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Electromagnetic Field Assisted Metallic Materials Processing: A Review

Zhuo Zhao,* Yanquan Chai, Shihong Zheng, Lisha Wang, and Yanping Xiao

Electromagnetic fields have been widely applied in the field of materials processing, preparation, and analysis. The effectiveness during such processing is, however, highly dependent on the physics of the applied electromagnetic field as well as the electromagnetic responses from the materials. In order to improve the efficiency of electromagnetic field processing, understanding the fundamentals as well as the engineering of the corresponding electromagnetic effects is crucial. Focusing on metallic materials, this research gives a critical overview and discussion on different electromagnetic effects. Subsequently, the electromagnetic responses in different electromagnetic technologies are further discussed. Specifically, the industrial application potential for inclusion removal from liquid metals is evaluated and the energy coefficient is noticed to be substantially improved by increasing the magnetic flux density.

1. Introduction

Electromagnetic processing of metallic materials is of significant importance and has already attracted worldwide attentions because of the unique physiochemical effects of an electromagnetic field. Recently, the development of electromagnetic apparatus is also noticed to be booming and the cost of a representative set-up becomes more effective than ever before. In general, electromagnetic interaction are implemented in four types of fields, i.e., a static magnetic field with or without a current; electromagnetic field generated by a direct or alternative current; traveling or alternative magnetic field; and high magnetic field.[1] By using a suitable electromagnetic field or set-up, a number of phenomena and effects have been observed including liquid (liquid metals or solutions) flow pattern control, morphology modification during solidification of liquid metals and crystallization of organic compounds, and removal and manipulation of non-metallic inclusions in a liquid metal. Among these effects, processing of metallic materials in order to obtain required physiochemical/mechanical properties is of great interest in the field of metallurgy and materials engineering. For liquid metals, their purification or subsequent process for preparing metallic materials is specifically relevant to the behavior of metallic/non-metallic particles under an electromagnetic field.[2–5] These non-metallic or metallic particles may be segregated, agglomorated, aligned by the electromagnetic field and these effects are directly corresponding to the electromagnetic responses from the particles.[6] During the electromagnetic field processing, the efficiency is found to be highly influenced by the nature of the particles/inclusions and the difference from the liquid metal itself. It is, therefore, important to understand the nature and the role during the engineering of these electromagnetic field effects.

To get significant electromagnetic responses, both the electromagnetic field and properties of the processed materials need to be well understood and combined. For instance, in the case with solid particles (either as primary phase or reinforced particles) in a liquid metal, it needs to have significant difference in their physical/electromagnetic properties.[7] On the other aspects of electromagnetic processing of materials, the applications of electromagnetic fields have been rather broad ranging from solidification, chemical dissolution/leaching, electro deposition, heat treatment, and high temperature sintering etc.[5,8,9] The corresponding effects are varying with the type of applied electromagnetic fields.

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2. Electromagnetic Field Effects

2.1. Magnetic Damping

Convection is one of the most important phenomenon during liquid metal processing. It is usually caused

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thermally, for instance, when a thermal difference exists within the liquid metal. There are different types of convection, including buoyancy convection, Marangoni convection, and electromagnetic convection (caused by an electromagnetic force).[10] Convection plays a very important role in heat/mass transfer, compositional/structural segregation as well as solidification of a liquid metal.[11] It has been found that a static magnetic field suppress the motion of liquid metal, i.e., not parallel to the magnetic field direction. This principle is based on magnetic damping and is typically applied to damp the turbulence of liquid metals.[12] Subsequently, for instance, it contributes to reduce the inclusions entrapment and improve the surface quality during casting of steel.[13] The electromagnetic brake (EMBR) is a consequent technology and has been used widely in the steel industry.[14] By braking the turbulent flow from the submerged entry nozzle, the penetration depth of the liquid steel flow in the mold is limited and less inclusions are trapped in the melt. A schematic view is shown in **Figure 1**. Because the field is direct current, it can easily penetrate into the bulk of the liquid metal and is applicable to large scale processes.[15] Meanwhile, EMBR provides an added benefit, since the reduced velocity creates a higher temperature near to the meniscus than it for a non-reduced flow rate (Figure 1). In this case, the viscosity of the mold flux can be decreased and subsequently premature solidification of liquid metal may be prevented.[14]

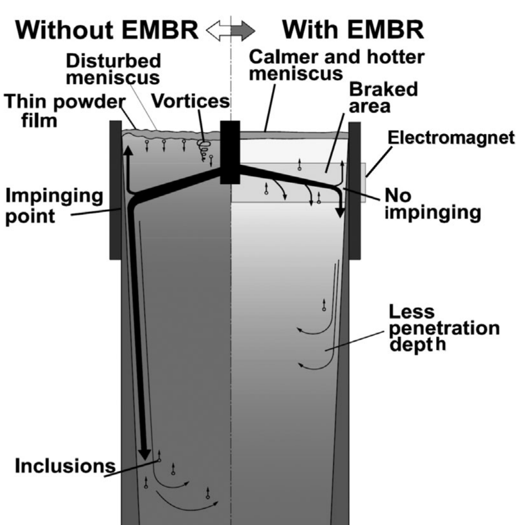

Figure 1. Effect of electromagnetic brakes (EMBR) on inclusion entrapment in steel during continuous casting[16] (color indicates different temperature).

The motion of liquid metal or that of solid particles/inclusions is also possible to be damped by combining a magnetic field and a direct current.[16–18] The direct current can be generated by using emerged electrodes in the liquid metal,[19] while an external permanent or electro-magnet may be used to generate the magnetic field. The liquid metal experiences electromagnetic forces, when it flows through the electromagnetic field and the solid particles in the melt experiences a counteractive force even though it may not experience the electromagnetic force directly, which is related to the conductivity of the materials.[20] It indicates that the migration behavior of solid particles in a metal can be controlled with the aim to prepare metal matrix composite.[21]

2.2. Electromagnetic Stirring and Induction Heating

Conductive melt, i.e., liquid metal or molten salt, can be stirred by the following approaches: (i) by an alternating current magnetic field, for example the melt can be stirred during induction heating, cold crucible electromagnetic melting, and electromagnetic levitation; (ii) by an pulsed magnetic field; (iii) by a moving magnetic field, such as a rotating magnetic field; and (iv) by imposing a non-parallel magnetic field and electrical current simultaneously.[22,23] When an alternative magnetic field is applied by an induction coil, it can induce eddy currents in the liquid metal and a Lorentz force on the metal can be subsequently induced. Lorentz force is considered to be a body force and it will bring internal motion of the liquid metal without imposing mechanical contact. This phenomenon is called "magnetic stirring" and it has been used for melt mixing and mass transfer enhancement. However, during magnetic stirring, "skin depth" δ is found to be rather important to determine the efficiency of a magnetic stirring process when an alternative magnetic field is applied. It can be expressed as[24]

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

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

There are usually two conditions for evaluating the effect of skin depth. When the frequency of the alternative magnetic field is low (e.g., 1 Hz), the electromagnetic field can penetrate through the liquid metal rather easily, since the skin depth (more than centimeter range at 1 Hz) is possibly much larger than the depth of the liquid metal.

The representative examples are traveling[25,26] or rotating[27] low frequency alternative magnetic fields and they are frequently applied during heating of metallic materials and the metal cleanliness improvement.[28] In the case of improving metal cleanliness, non-conductive inclusions are pushed to the wall of a container and subsequently separated. However, there is not much recent activity in this field and the difficulty in removing micro-meter sized inclusions may be one of the crucial reasons.

In the case of a high frequency, for example 1 kHz, the skin depth can be rather small (in millimeter range at 1 kHz). This depth can be smaller than the sample thickness. As a result, the electromagnetic field is shielded from the metal interior and only penetrates a thin surface layer of the metal. At the same time, an induced current is generated in this thin layer and can be used to modify the surface quality of a metal billet during its casting.

Magnetic stirring can also be generated by using a rotating magnet as shown in **Figure 2**. This rotation can either working by rotating the metal or rotating the magnet. The interactions between the electromagnetic field and liquid metal can control the crystal growth during solidification. As a consequence, a local temperature increase and tunable flow of the liquid metal can be aroused by the rotating electromagnetic field, with which the nucleus size will be decreased in order to promote heterogeneous crystal growth. As given in Figure 2, the morphology of the primary tin phase in a hypoeutectic Sn–Bi alloy is found to be modified from coarse dendrite into equiaxed dendrite by implementing a rotation magnetic field during solidification.[29]

By further combining, a rotating magnetic field and the principle of the induction effect, new heating technology of metallic materials has been developed. As shown in **Figure 3**, a direct current in a coil is applied to induce a

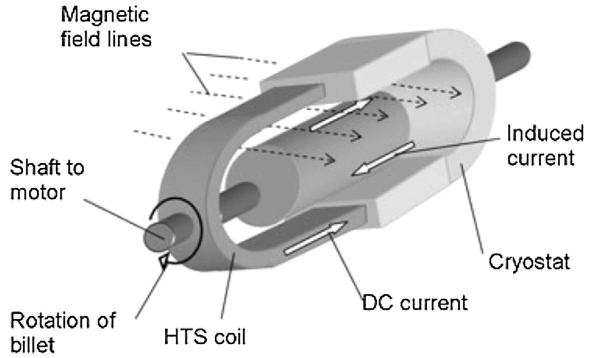

Figure 3. Induction heating of aluminum billet.[30]

static magnetic field with the magnetic line direction perpendicular to the axis of an aluminum billet. When the aluminum billet is rotated around its axis, an eddy current at the skin of the billet can be induced. The induced current subsequently generates resistive heating in the billet.[30]

2.3. Pinch Effect

According to Ampere's circuital law, an electric current either direct or alternative can induce a perpendicular magnetic field to the current in a liquid metal. This subsequently generates a Lorentz body force in the melt. The force in the liquid metal is in the radial direction pointing inward if the container of the liquid metal is cylindrical. As a result, this Lorentz force tends to compress the liquid metal because of its high conductivity which is called "pinch effect". If there are materials or solid particles with much smaller conductivity than the liquid metal, they will be pushed away

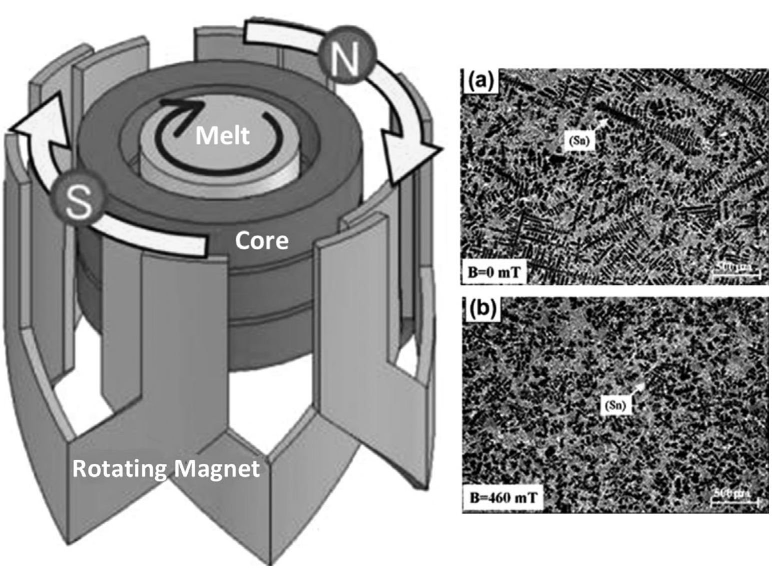

Figure 2. Effect of a rotating magnet on the solidification morphology of Bi–Sn alloys a) no magnet and b) with a magnet.[29]

from the center and a separation of the materials from the metal can be observed.[19] More commonly, low frequency AC currents (e.g., 50 Hz) are used.[31] The Lorentz force also possible generates secondary flows in the liquid metal,[31] and one of them named axisymmetric flow in the case of radially non-uniform conductor. In industry, this phenomenon in the process of vacuum-arc remelting (VAR) can generate an additional "pinch effect" on the melt, which may help to remove impurities from an ingot.[32]

The pinch effect can also appear as "electromagnetic pressure". It results in EM effects that the shape of liquid metal and finally the solidified surface can be effectively influenced. **Figure 4** shows that this effect is possibly used for controlling the surface quality of solidified metals which can be critical for their mechanical properties.[33,34]

2.4. Strong Static Magnetic Field Effect

A strong static magnetic field is different from a traditional static magnetic field, which is usually generated by a permanent magnet or traditional electromagnet where the limitation is 1 or 2 Tesla.[35] A strong field can be generated by a superconducting magnet and/or a Bitter electromagnet and the magnitude can reach more than 10 Tesla.[35]

By imposing a strong magnetic field, the magnetic Faraday force (Equation 2)[36,37] in a gradient magnetic field and the Lorentz force (Equation 3) in an electromagnetic field are both substantially increased both for metallic or non-metallic materials. During liquid metal processing, it is very commonly primary or pre-added particles existing in the melt and they may experience a different magnetic force from the liquid metal, when their magnetic or physiochemical properties are different.

The magnetic Faraday force can be expressed as

$$f^{\mathrm{gr}} = \chi_{\mathrm{M}} B \frac{dB}{dx} \tag{2}$$

where χ_{M}, the magnetic susceptibility of the corresponding material (metal or particle); B, the magnetic flux density; and x is the magnetic field line direction.

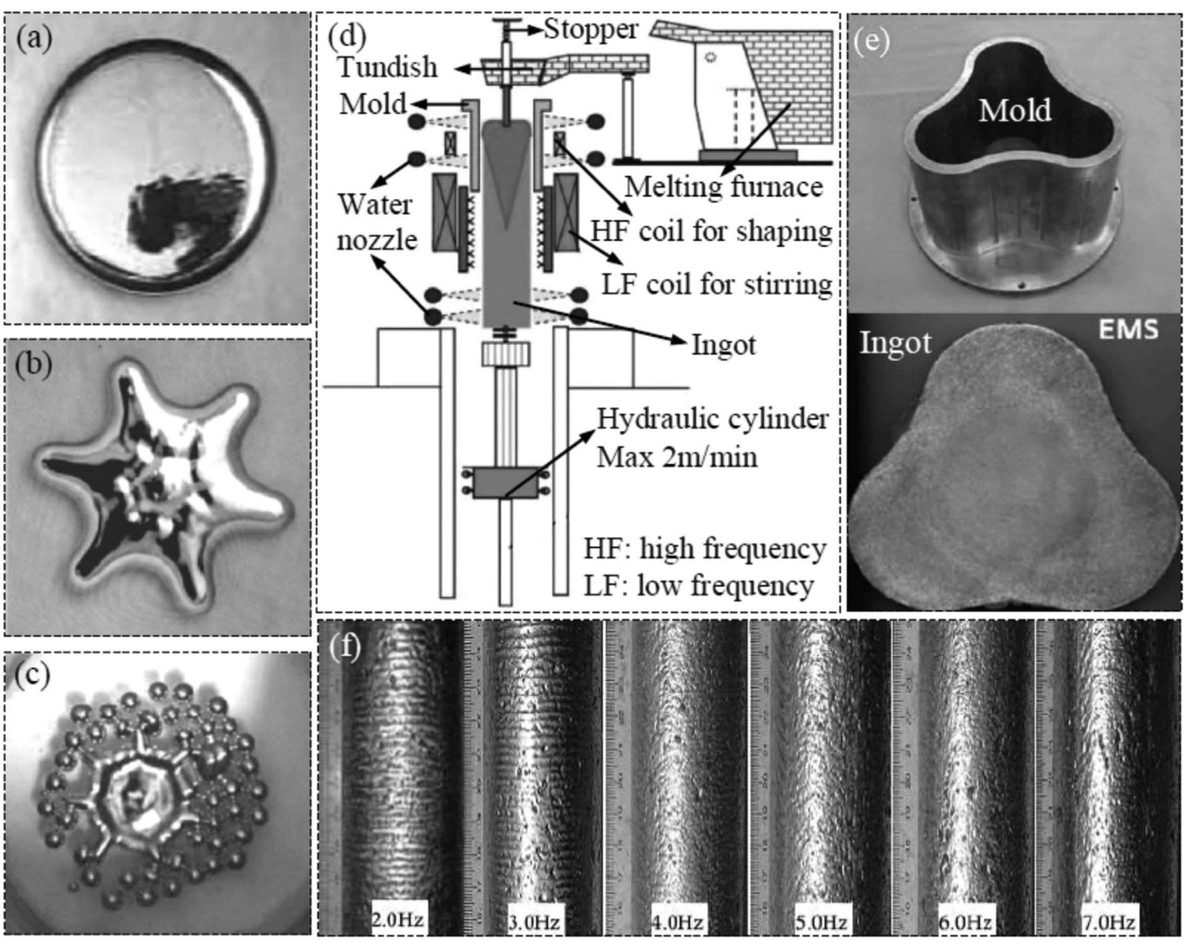

Figure 4. Electromagnetic effect on shaping of metallic materials a) mercury drop without EM effect; b) mercury drop is shaped by magnetic field with frequency of 2.1 Hz; c) gallium drop is emulsified by magnetic field with frequency of 6.2 Hz; d) equipment for the near-net shape continuous casting; e) mold of equipment shown in d) and the ingot; and f) products of soft-contact continuous casting under different electromagnetic field frequencies.[22]

The Lorentz force is expressed by

$$f^{\mathrm{L}} = J \times B \tag{3}$$

where J is the imposed current density in the liquid metal.

In early research, it has been found that migration and separation of primary phase during solidification of a liquid metal can be induced corresponding to the magnetic Faraday force, for example, primary Si in Al–Si alloys[12,36,38–41] Segregation of primary phase had been observed and gradient metallic materials could be prepared by using the magnetic Faraday force.[42] When solid particles/inclusion exist in the liquid metal, electromagnetic Archimedes force is applied to the solid particles:

$$f_{\mathrm{P}}^{\mathrm{EA}} = -\frac{3}{2}\frac{\sigma_{\mathrm{M}} - \sigma_{\mathrm{P}}}{2\sigma_{\mathrm{M}} + \sigma_{\mathrm{P}}} J \times B \tag{4}$$

where $f_{\mathrm{P}}^{\mathrm{EA}}$ is the force density, σ_M and σ_{P} are the electrical conductivity of the liquid metal and the non-conductive inclusion, respectively.

Because of this force, the magnetic responses can be very different between the liquid metal and the solid particles. With this principle, the preparation of gradient metal matrix composite materials by using an EM field can be possible. When the magnetic field is sufficiently strong or the magnetic response is high enough, interaction between weakly magnetic particles can also be observed, which results in chain-like morphology.[21]

In a static magnetic field, a magnetic free energy is induced on the applied material. By considering a crystal (tetragonal for instance) with magnetic anisotropy, it means the magnetic susceptibility tends to be different in different crystal axes. For instance, the magnetic free energies in different axes for a tetragonal crystal can be expressed as[9]

$$G_{\mathrm{m}}^{\mathrm{a,b}} = -\frac{V\chi_{\mathrm{a,b}}}{2\mu_0}B^2 \text{ and } G_{\mathrm{m}}^{\mathrm{c}} = -\frac{V\chi_{\mathrm{c}}}{2\mu_0}B^2 \tag{5}$$

where $\chi_{\mathrm{a,b}}$ and χ_{c} are the magnetic susceptibilities in the a-, b-, and c-axes of the crystal, respectively.

In a liquid metal or solution, the magnetic response from the crystal with magnetic anisotropy needs to be large enough and the magnetic free energy difference between different crystal axes should be larger than the thermal energy of the liquid. Consequently, the crystal becomes tunable and the orientation during solidification of the liquid metal can be controlled. Additionally, a critical particle volume for a certain material in order to experience significant magnetic effect exists and the magnetic free energy difference can be defined as[8]

$$\left|\Delta G_{\mathrm{m}}\right| = \left|G_{\mathrm{m}}^{\mathrm{c}} - G_{\mathrm{m}}^{\mathrm{a,b}}\right| = \left| -\frac{V\left(\chi_{\mathrm{c}} - \chi_{\mathrm{a,b}}\right)}{2\mu_0}B^2\right| > k_{\mathrm{B}}T \tag{6}$$

where k_{B} is the Boltzmann constant.

When the magnetic free energy difference is significant, the primary crystal or non-metallic particle can be aligned

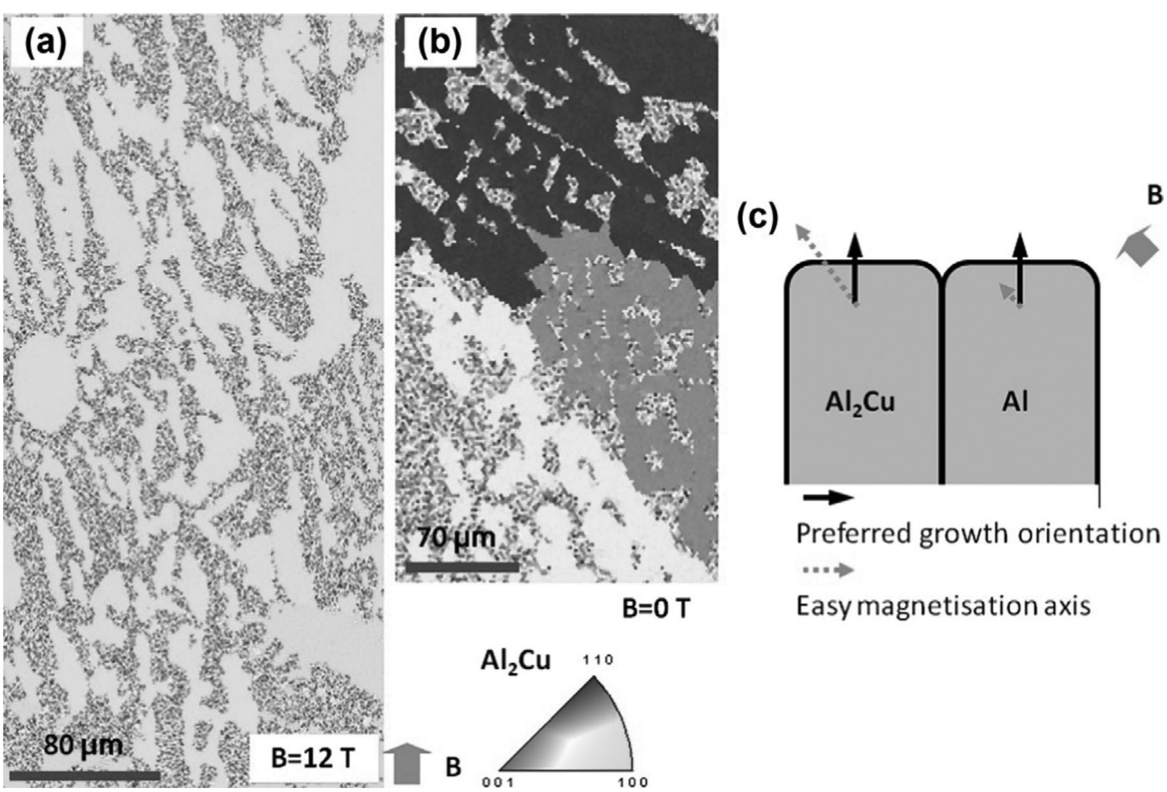

Figure 5. Strong magnetic field alignment of weakly magnetic metals.[43]

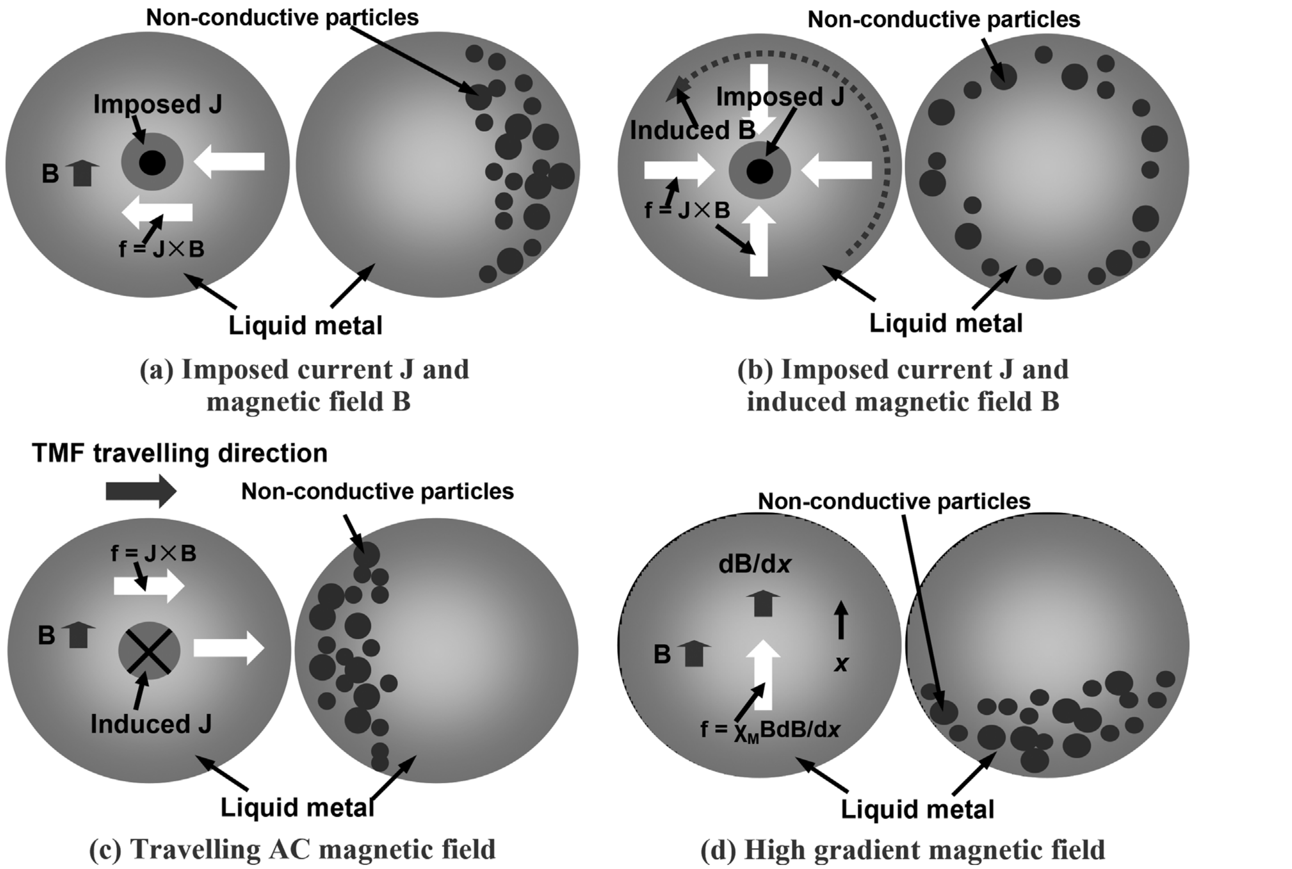

Figure 6. Different scenarios for inclusion removal from liquid metal using electromagnetic fields. a) direct electromagnetic field; b) alternative current; c) Traveling and alternative magnetic field (TMF); and d) High gradient magnetic field.[46]

by the magnetic field to a position with the lowest system magnetic free energy. When $G_m^{a,b} > G_m^c$, c-axis of the particle will be aligned to the magnetic field direction, while the c-axis of the particle will be aligned perpendicular to the magnetic field if $G_m^{a,b} < G_m^c$. **Figure 5** gives the solidification morphology of Al–Cu alloy with or without a high magnetic field. Magnetic alignment of Al_2Cu phase and competition between the easy magnetization axis and the preferred growth orientation was clearly observed.[43] In recent years, strong magnetic field effects had been well investigated and a range of other effects had already been realized, including magnetic segregation of weakly magnetic materials, magnetic levitation, magnetic induced interfacial energy, magnetic induced/damped diffusion etc., which can be found in recent reviews.[5,8,44,45]

3. Industrial Application Potential – A Specific Case Analysis on Electromagnetic Field Assisted Inclusion Removal from Liquid Metals

The application of some EM fields in industry has been well established, ranging from EMBR, induction heating, cold crucible etc.[8,19,22,42,44] One of the important aspects for the engineering of electromagnetic fields is for clean metals production. The physics of electromagnetic field assisted inclusion removal depends on the nature of the applied EM field. A range of research had been conducted concerning improving the removal efficiency by tuning the

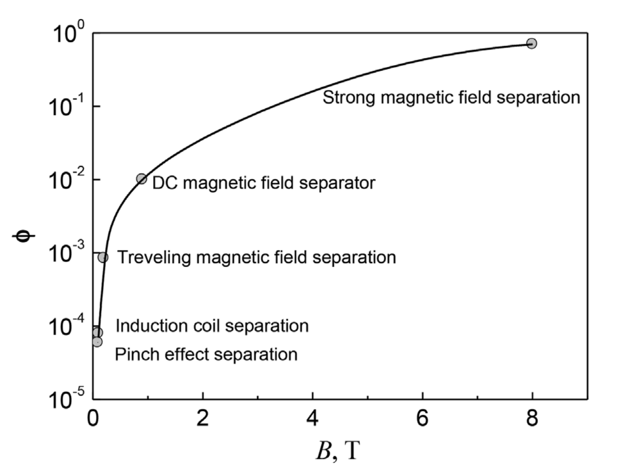

Figure 7. The energy coefficients (φ) versus magnetic flux density (B, T) of five representative separation technologies for inclusion removal from a liquid metal.

Electromagnetic [EM] fields			DC magnetic field	AC magnetic field		DC/AC current	DC magnetic field and DC/AC current	Strong static magnetic field and high gradient
				Low frequency	High frequency			
EM effect	*a*	Magnetic Damping	✓					✓
	b	Magnetic Levitation			✓			✓
	c	Electromagnetic separation		✓	✓	✓	✓	✓
	d	Electromagnetic stirring		✓	✓			
	e	Electromagnetic heating			✓	✓	✓	
	f	Pinch effect				✓	✓	
	g	Magnetic Vibration		✓	✓	✓		
	h	Unstable flow[a)]		✓	✓	✓		
	i	Magnetic texture	✓					✓
	j	Thermoelectric magnetic effect	✓				✓	✓
Technique/application			Electromagnetic brake (EMBR)[a]	Traveling magnetic field (TMF)[c]	Ingots surface quality controlling[c,e,g,h]	Metal recycling[c]	EM solidification[e,f,j]	EM solidification [a,b,i,j]
			EM casting[a]	Rotating magnetic field (RMF)[d,g,h]	Levitation melting[b,d,e]	Vacuum-arc remelting[e,f,g,h]	Materials preparation[c,j]	Materials preparation[a,c,i,j]

Table 1. Continued

Electromagnetic [EM] fields	DC magnetic field	AC magnetic field: Low frequency	AC magnetic field: High frequency	DC/AC current	DC magnetic field and DC/AC current	Strong static magnetic field and high gradient
	EM solidification[a,i,j]	Shaping of liquid metals[d,g,h]	Soft contacting solidification[b,e]	Hall-Heroult process[e,h]	Magnetic pumping[f]	EM assisted phase transformation[a,i]
		Liquid metal emulsion[d,g,h]	Physical properties measurement[b,c,g]		Liquid metal velocity measurement[c,f]	
Device/facility	Electromagnets Permanent magnets	Induction furnace	Induction furnace Cold crucible furnace	Arc furnace Aluminum reduction cell	Electromagnets	Superconducting magnet
References	[15,48–50]	[24,27,51–54]	[14,24,31,55–62]	[31,32,63]	[14,15,18,48,49,64–68]	[8,69–72]

[a)]Unstable flow indicates the turbulence induced by an AC field or the axisymmetric flow induced by a current.

Table 1. A summary for electromagnetic field processing of metallic materials (part of the information extracted from.[73])

electric and magnetic fields in the removal process.[19] **Figure 6** shows the principles of solid particles migration in a liquid metal under different EM fields.

As given by Equation 4, solid particles in a conductive liquid metal experience the electromagnetic Archimedes force with which a Lorentz force is working on the liquid metal. In order to separate the solid particles from the liquid, the conductivity of the particles needs to be significantly small comparing with the liquid. In this case, it is always a combined EM field with a current and an imposed magnetic field. Therefore, the energy efficiency is always an important criteria to evaluate the efficiency of the electromagnetic processing. It has been known that in a traditional electromagnetic process for inclusion removal, the supplied power is mostly consumed by heating the liquid metal.[19] The Joule heating density can be calculated by

$$Q_{\mathrm{J}} = \frac{J^2}{\sigma_{\mathrm{M}}} \tag{7}$$

The driving force for inclusion removal can be represented by the force working directly on the inclusion particles as $f_{\mathrm{P}}^{\mathrm{EA}}$. Therefore, the effective energy on the solid inclusion migration/removal is

$$E_{\mathrm{P}} = f_{\mathrm{P}}^{\mathrm{EA}} \times v_{\mathrm{P}} \tag{8}$$

where v_{P} is the terminal velocity of an inclusion.

The velocity is obtained via

$$v_{\mathrm{P}} = \frac{d_{\mathrm{P}}^2}{18\eta_{\mathrm{M,B}}} f_{\mathrm{P}}^{\mathrm{EA}} \tag{9}$$

where d_{P} is the diameter of the inclusion particle, $\eta_{\mathrm{M,B}}$ is the apparent viscosity of the melt in a specific magnetic field.

By substituting Equation 8 to 9, the energy to intrigue inclusion removal can be expressed by

$$E_{\mathrm{P}} = \frac{d_{\mathrm{P}}^2}{18\eta_{\mathrm{M,B}}} \left(\frac{3}{2} \frac{\sigma_{\mathrm{M}} - \sigma_{\mathrm{P}}}{2\sigma_{\mathrm{M}} + \sigma_{\mathrm{P}}} J \times B \right)^2 \tag{10}$$

An energy coefficient η is subsequently defined by the ratio of E_{P} to Q_{J}. It can be used to the energy efficiency of a electromagnetic process for inclusion removal.

$$\eta = \frac{E_{\mathrm{P}}}{Q_{\mathrm{J}}} = \frac{\sigma_{\mathrm{M}} d_{\mathrm{P}}^2}{32\eta_{\mathrm{M,B}}} B^2 \tag{11}$$

On the other hand, the dissipation energy lost due to heating the liquid metal is calculated by

$$d_{\mathrm{J}} = Q_{\mathrm{J}} t = \frac{J^2}{\sigma_{\mathrm{M}}} t \tag{12}$$

where t is the processing time for inclusion removal.

The energy coefficient is strongly determined by the separator design and a detailed comparison of different inclusion separators is provided by.[19,47] The typical results are shown in **Figure 7**. It can be found that the strong magnetic field separation method bears the highest energy coefficient. By using a strong magnetic field, a smaller current density is required to reach the same removal efficiency of inclusions from a liquid metal and the heat loss can be dramatically decreased according to Equation 7. It will also increase the stability of the liquid metal temperature and should be beneficial for process control. A case study had been carried out on inclusions removal from liquid aluminum.[12] In a gradient magnetic field without the electromagnetic Archimedes force, the migration time for 1 mm of an inclusion (diameter of $20\,\mu$m) was found to be <20 s, when the magnetic field gradient product is $\approx 10\,T^2\,m^{-1}$.[8] This force, however, only reaches the same magnitude with its gravity force of the inclusion particles at a gradient product of $600\,T^2\,m^{-1}$. It means the removal efficiency will be rather low by using only a high gradient magnetic field, especially for the removal of small inclusions.[8,12,44] By using a combined electromagnetic field, it is found that the electromagnetic force magnitude is improved significantly. For instance, the electromagnetic Archimedes force of a 10 T magnetic field and $1500\,kA\,m^{-2}$ current density can be 500 times larger than the magnetic force in a gradient field. Detailed investigations have been given in ref.,[12] where alumina inclusion of $5\,\mu$m can be totally removed in 2 s in a 40 mm refractory tube from liquid aluminum.

However, the implementation of a strong magnetic field into a real industrial process is still in progress. One of the drawbacks for the application incurs from relatively high capita and maintenance cost. Concerning this, detailed economic evaluation needs to be further carried out, by considering the total cost as well as profit in a process with strong magnet implemented and a proper magnitude of the magnetic field density shall also be designed in accordance to the industrial practice. Nevertheless, further improvement on advanced materials preparation for magnetic field generation in order to decrease the cost of a magnet is of high importance.

4. Conclusions and Discussion

This paper overviews the recent progress of electromagnetic fields processing of metallic materials. A range of electromagnetic effects on the metallic materials morphology or flow behavior as well as on the corresponding particles have been observed and applied in the field of metallurgical and materials engineering. As given in **Table 1**, the effects include magnetic damping, magnetic levitation, pinch effect as well as magnetic texture, and thermoelectric magnetic effect, etc. All the effects depend, significantly, on the electromagnetic response from the processed material and physics of the applied EM field. In general, four types of representative EM fields are used to process metallic materials: (i) traditional static magnetic field with or without an electrical current; (ii) only imposing a direct or alternative current; (iii) traveling or alternative magnetic field; and (iv) a strong static magnetic field with a high gradient or a current. From both scientific and industrial perspectives, electromagnetic fields have been widely applied to control the quality of metal billets, prepare engineering materials, and measure fine physiochemical properties of materials. Recent development in improving the magnetic flux density has enable more significant magnetic effects on weakly magnetic materials. On one important aspect, an EM field can be applied to modify the chemical or physical behavior of a material till the molecular level. Because of this, magnetic levitation of liquid metal and solute diffusion control by applying a specific magnetic field have been achieved. However, in-situ applications are still not enough and the cost of a magnet with strong enough magnetic flux density may be one of the reasons. On the other aspect, by increasing the magnetic flux density, the energy consumption can be highly decreased, when processing liquid metals where using a strong magnetic field is potentially a promising tool to remove very fine inclusions, although the design of industrial systems needs to be further elaborated to meet practical applications. Furthermore, EM field assisted advanced materials preparation can also be considered to extend its applications.

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