. For comparison purposes, in different configurations the current was changed to ensure a constant average radial force acting on the casting.

The influence of height of inductor and conductive elements on field uniformity

The addition of the conductive elements to the mold makes the cast more similar to the theoretical case where the electromagnetic field acting on the molten metal is ideally uniform. It is then logical that the greater height of the conductive elements, the less stirring of the molten metal occurs. Certainly, it was necessary to assess the exact height that was sufficient in this case. To achieve this, how the height of the conductive elements together with the height of the inductor affect the uniformity of the field was examined.

$$T = \int_V |\nabla \times \boldsymbol{f}_e| dV / \int_V (\boldsymbol{f}_e \cdot \boldsymbol{n}) dV \tag{13}$$

Optimization of the parameters was carried out based on Criterion (13) that expresses the ratio of the total curl of the electromagnetic force field (expressing, according to Condition (1), the degree of molten metal instability) to the total force acting in desired direction $\boldsymbol{n}$. The minimisation of this value brings us closer to the ideal solution, in which the electromagnetic forces cause a pressure gradient in the metal but do not set it in motion. This measure allows the optimisation of the casting system to be carried out without time-consuming hydrodynamic calculations.

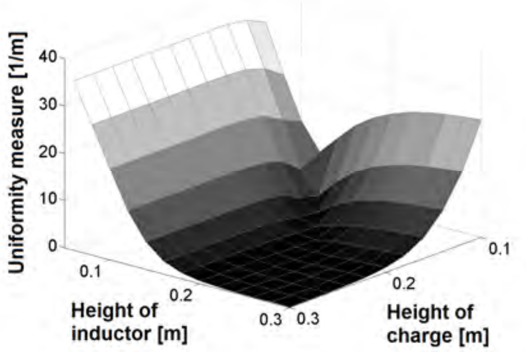

Fig. 4. Dependence of field uniformity measure on height of inductor and the height of charge

Rys. 4. Zależność miary jednorodności pola od wysokości wzbudnika i wsadu

Figure 4 presents the dependence of the measure of field uniformity on the height of the inductor and the height of the charge, which is the height of the cast and the conductive elements of the mold added together. The clear valley on the measure surface indicates that the basic condition to be satisfied in order to obtain a uniform field distribution is that the height of the inductor should be equal to the height of the charge. After analysing the diagram, it can be noticed that the initial fast rate of improvement in the field uniformity decreases with greater heights of charge and inductor, which proves that starting from the height of 0.3 m, their further elongation is pointless, especially since it would cause an increase in power unnecessarily consumed by the inductor in order to maintain a constant average value of electromagnetic force acting on the metal in a radial direction.

The influence of inductor and charge heights on particles trajectories

Determination of the particles trajectories requires long hydrodynamic calculations to be carried out for each individual configuration of the casting system. For this reason, on the basis of the results obtained in the above point, further analysis was limited to the configuration where the height of the inductor was equal to the height of the charge. Simulations were carried out for the configuration without the conductive elements added, for the configuration with the conductive elements at a height equal to half the height of the cast, and for a system with the conductive elements at the same height as the cast.

After the electromagnetic force acting on the non-conductive particle is equated to the Stokes resistance force, it is possible to determine the maximum speed that a particle reaches for a particular density of electromagnetic force acting on the molten metal

$$\boldsymbol{v}_p = -d^2 \boldsymbol{f}_e \eta^{-1} / \mathbf{24} \quad (14)$$

Dependence (14) shows that the particle velocity is quadratically dependent on its diameter, which means that the impact of the electromagnetic field on the smaller particle sizes is smaller even though the intensity of its action on the molten metal motion remains the same. This indicates that the particles separation effectiveness decreases significantly with their size, which is why separate simulations were performed for the three different diameters of reinforcement particles – 25, 50 and 100 μm.

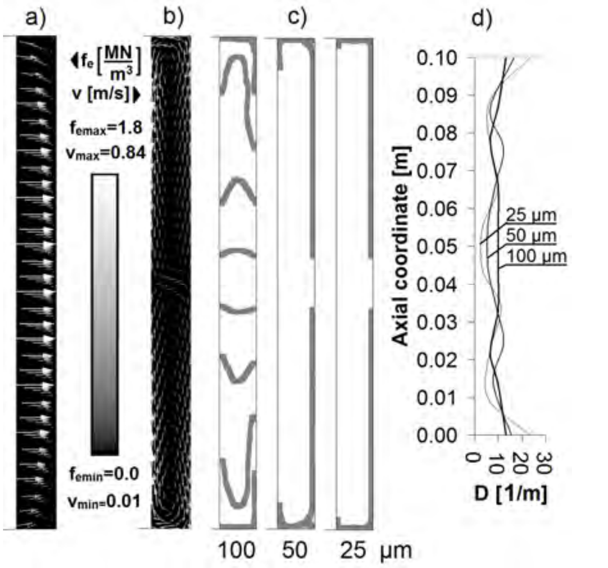

Fig. 5. Casting system without conductive elements: a) distribution of electromagnetic force field, b) structure of matrix flow, c) trajectories of representative particles, d) linear reinforcement distribution on inner wall

Rys. 5. Układ odlewniczy bez elementów przewodzących: a) rozkład pola sił elektromagnetycznych, b) struktura przepływów osnowy, c) trajektorie reprezentatywnych cząstek, d) liniowy rozkład zbrojenia przy wewnętrznej ścianie

Figure 5 presents the results of the simulation performed for the system without the conductive elements. The analysis concerned the trajectory of the representative particles initially located at the outer wall of the cast, i.e. those that had to travel the longest distance. It can be seen that because of the intense flow of the liquid metal (Fig. 5b) caused by the non-uniform force field (Fig. 5a), the trajectories of the particles of all the sizes analysed here were distorted so strongly (Fig. 5c) that it was impossible to obtain a uniform reinforced layer at the inner wall. In fact, only the particles with a diameter of 100 μm reach the inner wall after 0.15 s, the others are pushed by the flow and buoyancy toward the ends of the cast.

Figure 5d shows the distribution of reinforcement on the inner wall of the bush. Since the used model of process does not take into account the interactions between the particles and solidification (all particles reach the wall), it is not possible to estimate the final spatial distribution of the particles in the casting. Instead, a measurement expressing the linear distribution of the reinforcement on the inner wall was proposed:

$$D(z) = \frac{dV}{dz}\frac{1}{V_t} \quad (15)$$

where: z - the axial coordinate, dV/dz - reinforcement volume per unit length of the inner wall, V_t - total volume of reinforcement.

This measure does not depend on the concentration of reinforcement and can be only used for a low concentration of reinforcement.

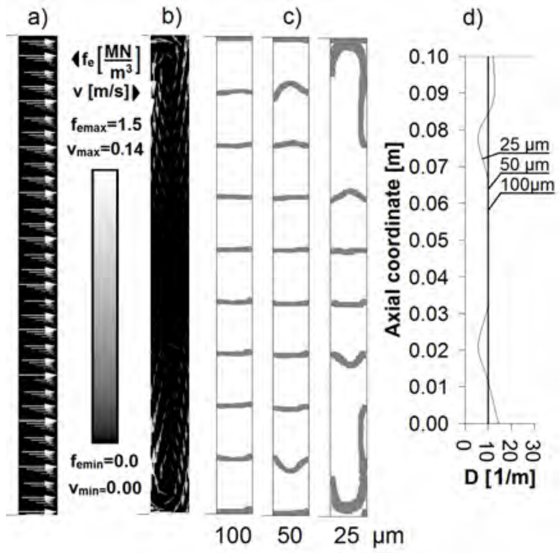

Fig. 6. Casting system with conductive elements of height equal to half height of cast: a) distribution of electromagnetic force field, b) structure of matrix flow, c) trajectories of representative particles, d) linear reinforcement distribution on inner wall

Rys. 6. Układ odlewniczy z elementami przewodzącymi o połowie wysokości odlewu: a) rozkład pola sił elektromagnetycznych, b) struktura przepływów osnowy, c) trajektorie reprezentatywnych cząstek, d) liniowy rozkład zbrojenia przy wewnętrznej ścianie

Figure 6 presents the results for the casting arrangement with the conductive elements added to the mold, their height being equal to half the height of the cast. The particles with diameters of 100 and 50 μm reach the inner wall almost unhindered after 0.12 and 0.34 s, respectively. In the case of the particles with a diameter of 25 μm, a significant distortion of their trajectories can be observed. This is caused by the fact that, in contrast to the bigger particles, they do not reach their destination point before the liquid metal starts to flow due to field non-uniformity.

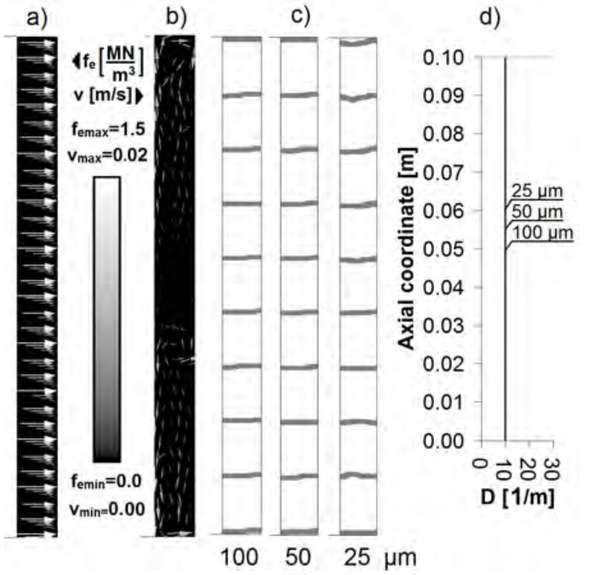

Fig. 7. Casting system with conductive elements of height equal to height of cast: a) distribution of electromagnetic force field, b) structure of matrix flow, c) trajectories of representative particles, d) linear reinforcement distribution on inner wall

Rys. 7. Układ odlewniczy z elementami przewodzącymi wysokości odlewu: a) rozkład pola sił elektromagnetycznych, b) struktura przepływów osnowy, c) trajektorie reprezentatywnych cząstek, d) liniowy rozkład zbrojenia przy wewnętrznej ściane

TABLE 1. **Electromagnetic comparison of casting setups**
TABELA 1. **Porównanie układów odlewniczych pod względem elektromagnetycznym**

Casting system	No cond. elements	Cond. el. $H = 0.5{\cdot}H_{ind}$	Cond. el. $H = H_{ind}$
Current [kA]	1.0	1.8	2.7
Flux density in casting [mT]	174	159	158
Supply power [kW]	16.6	26.9	40.1
Power loss [%]	41.4	66.4	77.1
Average radial force per power [N/W]	38.2	23.6	15.8

The results for the elements of the height equal to the height of the cast are presented in Figure 7. The weak, irregular flow (Fig. 7b) does not disturb the particles motion. Moving the non-uniformity of the field far away from the casting caused all the particles to reach the inner wall (after 0.11, 0.33 and 1.77 s) almost undisturbed by the matrix flow. This results in uniform distribution of all the sizes of reinforcement (Fig. 7d).

Table 1 shows that the homogenization of the electromagnetic force field is realized at the expense of a higher power loss (mainly in the conductive elements of the mold).

CONCLUSION

The presented model of the process and the simulations based on it confirmed that it is possible to obtain local reinforcement at the inner wall of a cylindrical bush by exposure of the metal poured into the mold to the action of an alternating electromagnetic field generated by an internal inductor. This solution is an interesting alternative to other production methods of locally reinforced metal matrix composites. The analysis proved that the size of the inductor and the conductive elements of the mold should be selected depending on the size of the reinforcement particles. Contrary to earlier studies concerning a bush of similar dimensions reinforced at the outer wall, in which for smaller particles a special inductor with a variable coil diameter was needed to additionally uniform the distribution of the electromagnetic force field, in the case of inner wall reinforcement, a regular inductor proved to be sufficient also for small particle sizes.

The use of special inductors cannot replace the use of conductive elements of a mold moving a field distortion away from the liquid metal. Therefore, the presented solution can be used only for castings whose geometry allows one to electromagnetically extend their inner channels by such elements.

Acknowledgements

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