Recent development and prospect of electromagnetic processing of materials

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Abstract

Application of electromagnetic force to materials processing, so called Electromagnetic Processing of Materials (EPM) has been recognized as a cutting edge technology, especially in the fields of advanced materials processing. The background to promote EPM is described. The present state of EPM is given through a brief introduction of several examples of the applications of a high frequency magnetic field, a DC magnetic field, DC magnetic and electric fields, and a traveling magnetic field. Furthermore, a high static magnetic field has been applied to generate compression waves in molten metals. As other examples of the application of a high static field, the crystal orientations in thin films in vapor deposition and electrodeposition processes and those in carbon fibers in a graphitization process are described. Finally the future view of EPM is revealed. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Electric energy has been used in metals and materials processing for an extended period of time in melting, refining and solidification. These processes included the passage of a current through conducting mediums such as molten metals and electrolytes. While there has been an awareness that Magnetohydrodynamics (MHD) phenomena were inherently associated with these technologies, early works on MHD in metals processing became more widely known as a consequence of a symposium held in 1982 by the International Union of Theoretical and Applied Mechanics (IUTAM) at Cambridge University, England [1].

Encouraged by the symposium, the Iron and Steel Institute of Japan (ISIJ) pointed out that such an application had to be studied, and inaugurated the Committee of Electromagnetic Processing of Materials in 1985. Beginning in the iron and steel industry, this new movement has grown and the first International Symposium on Electromagnetic Processing of Materials (EPM) was held in Japan (Nagoya) in 1994, the second in Paris in 1997 and the third in Nagoya again in 2000. Based on the recognition of the importance of EPM, the Ministry of International Trade and Industry of Japan has started the national project based on the academic knowledge obtained in EPM research activity. Furthermore, the Ministry of Education, Science, Culture and Sports of Japan has selected the research on New Development in EPM as one of the Scientific Researches on Priority Areas in 1998.

2. Functions of electromagnetism applied to materials processing

There are several functions making use of Lorentz force that are applicable to the materials processing as follows. The function of shape control is based on the magnetic pressure given as \( P_m = B^2/2\mu \). The function of fluid driving is induced by imposing a direct electric current and a magnetic field, \( \mathbf{F} = \mathbf{J} \times \mathbf{B} \), or by imposing a traveling magnetic field (TMF). The function of flow suppression appears when applying a direct magnetic field on moving molten metal, based on the principle of \( \mathbf{F} = \sigma (\nabla \times \mathbf{B}) \times \mathbf{B} \). The function of levitation appears when the gravity force balances with the electromagnetic force, \( \mathbf{J} \times \mathbf{B} = \mu \mathbf{g} \). When electromagnetic force is much larger than the gravity force or the adhesion force due to surface tension, \( \mathbf{J} \times \mathbf{B} > \max (|\mu \mathbf{g}|, 6\pi \sigma a^2) \), the function of splashing takes place. The Joule heat, \( q = |\mathbf{J}|^2/\sigma \), indicates the function of heat generation.

Regarding a magnetization force given as \( (\chi/\mu)(\mathbf{B} \cdot \nabla)\mathbf{B} \)
and $M \times B$, which is familiar to us as the force to attract iron to a magnet, the functions of crystal orientation and alignment of solidified structures are useful in the materials processing.

3. Present state of research and development in EPM

3.1. Application of high frequency magnetic field

3.1.1. Improvement of surface quality of cast steel

The improvement of the surface quality of continuously cast steel is indispensable for directly connecting the continuous casting stage to the rolling stage, which will provide a large amount of energy saving due to the elimination of the process of reheating slabs and the process of surface treatment. As surface defects usually arise at the interface between a mold and molten metal, the electromagnetic casting (EMC) [2] developed in aluminum industry can be regarded as an ideal method. In EMC a molten metal is confined not by a mold but by the magnetic pressure, i.e. EMC is a moldless casting. However, it is almost impossible to apply EMC to the casting of steel due to the higher density and faster casting velocity in steel than those in aluminum. These days an alternative process for improving the surface quality for steel has been found where an alternating magnetic field is imposed from the outside of a mold [3]. It was revealed that the reduction of the hydrostatic pressure between a mold and molten metal due to the magnetic pressure and the stabilization of meniscus are the main crucial factors to obtain a good surface quality in this process. Photo 1 shows the effects of the magnetic field intensity on the surface aspect of cast steel [4]. Fig. 1 shows the effect of the imposed magnetic field on the surface roughness of cast steel [4].

An intermittent high frequency magnetic field, for which a field pattern is given in Fig. 2, was newly proposed for control of the oscillating behavior of meniscus [5]. Furthermore, the intermittent frequency of the field has been synchronized with mold oscillation so as to suppress the resonance effect on the wave motion of a molten metal [5]. The solidification taking place in this way has been named Soft Contacting Solidification [3] because of the appearance of a soft contacting condition as the reduction of the hydrostatic pressure and this technology, which has been selected as a national project of the period of...
in a crucible using the magnetic pressure, this process enables the melting of a charge without contamination from the crucible under an arbitrary atmosphere. Thus, the cold crucible is indispensable for melting metals with high melting points and chemically reactive properties.

There are two types of cold crucibles. One is the levitation type in which the maximum levitated load of molten metal is presently as high as 55 kg [6] and the national project aiming a large size crucible as much as 1000 kg is running in Japan. The molten intermetallic compound of TiAl was successfully cast into a turbocharger by combining this type of cold crucibles with the technology of precise casting, as seen in Photo 2 [7].

3.2. Application of DC magnetic field

3.2.1. Electromagnetic brakes

A DC magnetic field can suppress any fluid motion not parallel to the applied magnetic field lines. An electromagnetic brake (EMBR) is a typical example using this function. Electromagnetic brakes have been used in commercial continuous casters to improve the surface quality of cast steel and reduce the entrapment of inclusions into solidified steel. The electromagnetic brakes may be classified into two types, as shown in Fig. 4 [8]. Type A has a DC magnetic field applied locally near the outlet of an immersion nozzle to brake the discharge flow directly. Type B has been developed where the magnetic field is imposed over the width of a strand pool [9]. Regarding the technology of electromagnetic brakes a TMF is also useful and competitive tool against EMBR.

3.2.2. Bimetallic slab [10]

In order to produce bimetallic slabs in a continuous casting process, a DC magnetic field, which has the function to suppress the fluid motion, has been applied. A schematic illustration of a test caster is shown in Fig. 5. Molten steels of different composition kept in two tundishes were discharged through the immersion nozzles A and B to the upper and the lower parts of the molten pool which were bordered by a level DC magnetic field. An 18-8 type stainless steel and a plain steel were poured into the upper and the lower parts, respectively. Photo 3 shows the etched cross section of the bimetallic slab. It is seen that the outer layer of stainless steel and the inner part of plain steel are clearly separated. This implies that the plain steel in the lower pool did not reach the upper pool of the stainless steel because the circulation through the region of the level magnetic field was substantially confined by the DC magnetic field.

3.3. Application of DC magnetic and electric fields

Due to the increasing demand for high quality metals, the purification of molten metal is becoming increasingly crucial. As a result, reasonable methods for the separation and removal of inclusions from molten metals are being demanded. The principle of electromagnetic elimination
of inclusions was firstly proposed by Marty and Alemany [11], in whose work DC magnetic and electric fields were perpendicularly imposed on a molten metal. In principle, electromagnetic force is induced in the metal and not in the inclusions due to their low electric conductivity. By the reaction of the electromagnetic force induced in metal, the inclusions are pushed into the direction opposite to that of the electromagnetic force, as shown in Fig. 6. The force acting on the inclusions is named electromagnetic Archimedes force.

To confirm the principle, a model experimental work [12] was conducted by the use of a NaCl aqueous solution, which contained polyethylene particles with their density adjusted to that of the solution, and was filled in a U-shaped tube. Under the imposition of a magnetic field perpendicular to the figure plane, an electric current was imposed from the left hand tube to the right hand one using a battery, as shown by a solid line in Fig. 7. As in this case the electromagnetic Archimedes force is induced in the outer direction of the U-shaped tube, polyethylene particles gathered on the outer sidewalls of the tube. When the electric current was imposed inversely by the battery as shown by a dotted line, the particles gathered on the inner sidewalls of the tube. The electromagnetic elimination of inclusions mentioned here was also demonstrated in a model experiment using molten tin containing Al2O3 inclusions and the principle was confirmed [12].

3.4. Application of Traveling Magnetic Field [13]

We proposed a new method for eliminating inclusions in a metal by using a TMF, which used to be adopted for transport and mixing of molten metals. The concept of the method is given in Fig. 8, where the molten metal flows in the y-direction through tubes and the traveling direction of the magnetic field is in the z-direction. The molten metal flow in the z-direction forced by TMF is constrained by the surrounding walls of tubes. Then, inclusions are
moved in the direction opposite to the traveling direction of the magnetic field and gathered on the walls due to the electromagnetic Archimedes force. The idea of the electromagnetic elimination of inclusions using TMF was demonstrated in a model experiment using molten aluminum containing Al$_2$O$_3$ inclusions and confirmed, as shown in Photo 4.

4. Materials processing by use of a high static magnetic field

By the advance in super-conducting magnets, a high magnetic field has become readily available and is being applied in various fields of science. In this trend many interesting phenomena relating to a high magnetic field have been found and a new academic field named Science RELating with a High Magnetic Field is going to open a gate. In order to connect the seeds sprouting from the new academic field with the needs of Materials Science and Engineering, the new field of Materials Processing by Use of a High Magnetic Field will grow under the umbrella of EPM. By researching Materials Science and Engineering from the viewpoint of a high magnetic field, the creation of new and functional materials and the development of rational materials processing are expected. Utilization of a high magnetic field in materials processing is classified in Table 1.

4.1. Morphology tailoring of electrodeposits [14]

Mogi has studied a high static magnetic field effect on pattern formation of electroless deposits of metals to develop a new processing method of morphology tailoring. Ag metal-leaves, which are deposited by a chemical reaction of $2\text{Ag}^{+} + \text{Cu} \rightarrow 2\text{Ag} + \text{Cu}^{2+}$, were grown two-dimensionally between two glass plates, and a magnetic field as high as $8 \text{T}$ was applied perpendicular to the plate using a superconducting magnet. The magnetic field considerably changes the growth pattern, as shown in Photo 5. This effect could be categorized into the enhancement of Lorentz force in ultra small current in Table 1.

4.2. Generation of compression wave in a liquid metal [15]

Compression waves have useful functions such as degassing, acceleration of reaction rate, refinement of solidified structures, dispersion of substances in a molten metal in metallurgical processes. The mechanical method using electrostrictive or magnetostriuctive vibrators has been applied to these processes. However, the method has been restricted to laboratory scale experiments because of the problems such as contamination due to the dissolution of a transmitter, the attenuation of the power of a transmitter, and the limit of the power generated by a vibrator. To overcome the above problems, the development of a non-contacting operation is indispensable. In fact it was reported that the imposition of a high frequency electromagnetic field could generate compression waves in a liquid metal directly [16]. This non-contacting method is very attractive though the excited pressure was too weak to apply on practical processes. On the other hand, a static magnetic field of about $10 \text{T}$ over about $10^{-1} \text{m}$ size has become available due to the development of superconducting technologies. Thus, in order to intensify the pressure of the compression waves, DC and AC magnetic fields were simultaneously imposed on a liquid metal. The alternating magnetic field of $60 \text{kHz}$ was imposed on a metal by a 10-turns coil surrounding the vessel. Pressure oscillations with the double frequency of that in AC magnetic field were detected by a sensor located.
in the center of the metal. This experimental result revealed that the observed pressure was acoustic and the compression waves were generated. The results obtained under the different intensities of DC and AC magnetic fields are shown in Fig. 9. The solid line is a theoretical prediction. The detected pressure increases with increase of the product of the magnetic fields though the measured pressure appeared rather less than the theoretical prediction. It is noticed that the maximum pressure observed in the experiment was close to one atmospheric pressure at which cavitations can take place in a liquid metal. This fact implies that this process is hopeful for applications in practical operations.

4.3. Possibility of utilization of magnetization force

When making use of a magnetization force, which may be expressed as \( F = (\chi/\mu_0)B \text{grad}B \) or \( F = M \times H \) for isotropic paramagnetic and diamagnetic materials, we have to pay attention to the value of a magnetic susceptibility \( \chi \). So far the utilization of the magnetization force has been limited to ferromagnetic materials such as iron and nickel since \( \chi_f(\approx 10^3) \) in the ferromagnetic materials and \( \chi_n(\approx 10^{-3}) \) in the nonmagnetic (paramagnetic and diamagnetic) materials are very different and the ratio of \( \chi_n \) to \( \chi_f \) is as low as \( 10^{-6} \). That is, the magnetization force appearing in the nonmagnetic materials has been neglected. These days the development of super-conducting magnet technologies

Photo 5. Magnetic field dependence of the metal-leaves patterns in electroless deposition [14].

Fig. 9. Comparison between the detected and theoretically predicted pressures on the plane in pressure and product of DC and AC magnetic fields.
This fact and the scientific background mentioned above are very promising to open the gate of a new EPM, in which non-metallic materials will be included. In Photo 6 we can see candlelights deformed due to the magnetization force by the imposition of a magnetic field.

4.4. Crystal orientation [18]

The crystal orientation is one of the most crucial factors to determine the electric, magnetic and mechanical properties, etc., so that the development of crystal alignment method has been desired. As in general, a unit crystal has different magnetic susceptibilities depending on the crystal orientation, the utilization of this property enables us to develop crystal alignment methods.

Electrodeposition and vapordeposition processes and graphitization process of carbon fibers were carried out under a high magnetic field. The crystal orientation in films obtained in the former two processes was studied and the strength of carbon fibers in the latter process was examined.

4.4.1. Electrodeposition

Zinc crystal has a h.c.p. lattice with magnetic anisotropy where magnetic susceptibilities along \( a \)-or \( b \)- and \( c \)-axes are \( \chi_{a,b} = -1.81 \times 10^{-5} \) and \( \chi_c = -1.33 \times 10^{-5} \), respectively. In a magnetic field, the crystals are so rotated that the crystal axis with the largest susceptibility should be in parallel to the direction of the magnetic field, i.e. \( c \)-plane in Zinc film will be in parallel to the direction of the magnetic field. Thus, we can expect \( c \)-plane orientation when a substrate as cathode is set in perpendicular to the magnetic field. At first the substrate was set in perpendicular to the field and was electrodeposited at 700 A/m². Fig. 10 shows the relationship between the orientation indexes of electrodeposited films and the imposed magnetic flux density. Orientation indexes of \( c \)-plane (002) increase with increase of the magnetic flux density. That is, the higher the magnetic flux density is the more conspicuously the effect of the magnetic field appears.

![Fig. 10. The relationship between magnetic flux density and orientation index of zinc electrodeposits obtained at \( J = 700 \) A/m².](image)

![Fig. 11. Distribution of orientation index of \( c \)-plane under the different magnetic flux density.](image)
4.4.2. Vapor deposition

Bismuth was vapor deposited in a superconducting magnet. The orientation indexes of the c-plane (003) in Bismuth were plotted along the distance from the target under the different magnetic intensities as shown in Fig. 11. In the case of 0 T no specific orientation is clearly observed at all. The orientation indexes, however, surely increase with increase of the intensity of magnetic field and along the distance from the target. In order to make the magnetic orientation tangible the magnetic energy accumulated in a particle should exceed the thermal energy.

\[ \frac{1}{2} \mu_0 \Delta \chi H^2 V > kT, \]  

where \( \mu_0 \) is the permeability in vacuum, \( \Delta \chi \) the difference of magnetic susceptibilities along crystal orientations, \( H \) the imposed magnetic field, \( V \) the volume of the particle, \( k \) the Boltzmann’s constant and \( T \) the absolute temperature.

From the above equation it can be imaged that the orientation due to the magnetic field could be suppressed in the vicinity of the target due to the thermal energy introduced by a laser source. Molecules evaporated from the surface of the target agglomerate to become a particle during flying from the target to the substrate and the particle feels the magnetization force when the volume of the particle exceeds to the value in which Eq. (1) is satisfied.

4.4.3. Graphitization process of carbon fibers

The relation between the tensile strength and the diameter of graphitized fibers is shown in Fig. 12. The increase of the tensile strength to more than 30% has been established by imposing a magnetic field, particularly in a direction parallel to the fiber axis rather than perpendicular to it. However, no difference in the degree of crystal orientation obtained by X-ray diffraction analysis has been detected between the samples treated with and without the magnetic field. Thus, the magnetic field could have the function of decreasing flaws on which the tensile strength of carbon fibers strongly depends.

4.5. Magnetic phase transformation [19,20]

In iron-based alloy, there are many solid-solid phase transformations in which the magnetic moment of parent phase and product phase is largely different, and it is expected that these transformations are affected by a magnetic field. The influence of the magnetic field has been studied in such transformations as recovery, recrystallization, precipitation, ordering, spinodal decomposition, diffusional transformations and martensitic transformation. In these phase transformations, not only the difference of magnetic moment but also magnetocrystalline anisotropy, shape magnetic anisotropy, induced magnetic anisotropy and magnetostriction affect nucleation and growth rate, transformation kinetics, variants and microstructure of product phases.

When steel plates of 0.6% C is subjected to the \( \alpha \rightarrow \gamma \) inverse transformation at 745 °C in the magnetic field of 8 T, the microstructure that consists of a stripe shape in parallel to the magnetic field and network shape in perpendicular to the field were obtained as shown in Fig. 13 [20]. Light area represents \( \alpha \)-phase of initial martensite and dark area is \( \gamma \)-phase generated by the inverse transformation. These figure show (a) the cross section parallel to the magnetic field; (b) the cross section perpendicular to the field; and (c) the microstructure of a specimen subjected to the same treatment but in zero magnetic field. The \( \alpha \)-phase grows along the direction of the applied magnetic field (see (a)) and a honeycomb structure is seen in (b).

5. Conclusions

Fig. 14 reveals an overview of the EPM as a tree. The
roots indicate the academic background supporting this engineering field as follows:

\[
\text{electromagnetic processing of materials} \quad \left\{ \begin{array}{l}
\text{materials processing} \\
\text{magnetohydrodynamics} \\
\text{transport phenomena} \\
\text{thermodynamics}
\end{array} \right. \\
\text{electromagnetism fluid mechanics} \\
\text{magnetic science and technology}
\]

The branches predict functions of electromagnetism and the leaves in each branch show processes and technologies related to the corresponding function as described in the previous chapters.

EPM is based on Materials Processing, MHD and Materials Science and Technology, where the functions of electromagnetism are utilized for the processing of electrically conductive materials. Next to the tree, saplings of the utilization of a high static magnetic field sprout, in which the magnetization force could play an important role in not only electrically conductive materials but also non-conductive ones. The rapid development of super-conducting magnetic technologies should be very promising in the way to push the new field into the realization of actual industrial applications.

In order to develop EPM as a new engineering field, the discovery of new functions which should exist on the boundary among Materials Processing, MHD and Magnetic Science and the successful applications of these functions should be indispensable.

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