Modeling acoustic effects during casting nanocomposites under electromagnetic field

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***Abstract*— Casting is one of the most cost-effective method to produce metal matrix nanocomposites. However, its is extremely difficult to disperse nanoparticles uniformly in metal matrix due to their large surface-to-volume ratio and their low wettability in liquid metal, which cause their agglomeration and clustering. The paper presents a model of the process of casting nanocomposite, where an alternating electromagnetic field is used to induce a standing acoustic wave in molten metal. The model requires the coupling of electromagnetic field, metal flow field and acoustic field. It allows to optimize parameters of the coil supply in order to produce a cavitation phenomenon in metal, which breaks up the agglomerations.**

***Index Terms*— magnetohydrodynamics, acoustic effect, nanocomposites**

I. Introduction

Metallic composites containing nanoparticles (e. g. SiC, Al_2O_3, graphene, nanotubes) offer distinct advantages such as high strength, high modulus and wear stress. Due to their characteristic, these materials are of great interest to the automotive, aerospace and defense industries. There are several methods for the production of metal matrix nanocomposites including mechanical alloying, vertex process and spray deposition, but these techniques have some disadvantages such as low productivity and high cost. Casting is a versatile and cost-effective method to manufacture nanocomposites with complex shapes.

However, due to a large surface-to-volume ratio of nanoparticles and their low wettability in molten metal, they tend to agglomerate as a result of van der Walls forces. Therefore, obtaining proper dispersion of nanoparticles in metal matrix is very difficult. Earlier studies involved the use a high-power ultrasonic probe to disperse nanoparticles in metal matrix [1][2]. Ultrasonic waves cause cavitation, which involves formation, growth and violent collapse of micro-bubbles in molten metal. This mechanism produces an implosive impact strong enough to break up the clustered nanoparticles and disperses them more uniformly in liquid. Drawbacks of the proposed method are a contact of the oscillating probe with composite suspension (which may dissolve in the liquid metal and contaminate it) and nonuniform extent of dispersion. It is maximum at the probe and gradually decreases with distance away from the probe.

The authors dealing with the use of the electromagnetics in metal matrix composites technology [3] have developed a new method for producing high-intensity ultrasonic wave in a nanocomposite suspension. This noncontact method uses an alternating electromagnetic field to induce a standing acoustic wave in molten metal which produces caviation in a liquid casting. This non-contact method does not have the drawbacks of the method using a ultrasonic probe.

The paper presents a model of the process and analysis of the impact of supply parameters on a pressure distribution in the casting.

II. Description of the Process

The research was conducted for a casting process of a aluminum cylinder reinforced with nanoparticles. The process begins with the preparation of a suspension of nanoparticles in liquid metal. The suspension is poured into a nonconductive ceramic mold and exposed to alternating electromagnetic field produced by a coil.

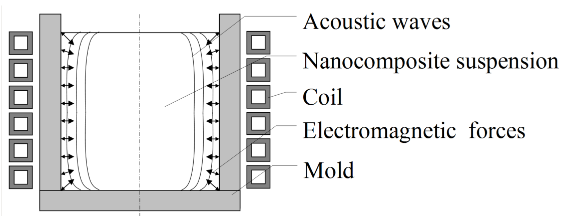

Fig. 1. Schematic diagram of the system for electromagnetically producing acoustic waves in the nanocomposite casting.

The schematic diagram of the process of electromagnetic casting is shown in Fig. 1. Oscillating in time distribution of the electromagnetic force field generates ultrasonic waves propagating through the liquid casting. Proper selection of frequency of the coil supply allows to obtain a standing wave in the casting as a result of interference between the primary wave and the reflected wave. Thanks to this, obtained high amplitude of acoustic pressure produces cavitation in the nanocomposite suspension.

III. Model of the Process

The model of nanocomposite casting under electromagnetic requires the coupling of electromagnetic field, metal flow field and acoustic field. Low values of currents induced by the flow of the metal and a constant temperature of the metal during the process allowed to use a weak (one-way) coupling between the electromagnetic model and the hydrodynamic model.

The electromagnetic field symbolic analysis was based on the commonly applied expression that makes use of magnetic vector potential $\boldsymbol{A}$ [3][4]:

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

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 (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 determination of the distribution of instantaneous electromagnetic forces density $\boldsymbol{f}_e$ acting on the liquid metal:

$$\boldsymbol{f}_e = \boldsymbol{J} \times \boldsymbol{B} = \frac{1}{2}\boldsymbol{J}_A \times \boldsymbol{B}_A \left(\cos(\varphi - \psi) - \cos(2\omega t + \varphi + \psi)\right) \tag{4}$$

where: $\boldsymbol{J}_A$, $\boldsymbol{B}_A$ – amplitude of the current density and the magnetic induction φ, ψ – phase shift of the current and the induction, ω – angular frequency of the supply current, t - time

Since the electromagnetic force induces not only acoustic waves but also the flow of metal, the acoustic field was calculated by a method involving direct solving of Navier Stokes equations for compressible fluid, instead of a popular method based on the acoustic wave equation [5][6]:

$$\rho\left(\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v}\right) = -\nabla p + \eta \nabla^2 \boldsymbol{v} + \frac{1}{3}\eta \nabla(\nabla \cdot \boldsymbol{v}) + \rho \boldsymbol{g} + \boldsymbol{f}_e 0 \tag{5}$$

$$\rho = \rho_{ref}\left(1 - (p - p_{ref})K^{-1}\right)^{-1} \tag{6}$$

where: ρ – fluid density depending on the pressure, $\boldsymbol{v}$ – velocity, p – pressure, η – dynamic viscosity, $\boldsymbol{g}$ - gravitational acceleration, p_{ref} – atmospheric pressure, ρ_{ref} - fluid density under atmospheric pressure, K – bulk modulus

IV. Results

In order to obtain in the casting a sufficient amplitude of acoustic pressure to induce cavitation, its is necessary to produce an acoustic wave with a frequency equal to the natural frequency of vibrations of the casting or its harmonics. According to (4) the oscillation frequency of the force (equal to the frequency of acoustic waves) is twice the frequency of the coil supply. Fig. 2 shows the dependence of instantaneous minimum pressure (absolute) in the casting (after reaching a quasi-steady state) on the supply frequency. As can be see in the graph, the pressure reaches a pronounced minimum for a supply frequency equal to half the acoustic natural frequency of the casting (70.15 kHz).

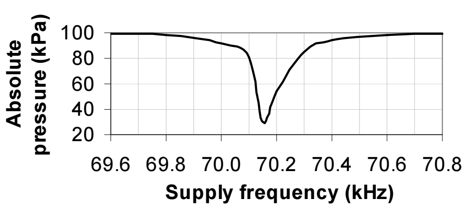

Fig. 2. Dependence of minimum instantaneous pressure on the supply frequency of the coil (for the supply current of 400 A).

The values of electromagnetic forces are squarely dependent on the supply current of the coil. Fig. 3 shows the dependence of obtained minimum instantaneous pressure (in quasi-steady state) on the coil current. For the current of 480A the pressure locally reaches values providing the conditions for cavitation. The current is very high for the used geometry of the coil. It can be reduced by increasing number of turns.

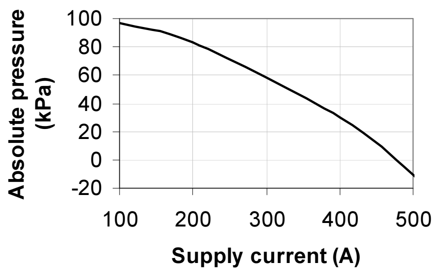

Fig. 3. Dependence of minimum instantaneous pressure on the coil current (for the frequency of 70.15 kHz).

Areas of low pressure (and thus caviation) are mainly present in the central zone of the casting (Fig. 4). Further increase of the current (or the number of turns) will expand this area. The existing at the same time an global electromagnetic stirring would allow to homogenize all the nanocomposite suspension in the casting.

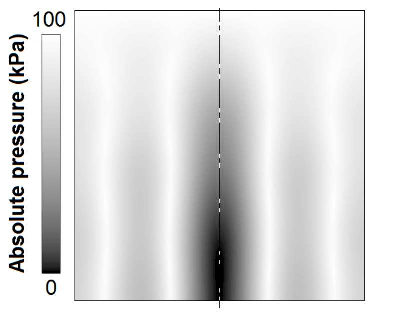

Fig. 4. Spatial distribution of minimum instantaneous pressure (for the current of 480 A and the frequency of 70.15 kHz).

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