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Research Article

Manufacture of Locally Reinforced Composite Discs by Casting in the Alternating Electromagnetic Field

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The paper discusses a new method of obtaining local particle reinforcement in the composite discs. In this method, the liquid composite suspension is poured into a mould and then exposed to the alternating electromagnetic field. The Lorentz force acting on the liquid metal causes the reinforcement to move towards one or both surfaces of the manufactured disc. The paper presents the process theory, the methodology for the casting system design, and the results of an experimental manufacture of one-side and two-side reinforced composite discs made of aluminium alloy.

1. Introduction

Composites are materials consisting of at least two different phases, which makes it possible to adjust their properties to particular applications through a suitable selection of parameters of the composite components. This quality has resulted in the widespread popularity of these materials and a wide range of their applications. Currently, the scientists specializing in composite materials are focusing with great interest on composites designed so as to have a heterogeneous structure and nonuniform distribution of properties, such as gradient composites [1–3] and locally reinforced composites [4], which allow even better adjustment of the material properties to the working conditions of the product manufactured from that material.

Considering the types of the matrix materials, three main groups of composites can be identified. They are polymer, ceramic, and metal composites. For both the first [5, 6] and the second groups [7, 8], numerous and often quite similar methods have already been developed to obtain the required spatial change in their structure and properties.

The focus of this study is the third group mentioned above, that is, metal matrix composites [9, 10]. For this type of materials, the available techniques of manufacturing products with variable spatial distribution of properties include, beside the relatively complex multistage methods of powder metallurgy [11, 12] and preform infiltration [3, 4], the casting methods where the migration of reinforcement particles in a molten matrix is obtained as a result of various physical forces such as the gravitational force [13] and the centrifugal force [14]. The nonuniform distribution of the reinforcement obtained through particles separation yields the required spatial change of the cast properties.

The subject of this study is a casting method based on the electromagnetic separation, which affects the particles suspended in a conductive matrix placed in the electromagnetic field. This phenomenon has already been used in the method for casting locally reinforced composites under the static magnetic field and the flow of a direct current [15–18]. This technique ensures one-directional change of the reinforcement fraction in composite casts. However, the necessity to ensure a uniform distribution of the electromagnetic field and current density field within the cast area limits the scope of its applications to the casts of the shape close to a cuboid.

Another method based on the electromagnetic separation of the reinforcement is casting under the alternating electromagnetic field. Most studies refer to casts made in the shape of a cylinder reinforced locally at the outer wall [19–21]. Higher frequencies of the electromagnetic field applied in these studies resulted in the reinforced layers not exceeding 1 mm.

The scientists at the Silesian University of Technology have developed a methodology for casting system design

which uses a low frequency field to obtain thicker reinforcement layers and a wider range of cast geometries. The studies so far have discussed the manufacture of a composite sleeve reinforced at both the inner [22, 23] and the outer walls [24, 25].

This paper presents the process of making the casts of a completely different shape, that is, locally reinforced discs. Thanks to the properties of the alternating electromagnetic field, with this method it is possible to manufacture not only discs reinforced on one side, but also discs reinforced on both sides, which is impossible using other methods of suspension casting. A potential widely used application of this technology is the manufacture of brake discs from light alloys.

The paper discusses the process theory, the design methodology of the casting system, and the results of an experimental manufacture of two types of a locally reinforced composite disc.

2. Process Theory

The process theory will be explained based on the manufacture of a one-side reinforced disc. Figure 1 presents a diagram of this process. The suspension, previously prepared using the mechanical stirring method [26], is poured into a mould cavity in the shape of a disc. Next a flat spiral inductor powered by alternating current generates the alternating electromagnetic field. Owing to the use of a nonconducting ceramic mould, the field affects the cast and induces eddy currents around the axis of the system. Their interaction with the magnetic field produces the Lorentz force density field acting on the liquid conducting matrix:

$$\underline{\mathbf{f}}_{\mathrm{L}} = \underline{\mathbf{J}} \times \underline{\mathbf{B}}, \tag{1}$$

where $\underline{\mathbf{J}}$ is current density versor and $\underline{\mathbf{B}}$ is magnetic induction versor.

The process of electromagnetic separation uses the constant component of the Lorentz force, which is directed along the axis of the disc, from the inductor towards the opposite surface of the disc:

$$\mathbf{f}_{\mathrm{Lc}} = \frac{1}{2}\mathrm{Re}\left(\underline{\mathbf{J}} \times \underline{\mathbf{B}}^{*}\right), \tag{2}$$

where $\underline{\mathbf{B}}^{*}$ is the complex conjugate of induction $\underline{\mathbf{B}}$.

As a result of the action of the Lorentz force, a pressure gradient is created in the matrix which, analogously to the hydrostatic pressure gradient caused by gravity, produces the electromagnetic buoyancy force which moves the particles in the direction opposite to the direction of this force. The value of the force acting on the particles was determined in the study [27]:

$$\mathbf{F}_{B} = -\frac{3}{2}\frac{\sigma_m - \sigma_p}{2\sigma_m + \sigma_p}\frac{\pi d_p^3}{6}\mathbf{f}_{\mathrm{Lc}}, \tag{3}$$

where σ_m is electrical conductivity of the matrix and σ_p is electrical conductivity of the particle.

A condition necessary to distribute the reinforcement as evenly as possible at one of the disc walls is to ensure one-directional, uniform action of the Lorentz force on the matrix. Any instances of nonuniformity of this force field will result not only in the change in the direction of the particles migration, but also in unnecessary stirring of the composite suspension which disturbs the desired distribution of the reinforcement in the cast.

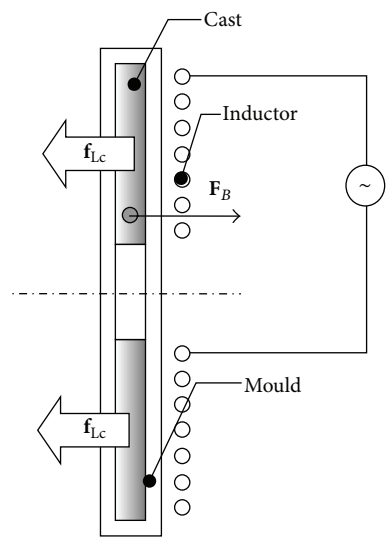

Figure 1: Diagram of the electromagnetic separation process in a one-side reinforced disc.

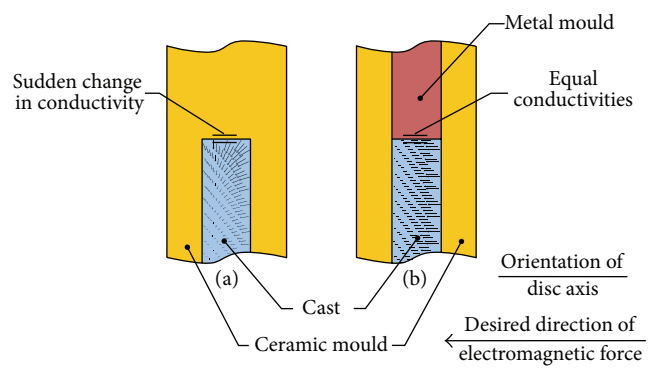

Figure 2: Zone of the disc edge: (a) standard mould, (b) mould with metal elements ensuring a uniform distribution of the field.

The principal cause of field nonuniformity at the outer and inner walls of the sleeve is the sudden change in conductivity between the area of the liquid cast and the ceramic mould (Figure 2(a)).

Due to deeper penetration of the electromagnetic field in this zone, a nonuniform electromagnetic force field is generated. Directions of the forces differ significantly from the desired direction along the axis of the disc.

A solution to this problem, as suggested in the study [24], is the electromagnetic expansion of the cast area by means of the metal elements of the mould with electrical conductivity equal to the conductivity of the liquid composite suspension (Figure 2(b)). This moves the field disturbance, caused by the change in electrical conductivity, beyond the cast area.

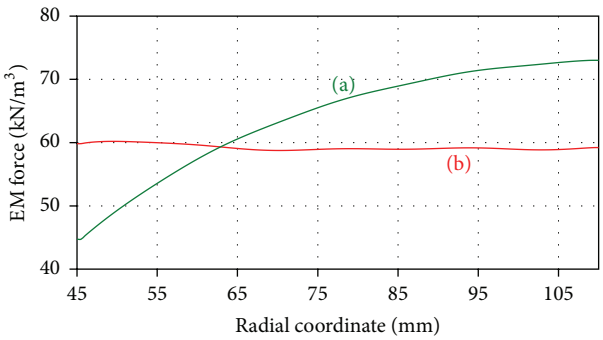

Figure 3: Distribution of the radial component of the Lorentz force at the wall on the inductor side: (a) standard inductor and (b) inductor with optimised geometry.

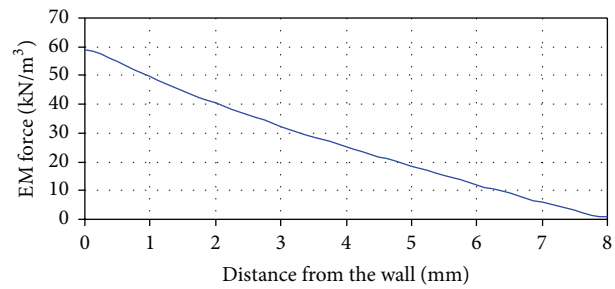

Figure 4: Drop in the density of the Lorentz electromagnetic force dependent on the distance from the cast wall on the side of the inductor (AlSi12CuMg alloy, frequency 1500 Hz).

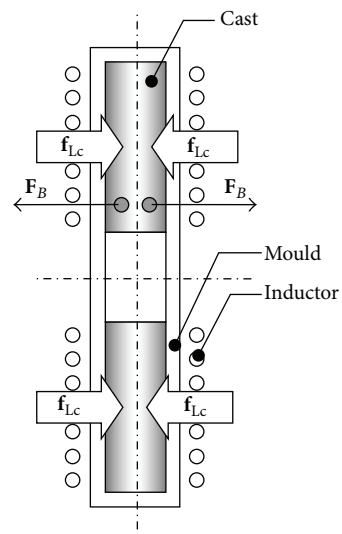

Figure 5: Diagram of the electromagnetic separation process in a two-side reinforced disc.

Another important cause of a nonuniform distribution of the force field in the cast is the spiral inductor used in the process. The diameters of the turns become smaller towards the axis and there are no turns in the center of the inductor, which results in the drop in the field strength along the radial coordinate. This is reflected in the analogous drop in the strength of the Lorentz force acting on the liquid cast. Figure 3 depicts the distribution of the axis component at the disc wall closer to the inductor for AlSi12CuMg alloy used in the experiment below and inductor supply frequency of 1500 Hz. In the case of a standard inductor, a significant change in its value along the disc radius is visible, which would significantly disturb the electromagnetic separation process.

The study [28] discusses the possibility of making the field distribution more uniform in the cast area by means of inductors with specialized geometry, such as inductors with variable spacing between turns and the cast, inductors with variable spacing between the turns, and inductors with variable turn heights. Among the above solutions, an inductor with variable turn spacing, which is relatively easy to make, is considered to be very effective. Such an inductor has already been successfully applied in a process of casting a composite sleeve reinforced at the outer wall [25].

The inner diameters of the inductor turns (and thus the spacing between the turns) were determined on the basis of numerical optimisation. The minimized criterion was the measure of the electromagnetic force field uniformity:

$$C_{\text{opt}} = \frac{\int_{V_c} \left|\nabla \times \mathbf{f}_{\text{Lc}}\right| \mathrm{d}V_c}{\int_{V_c} \mathbf{f}_{\text{Lc}} \cdot \mathbf{k}\, \mathrm{d}V_c}, \tag{4}$$

where $\mathbf{f}_{\text{Lc}}$ is the Lorentz force density, $\mathbf{k}$ is the desired direction of this force, and V_c is volume of the cast.

The optimisation was carried out using the Matlab Optimization Toolbox (the InteriorPoint algorithm). In order to determine criterion (4), the distribution of the electromagnetic force was calculated in the Ansys Emag software.

Undeniably, the effect of one-sided reinforcement of the disc may also be obtained by casting the disc horizontally and using the simplest method of reinforcement distribution based on gravitational sedimentation [3, 13]. However, electromagnetic separation also allows the manufacture of two-side reinforced discs, which is impossible with other suspension casting methods [3]. Here it is possible owing to the limited penetration of the alternating electromagnetic field through the metal cast, related to the concept of penetration depth of this field:

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}}, \tag{5}$$

where f is electromagnetic field frequency, μ is magnetic permeability, and σ is electrical conductivity.

Figure 4 presents the dependence of the Lorentz force density on the distance from the disc wall located closer to the inductor. As it can be seen, at the opposite wall the value of the electromagnetic forces acting on metal is close to zero as a result of nearly complete attenuation of the electromagnetic wave generated by the inductor.

The above phenomenon of electromagnetic shielding by the cast allows the system designed for casting one-side reinforced discs (Figure 1) to be duplicated, which yields the possibility of manufacturing two-side reinforced discs (Figure 5). In such a case, the whole casting system must be

Table 1: Inner diameters of the optimised inductor turns.

Turn number	1	2	3	4	5	6	7	8	9	10
Inside diameter [mm]	24.5	33.5	43.5	58.5	76.0	92.5	110.5	128.0	141.5	161.0

Figure 6: Flat inductor with variable spacing between the turns.

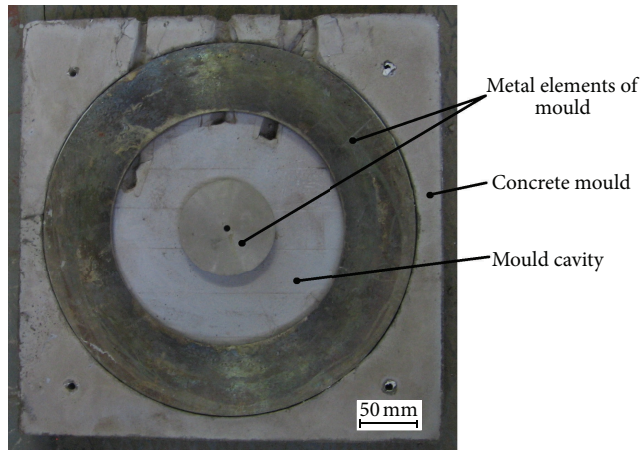

Figure 7: Half of the concrete mould with metal elements.

duplicated, including the optimised inductor as well as the ceramic and metal elements of the mould.

3. Experiment

The method was verified in an experiment where one-side and two-side reinforced composite discs were cast from AlSi12CuMg alloy reinforced with SiC particles of 63–106 μm. The initial weight fraction of the reinforcement in the composite suspension was 10%. The inner and outer diameters of the cast discs were 90 and 220 mm, respectively. The thickness of the one-side reinforced disc was 8 mm; the thickness of the other one was doubled and amounted to 16 mm. The process was performed at a casting station with the main component of a single or double flat inductor (Figure 6) with numerically optimised diameters of the turns (Table 1).

The casts were manufactured using a mould made of refractory concrete. Figure 7 depicts one half of this mould with visible elements made of copper-nickel CuNi30. These elements are characterised by conductivity similar to the conductivity of a liquid AlSi12CuMg alloy and produce a uniform electromagnetic field at the edges of the cast discs.

The mould was heated to 220°C in a resistance furnace before it was filled with composite suspension with the temperature of 720°C. In order to ensure proper mould filling, the electromagnetic field was turned on only after the entire mould cavity had been filled [29]. The inductor was supplied with a current of 1500 Hz and 420 A for approximately 8 seconds. Then, once the discs had completely set and cooled down, samples were cut out from the middle sections and ground with sandpaper 600 grit in order to photograph the obtained macrostructure of the discs. The samples were then polished with a diamond polishing paste to reveal

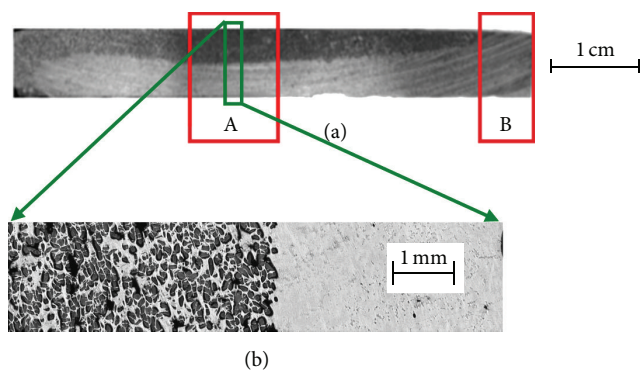

Figure 8: Macrostructure (a) and microstructure in the middle of area A (b) of a one-side reinforced disc.

their microstructure and conduct a statistical analysis of the reinforcement distribution across the thickness of the disc.

4. Results and Discussion

As it can be seen in Figure 8(a), the method yielded a one-side reinforced disc. The lack of reinforcement near the inner edge of the disc, the one closer to the axis (area B), results from imperfections in the geometry of the inductor used. Apart from some inevitable dimensional inaccuracies that occurred at the manufacturing stage, the likely cause is the difference between the actual conductivity of the mould elements and composite suspension and the conductivity assumed in the electromagnetic model used for the numerical optimisation of the geometry of this casting system [28]. Figure 9 shows a mechanism of creating a defect in the cast microstructure. The imperfection of the inductor results in the electromagnetic forces (black arrows) being weaker at

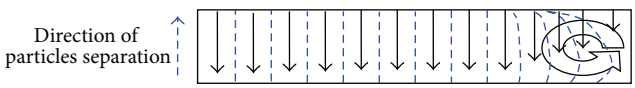

Figure 9: Mechanism of the defect in the cast macrostructure: black arrows, electromagnetic force, white arrow, flow of liquid metal, and dotted lines, trajectories of particles.

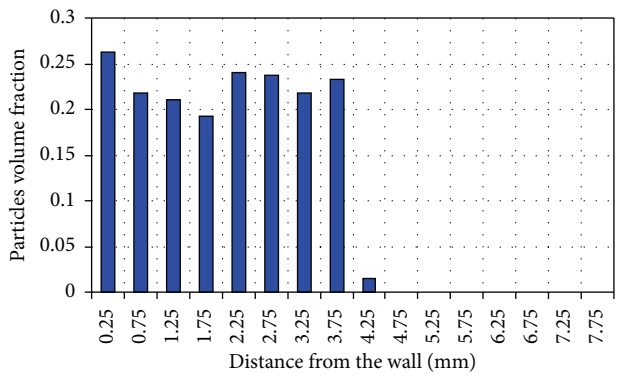

Figure 10: Distribution of the volume fraction of reinforcement of the one-side reinforced disc.

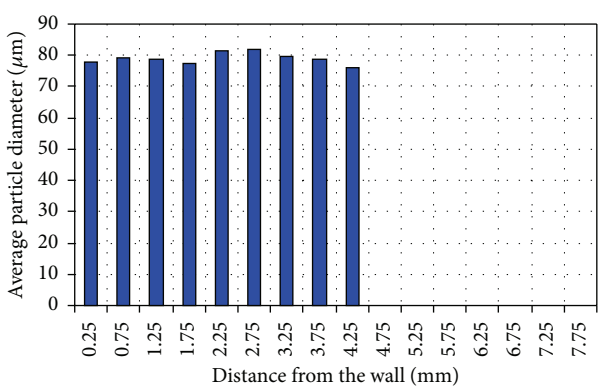

Figure 11: Distribution of the average particle diameter of the one-side reinforced disc.

the inner edge of the disc. The nonuniformity of the force field causes a local flow of the liquid metal (the white arrow), which disturbs trajectories of the particles (dotted lines) and carries them away from this area.

Figure 8(b) depicts the microstructure in the middle of area A marked in Figure 8(a). The statistical analysis of the image of this area indicates that within the reinforced layer the particles fraction is not subjected to significant changes and amounts to approximately 22% (Figure 10). What is more, there is no considerable particle size segregation taking place within this layer, as can be seen in Figure 11.

Owing to a casting system with two identical inductors located on both sides of the cast disc it was possible to obtain local reinforcement at both surfaces of the disc (Figure 12(a)). The overlapping electromagnetic fields generated by both inductors and the greater thickness of the disc enabling

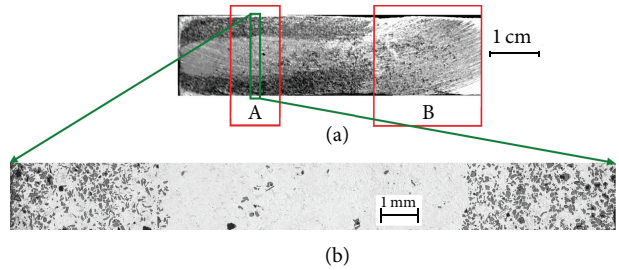

Figure 12: Macrostructure (a) and microstructure in the middle of area A (b) of the two-side reinforced disc.

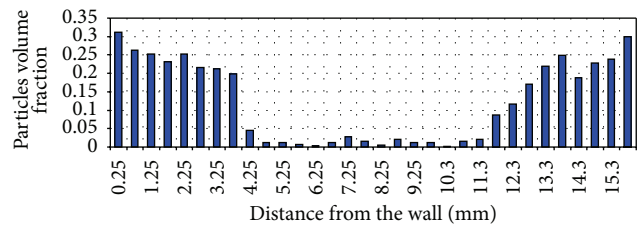

Figure 13: Distribution of the volume fraction of reinforcement of the two-side reinforced disc.

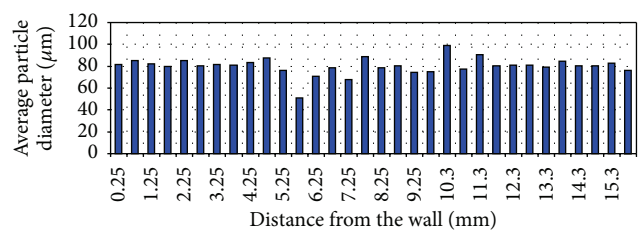

Figure 14: Distribution of the average particle diameter of the two-side reinforced disc.

the development of the stirring process of the composite suspension resulted in expansion of the defective macrostructure area (B), located by the inner edge of the disc.

The statistical analysis of area A (Figure 12(a)) points to the volume fraction of SiC particles at the mean level of 22% (Figure 13) within the area of the reinforced layer and to the constant distribution of the particle sizes (Figure 14). The overlapping of the opposite fields generated by both inductors caused that some particles in the central part (Figure 12(b)) did not undergo the process of electromagnetic separation and the boundary between the reinforced and nonreinforced zones is not as sharp as in the case of the one-side reinforced disc.

5. Conclusions

The paper presents a new method of casting composite discs in the alternating electromagnetic field. The theoretical analysis and experimental verification having been conducted, the following conclusions can be derived:

(i) The process of casting in the alternating electromagnetic field enables the manufacture of both one-side

and two-side reinforced composite discs. It ensures greater control of the reinforcement distribution in the casts than any other method of particle suspension casting.

(ii) The element of key importance to the success of the process is uniform distribution of the electromagnetic field acting on the area of the liquid cast. To achieve this goal it is necessary to utilise the conductive elements of the mould and the optimised geometry of the inductor.

(iii) The discussed process is very sensitive to any inaccuracies in the geometry of the inductor used.

(iv) Suitable selection of material for the conductive elements of the mould should enable the manufacture of locally reinforced discs made of other alloys.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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