



Non-metallic Particles Manipulation in Liquid Metals During Electromagnetic Processing

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Abstract

Research in manipulation of non-metallic particles in a liquid metal by using an electromagnetic (EM) field is promoted by both the requirement of more efficient materials design and the development of cost-effective electromagnetic apparatus. The particles of sub/micrometer sizes can be agglomerated, segregated, aligned and/or removed by applying a suitable EM field during liquid metal processing. The efficiency and applicability depends highly on the nature of the particles and the difference from the liquid metal matrix. In the present paper, the fundamentals/physics of non-metallic particles manipulation by EM processing are discussed and some potential application possibilities in industry are proposed.

To improve the efficiency of materials manipulation or obtain a metallic-based materials with required properties has been of broad interest. One of the topics by using an electromagnetic (EM) field concerns the manipulation/removal of non-metallic solid particles in a liquid metal and a variety of related processes using a static electromagnetic field and/or alternating electromagnetic field have been developed [1-4]. Among the processes, a range of electromagnetic effects have been realized which play key roles in determining the engineering of their applications. The physics of these effects are discussed in the following sections by considering different types of EM fields. In order to generate effective electromagnetic effects, the difference in physical/electromagnetic properties between the solid particles and the liquid metal needs to be significant [5,6]. As one of the consequences, the existence of the solid particles will directly influence the physical/chemical properties of the metal after solidification.

The fundamental of using an electromagnetic field for manipulation is that different electromagnetic forces on the liquid metal and particles can be generated because of the difference in their physical properties [7,8]. In general, four types of electromagnetic fields are usually used: (i) imposing a stationary magnetic field and/or a current; (ii) DC/AC current; (iii) AC magnetic field; and (iv) strong static magnetic field. Figure 1 gives a schematic view of the particle distribution against the liquid metal under different EM fields.

DC/AC Current

An imposed DC/AC current induces a perpendicular magnetic field providing a Lorentz force in a liquid metal. The Lorentz force on the liquid metal is always in the radial direction pointing inwards if a cylindrical conductor is considered (Figure 1). Since the Lorentz force attempts to compress the liquid metal, it is known as the “pinch effect”. When non-conductive particles are present, they will be collected at the wall by this effect [7]. The layer with accumulated particles presents distinct wear properties and graded metallic-based materials can therefore be prepared. In a current density of 4000 kA/m², the collection efficiency of 30 μm Al₂O₃ in liquid aluminum can reach 95% [9], indicating that it is a very efficient approach. However, the Lorentz force is rotational with the square of the current frequency and will generate secondary flows in the melt [9]. In another case, axisymmetric flows may be induced due to the non-uniformity of the radial pinch force when the imposed current is radically non-uniform in the cylindrical conductor. They are important factors to determine the particle distribution.

AC Magnetic Field

A time-varying magnetic field generated in an induction coil can induce eddy currents and subsequently a Lorentz force on a liquid metal. This body force produces internal fluid motion without mechanical contact making “magnetic stirring” a well recognized process. The “skin depth” δ is one of the most important parameters

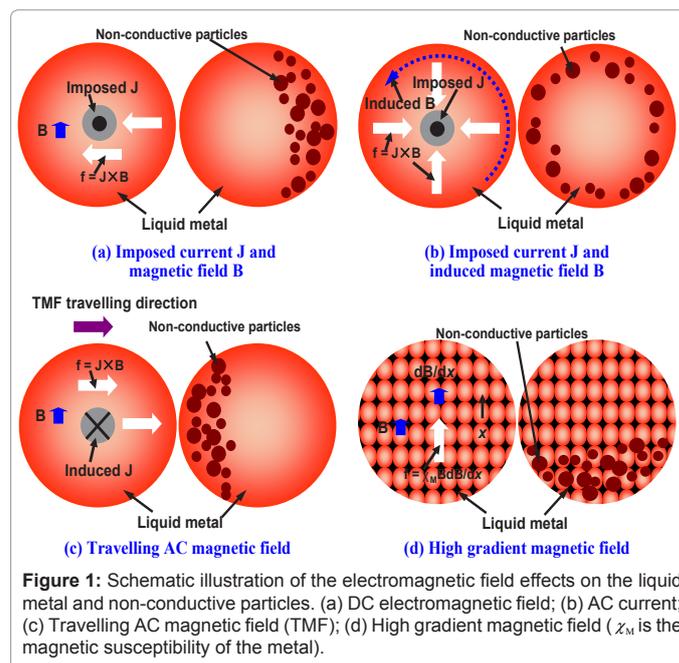


Figure 1: Schematic illustration of the electromagnetic field effects on the liquid metal and non-conductive particles. (a) DC electromagnetic field; (b) AC current; (c) Travelling AC magnetic field (TMF); (d) High gradient magnetic field (χ_m is the magnetic susceptibility of the metal).

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to evaluate the AC magnetic field effects. It can be expressed as [10]

$$\delta = \sqrt{\frac{2}{\mu\sigma\omega}} = \sqrt{\frac{1}{\mu\sigma\pi f}} \quad (1)$$

where μ the magnetic permeability, σ the electrical conductivity, $\omega = 2f$ the angular frequency and f is the frequency.

If the magnetic field frequency is low (e.g. 10 Hz), the field can easily pass through the liquid melt because the skin depth (in cm range at 10 Hz) may be larger than the sample thickness. More often, travelling [11,12] or rotating [13] low frequency AC magnetic fields are used in the process of particle removal from liquid metals [14]. As shown in Figure 1 (c), the induced current provides the source for the Lorentz force on liquid metal with the magnetic field. The non-conductive particles are pushed to one side of the cylindrical tube and can be separated.

When the frequency is high (e.g. 10 kHz), the skin depth becomes very small (in mm range at 10 kHz) and may be much lower than the sample thickness. It means that the magnetic field is shielded from the interior of the metal and the induced current exists only in a thin surface layer. A strong stirring effect will be generated in the liquid metal which contributes to improve the homogeneity of the particle distribution and de-agglomerate the cluster of small particles.

Static Magnetic Field with or without a DC/AC Current

A static magnetic field suppresses the liquid metal motion not parallel to the magnetic field lines. This effect is named magnetic damping. When non-conductive particles are present, their migration is also interfered due to the damping in the liquid metal motion. Usually, a combination of a DC magnetic field with a DC current is applied to control the non-conductive particle distribution in liquid metals [15-17]. The DC current is generated between electrodes inserted in the melt [7], while the static magnetic field is applied with permanent magnets or electromagnets. The apparatus can be designed easily. Under the field, the melt experiences electromagnetic forces while a counteractive effect is stimulated on the non-conductive particles due to their non-conductivity [18]. The principle is shown in Figure 1. It has been found that particles of $\sim 100 \mu\text{m}$ can be efficiently influenced and they can be collected to one side of the liquid metal in a short time [19]. However, it is hardly feasible to scale-up and it remains difficult to manipulate fine particles in the μm range. The generation of a magnetic field higher than 1 Tesla in a large volume remains difficult for conventional electromagnets and keeps the magnet at a temperature below the Curie temperature constitutes a significant technical problem [7].

Strong Static Magnetic Field

With the development of superconducting technology, a magnetic field of 10 Tesla or more becomes easily attainable [20-25]. The advantage of increasing the magnetic flux density is that the magnetic Faraday force in a gradient field as well as the Lorentz with an imposed current can be significantly increased. The particles with a distinct magnetic property experience a different magnetic Faraday force from the liquid metal (Figure 1 (d)).

The magnetic Faraday force is expressed as

$$f^{gr} = \chi_M B \frac{dB}{dx} \quad (2)$$

where f^{gr} is the magnetic Faraday force, χ_M the magnetic susceptibility of the metal and B the magnetic flux density.

The Lorentz force is given by

$$f^L = J \times B \quad (3)$$

where f^L is the Lorentz force and J is the current density.

The principle is given in Figure 1 (d) and a difference in magnetic properties (magnetic susceptibility χ) is required in order to manipulate the particles [26]. With the magnetic Faraday force, early research on liquid alloys such as Al-Si alloys evaluated the induced migration and separation [26-28]. The migration time for an alumina particle with a diameter of $20 \mu\text{m}$ to travel 1 mm was evaluated to be less than 20 seconds under a magnetic field gradient product of around $10 \text{ T}^2/\text{m}$ [26]. However, the force has a comparable magnitude with the gravity force in a high gradient condition for alumina particles (for instance, a gradient product of $600 \text{ T}^2/\text{m}$) and the manipulation efficiency of micrometer sized particles is very low [5,29].

Therefore, a DC current is usually combined by applying the Lorentz force to manipulate the small particles effectively [29]. The principle is the same as in a traditional DC magnetic field and a current. Detailed investigations have been given in [29] and the non-conductive particles experience the so-called electromagnetic Archimedes forces (f_P^{EA} equation (4)). Alumina particle of $5 \mu\text{m}$ can be totally collected to one side of the liquid aluminum in 2 seconds in a 40 mm cylinder crucible [29]. The magnitude of the electromagnetic Archimedes force with a 10 T magnetic field and $1500 \text{ kA}/\text{m}^2$ current can be more than 500 times larger than the magnetic Faraday force [29].

The electromagnetic Archimedes force is obtained as

$$f_P^{EA} = -\frac{3}{2} \frac{\sigma_M - \sigma_P}{2\sigma_M + \sigma_P} J \times B \quad (4)$$

where f_P^{EA} is the electromagnetic Archimedes force density, σ_M and σ_P the electrical conductivity of the liquid metal and the non-conductive particle respectively.

Energy Efficiency and Benefits of Using a Strong Magnetic Field

When a current is coupled during particle manipulation from a liquid metal, the energy efficiency is another important factor to be considered. In traditional electromagnetic processes, the power is mostly consumed to heat the melt instead of separating the particles [7]. The Joule heating per unit volume is derived from

$$Q_J = \frac{J^2}{\sigma_M} \quad (5)$$

The induced driving force f_P^{EA} for particle removal can be obtained by equation (4). Therefore, the effective power spent on the particle migration is

$$W_P = f_P^{EA} \times v_P \quad (6)$$

where v_P is the terminal velocity of a particle.

The terminal velocity is obtained from

$$v_P = \frac{d_P^2}{18\eta_{M,B}} f_P^{EA} \quad (7)$$

where d_P is the diameter of the particle, $\eta_{M,B}$ is the viscosity of the liquid metal in a magnetic field (calculated in [6]).

By substituting equations (4) to (7), the effective power to promote particle removal is

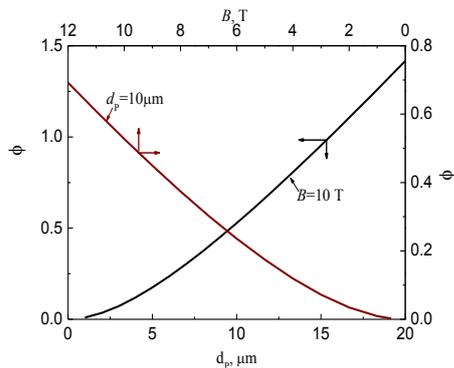


Figure 2: Effect of the particle size and magnetic flux density on the energy coefficient (ϕ). The calculation is based on alumina particles in liquid aluminum and the data needed for the calculation are taken from [30].

$$W_P = \frac{d_p^2}{18\eta_{M,B}} \left(\frac{3}{2} \frac{\sigma_M - \sigma_P}{2\sigma_M + \sigma_P} j \times B \right)^2 \quad (8)$$

The energy coefficient ϕ is defined as the ratio of the effective power W_P to the Joule heating Q_J , allowing to evaluate the energy efficiency of the process.

$$\phi = \frac{W_P}{Q_J} = \frac{\sigma_M d_p^2}{18\eta_{M,B}} \left(\frac{3}{4} B \right)^2 = \frac{\sigma_M d_p^2}{32\eta_{M,B}} B^2 \quad (9)$$

The dissipation energy due to the Joule heating is

$$q_J = Q_J t = \frac{J^2}{\sigma_M} t \quad (10)$$

where t is the electromagnetic field treatment time.

The two factors, magnetic flux density and particle size, are further considered. The calculated results are shown in Figure 2, revealing that the energy coefficient increases dramatically with the magnetic flux density. For particle size of 10 μm , the energy coefficient ϕ reaches around 1 which is much higher than in the conventional electromagnetic processes [7,8,30].

Conclusion

The fundamentals of electromagnetic field manipulation non-metallic particles in a liquid metal are discussed. It is found that two types of electromagnetic forces on the particles, i.e. Lorentz force/electromagnetic Archimedes force and magnetic Faraday force, are induced during electromagnetic field processing. At high temperatures, both the liquid metal and non-conductive particles are weak magnetic and the magnetic Faraday force is too small to reach an effective manipulation of micrometer sized particles. The Lorentz force can be further combined by applying a DC current. With a sufficiently strong magnetic field and suitable design, the energy coefficient can be highly improved. Therefore, using a strong magnetic field to manipulate micrometer sized particle in a conductive liquid metal is considered to be more promising and effective. However, additional research should be focused on scale-up and the design of industrial systems to meet practical applications.

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