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Creating Local Reinforcement of a Channel in a Composite Casting Using Electromagnetic Separation

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This article presents a new method to obtain local reinforcement in near-surface layers of channels in castings made of a particle-reinforced metal matrix composite in the alternating electromagnetic field generated by an inductor placed inside the channel. In centrifugal casting, the centrifugal force on the particles leads to the formation of composite structures, while in the proposed method, the electromagnetic force field on the particles results in the designed structure of the composite casting. The article reports the experimental verification of this method using an aluminium sleeve reinforced locally with SiC particles at the inner wall.

1. Introduction

The current development of functionally graded materials results from the ability to better adapt their properties. Materials with a widespread application include metal composites reinforced with particles or performs[1–3]. Products are metal castings of pistons and cylinders for engines and compressors, pumps, bearing elements, or even rocket engine nozzles.

Various methods of manufacturing functionally graded metal matrix composites reinforced with particles have been developed so far[4,5]. However, the most effective methods are casting techniques, in which different physical forces are used to move the reinforcement particles in a liquid matrix in the desired direction[6,7]. A popular casting method, which can obtain such an effect, is centrifugal casting[8–10]. A different density between the matrix and reinforcement materials exists in this method. Centrifugal force in heavier particles or buoyancy force in lighter particles makes it possible to obtain a radial gradient of reinforcement fraction in the casting. Centrifugal casting works quite well in casting reinforced with particles at the outer wall (e.g., pistons, shafts) because most of materials used as reinforcement have a higher density than the usually light matrix metal and they are pushed by centrifugal force towards the outer wall of the casting. If it is necessary to create local reinforcement on the inner channel wall in the casting, e.g. engine or compressor cylinder, the number of available materials narrows significantly to materials with the density less than that of the matrix, since in the place of centrifugal force, it is necessary to use the centrifugal buoyancy force, which moves the particles towards the axis of the casting[11,12].

Additionally, in centrifugal casting, it is possible to reinforce only one channel located around the mould rotation axis, which physically excludes, for example, casting an entire block of an engine or a compressor, where the surfaces of all cylinders would have been locally reinforced (Fig. 1). Even in a single channel casting with a high degree of asymmetry, the imbalance of the rotating masses may prevent the use of centrifugal casting.

If the electric conductivity of the reinforcement particles is significantly lower than that of the matrix in the vast majority of metal composites, electromagnetic buoyancy force[13] can be used to achieve particle separation.

Previous studies in this area used the static magnetic field and the flow of direct current through liquid metal forced through a pair of electrodes. This solution made it possible to obtain a linear gradient of reinforcement, analogous to casting graded composites using gravitational sedimentation[14,15].

The use of an alternating electromagnetic field makes it possible to achieve a radial gradient of reinforcement, which has a wider application than a linear gradient in such products as those mentioned earlier. Previous solutions used an inductor wrapped around a mould[16–19], achieving an increased concentration of reinforcement at the outer wall of the casting, which is the functional

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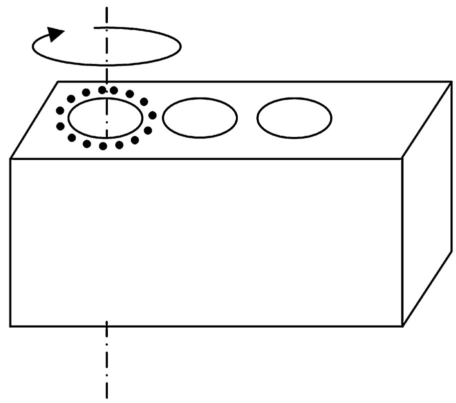

Fig. 1. Diagram of casting with asymmetry multiple channels.

equivalent of a standard centrifugal casting of composite with reinforcement material with the density greater than that of the matrix.

The article presents the use of an alternating electromagnetic field to obtain the local reinforcement of near-surface layers of channels in composite castings. The article describes the theoretical basis of the process of separating reinforcement particles using an inductor placed inside the channel, the methodology to obtain a uniform distribution of forces acting on the composite suspension to avoid its mixing, and experimental verification of this method using the example of a sleeve made of $AlSi_{12}CuMg$ alloy reinforced with SiC particles by the inner wall.

2. Theory of the Process

The concept of the separation of reinforcement in the liquid matrix is shown in Fig. 2. Previously prepared composite suspension is poured into a non-conductive, ceramic mould having the shape of the casting and subjected to an alternating electromagnetic field generated by a cylindrical inductor placed inside the casting channel. It is necessary to use a mould made of non-conductive material, because a metal mould would act as a screen for the electromagnetic field generated by the inductor, blocking its effect on the composite suspension.

Alternating electromagnetic field induces eddy currents $\boldsymbol{J}$ in the casting, whose interaction with the magnetic induction of field $\boldsymbol{B}$ gives rise to the electromagnetic force ($\boldsymbol{f}_e$), whose constant component acts on the liquid matrix in the direction towards the outer wall of the casting (white arrows in Fig. 2).

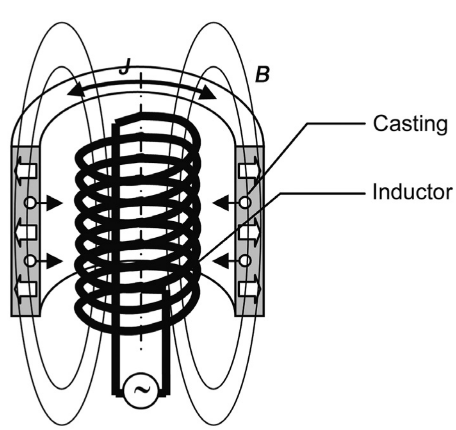

Fig. 2. Diagram of the electromagnetic separation process with an internal inductor.

$$\boldsymbol{f}_e = \boldsymbol{J} \times \boldsymbol{B} \quad (1)$$

As a result of the action of the electromagnetic force on the conductive matrix, the reinforcement particles are moved in the opposite direction by the action of the electromagnetic buoyancy force (black arrows in Fig. 2) described by the equation[13]:

$$F_e = -\frac{3}{2}\frac{\sigma_l - \sigma_p}{2\sigma_l + \sigma_p}\frac{\pi d_p^3}{6} f_e \quad (2)$$

where σ_l is electrical conductivity of the liquid matrix, σ_p is electrical conductivity of the particle, and d_p particle diameter.

Unfortunately, the situation shown in Fig. 2 is not entirely true. In the diagram, the electromagnetic force only has a radial component, and its value is uniform over the length of the casting. In reality, the presence on the ends of the casting of the boundary between the area of the molten conductive metal and the area of the ceramic, non-conductive mould, causes the formation of heterogeneity of the electromagnetic field, and thus heterogeneous distribution of the electromagnetic forces act on the liquid metal. This causes two adverse effects (Fig. 3):

(1) In this area, the particles are displaced not only in the direction of the inner wall, but also towards the ends of the casting,
(2) Heterogeneity of the force field acting on the liquid metal causes its mixing, which destroys the separation of reinforcement obtained by the action of electromagnetic buoyancy.

In Reference [20], a solution of this problem was proposed through the use of conductive elements of the mould, which by extending the casting in the electromagnetic sense causes a disturbance of the force field beyond the area of the liquid casting (Fig. 4). As a result, the electromagnetic force in the area of the casting only has a radial component, and does not cause stirring of the liquid metal.

For the conductive elements of the mould, precise selection of material is necessary to obtain a uniformly distributed electromagnetic field and prevent the composite suspension stirring. Due to too high electrical conductivity of these elements, flow of liquid metal appears again but its direction is opposite to that in the mould without the conductive elements (Fig. 5).

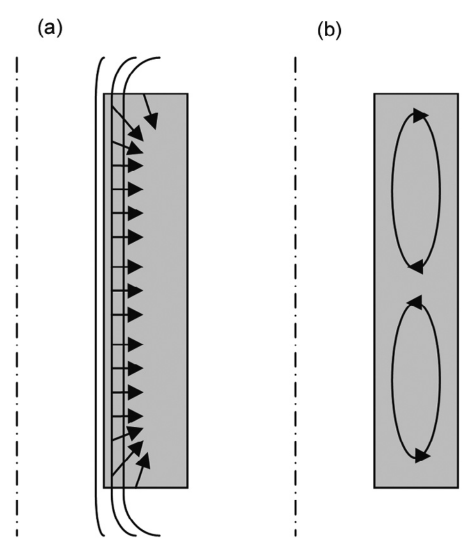

Fig. 3. Heterogeneity of the electromagnetic force field (a) and the flow of composite suspension (b) in a standard, non-conductive mould.