Progress on High Magnetic Field-Controlled Transport Phenomena and Their Effects on Solidification Microstructure

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The recent contributions on changes induced by high magnetic fields in transport phenomena, such as convection, solute diffusion, solute or phase migration in the liquid, are reviewed and analyzed. Selectivity provided by the Lorentz, thermoelectromagnetic (a special kind of Lorentz force), and magnetic forces or combinations enables the control of transport phenomena in liquids. This possibility, together with the capability of the transport phenomena to affect solidification in alloys, allows a level of control over solidification microstructures. As a result, recent relevant work can be found dealing with the effects of high magnetic fields on transport phenomena and the corresponding solidification microstructure evolution of alloys, based on the Lorentz, thermoelectromagnetic, and magnetic forces or combinations thereof.

KEY WORDS: high magnetic fields; convection; solute diffusion; solute or phase migration; solidification microstructure.

1. Introduction

The quality of solid materials depends on the microstructure, which is affected by the complicated phenomena of heat/mass transport during solidification. A comprehensive understanding of the evolution of transport phenomena during solidification is essential for the prediction and control of the final microstructure and properties of materials. In recent years, the effect of high magnetic fields on the solidification of alloys has attracted much attention for more precise control of microstructures. In particular, a significant portion of research has been directed to investigating the effect of high magnetic fields on transport phenomena such as convection, solute diffusion, and solute or phase migration in alloy melt. Results have indicated that these transport phenomena exhibit different behaviors in high magnetic fields compared with those under normal conditions. However, the whole physics is very complex, because transport variables are coupled.

Under high magnetic field conditions, the modification of the transport phenomena was produced by the application of the Lorentz force, thermoelectromagnetic force (TEMF, a special kind of Lorentz force), and magnetic force. In a magnetic field, if there is an electric current caused by the movement of an electrically conducting or partially electrically conducting fluid in the field, a Lorentz force will be produced through the interaction of the electric current and the applied magnetic field; if there is a thermoelectric current at a liquid/solid interface caused by the Seebeck effect, a TEMF will be produced by the interaction of the current and the applied magnetic field; if there is a magnetic field gradient, a magnetic force will be induced by the interaction of the magnetization of the material and the imposed magnetic field gradient. Because these forces show braking or driving effects on materials depending on the magnetic field conditions, their effects on transport phenomena are either cooperating or competing with each other.

Because microstructures are directly related to convection, solute diffusion, solute or phase migration, research has then been extended to understand the evolution of solidification microstructures with these magnetic field-modified transport phenomena. The results suggested that the attendant transport phenomena in high magnetic fields can have a profound impact on the development of the solidification microstructure. There arises then the possibility of a direct processing route in the in situ control of transport phenomena and thus solidification by high magnetic fields.

This paper reviews the progress on high magnetic field-controlled transport phenomena and their effects on solidification microstructure. In Sec. 2, the evolution of convection, solute diffusion, and phase or solute migration in liquids in high magnetic fields and the synergism between these transport phenomena and high magnetic field are discussed first. Next the development of the solidification microstructure with these magnetic field-modified transport phenomena is discussed in Sec. 3, where emphasis is given to new findings related to the magnetic field-modified phase or solute migration. Sec. 4 provides a summary.
2. Controlling Transport Phenomena with High Magnetic Fields

A number of experimental investigations and numerical simulations have been performed. Their goal was to explore the effect of high magnetic field on transport phenomena during solidification. This study is undertaken with the objective of providing an insight into the evolution of convection, solute diffusion, and phase or solute migration in liquids in high magnetic fields, with an emphasis on understanding the synergism between transport phenomena and high magnetic field.

2.1. Control of Convection

2.1.1. Suppressing Natural Convection

It is an established physical fact that the movement of an electrically conducting fluid, completely or partially, can be suppressed by a Lorentz force in the presence of a magnetic field; much experimental evidence supports this conclusion. This phenomenon is also being successfully used in some high temperature processes such as solidification to weaken the convective flows.

Based on the theoretical analysis of magnetic-field suppression on thermal convection in electrically conducting fluids performed by Chandrasekhar, Utech and Flemings successfully eliminated solute banding caused by turbulence convection in a Te-doped InSb crystal by applying a magnetic field during crystal growth. Following their work, extensive numerical and experimental studies were conducted to examine the effects of magnetic field on the flow structure and stability of liquid metals. Some of the numerical studies have focused on the natural convection in cavities or cylindrical annuli with a broad range of physical and geometrical parameters. Oreper and Szekely reported that the magnetic field can suppress natural convection and the extent to which convection can be suppressed depends on the strength of the magnetic field. Venkatachalappa and Subbaraya presented numerical results for a fluid in a rectangular enclosure in a vertical magnetic field with uniform heat flux from the side wall. The results show that the temperature and velocity fields were significantly modified by the application of a magnetic field. Similar research, performed by Rudraiah et al., confirmed this modification and further suggested that the rate of heat transfer was decreased through suppressing convection. Some of the other numerical studies have also been made to examine the effects of magnetic field on Czochralski crystal growth and other phase change problems. The numerical results showed that the oscillatory flow in the Czochralski melt can be suppressed by applying a magnetic field. Furthermore, suppression is strongly dependent on magnetic field direction, namely, an external magnetic field aligned perpendicular to the heated vertical wall was found to be more effective than a field applied parallel to the wall. For the Czochralski growth of large diameter (> 300 mm) crystal, the application of a cusp magnetic field has also been paid much attention due to the three-dimensional control of the distribution of the magnetic flux density in the melt. Numerical simulations have played an important role in understanding the development of convection in magnetic fields. However, experimental work on natural convection in a melt is very limited, especially concerning the direct measurement of thermally induced melt convection. Some previous experimental investigations focused on temperature measurements from which magnetic suppressing effects are deduced. For example, Okada and Ozoe measured temperature profiles in molten gallium contained in a cubic cavity and confirmed the suppression of natural convection induced by temperature gradients using a magnetic field. With the help of the hot-wire probe technique, Xu et al. obtained direct measurements of the melt flow velocity in molten gallium with and without an imposed magnetic field. Magnetic field suppression of convection was observed in both the measured velocity and temperature profiles. Bonvalot et al. and Yasuda et al. investigated experimentally high magnetic field suppression of convection in metallic melts using a magnetic levitation method. In the work of Yasuda et al., they observed using a CCD camera the motion of Cu and Ni melts which were levitated by the simultaneous imposition of static and alternating magnetic fields. Figure 1 shows the shape sequence of the levitated Cu melt. By applying a static magnetic field, suppression can be seen in the oscillations, convection, and rotations about axes perpendicular to the static magnetic field direction.

2.1.2. Thermo-electromagnetic Convection

During the growth of mixed or doped crystals or of alloys, an externally applied static magnetic field can create thermo-electromagnetic convection (TEMC). A thorough description of TEMC was provided by Shercliff. Based on the flow of liquid metals in cooling devices, he gave an excellent outline of the TEMC theory and an order of magnitude estimation of the corresponding flow velocities as a function of the applied magnetic field. In 1966, Youdelis and Dorward performed a directional solidification experiment involving an Al–Cu alloy in a magnetic field and measured the effective partition coefficient. They found unexpectedly that at high pulling rates, the partition coefficient decreased with the field suggesting that solute diffusion had been field enhanced. However, they did not attribute the change of the partition coefficient to TEMC. One of the earliest proofs of TEMC in crystal growth was given by Gel’fag and Gorbanov. They reported that during the growth of InSb crystals using the Czochralski method, the application of a magnetic field would cause a strong deformation in the crystal shape that occurred because of the appearance of TEMC flows. The following theoretical studies gave configurations in crystal growth in which thermoelectric currents are strong enough to create TEMC: 1. The Seebeck coefficient of the solid and the liquid are different and the solid/liquid interface is not isothermal; 2. The Seebeck coefficient is a function of composition and there is a concentration gradient along the isothermal solid/liquid interface. 3. The melt and the container have different thermoelectric powers and the melt-container interface is not isothermal. Apart from these theoretical studies, other researchers have performed a series of directional solidification experiments in magnetic fields to investigate the TEMC effect. The striation- and freckle-type segregations, mainly observed in some semiconductor crystals and alloys respectively, evidenced the presence of TEMC at
the growth interface and mushy region. Recently, using an in situ synchrotron X-ray imaging method, Wang et al. observed the motion of detached fragments of dendrites driven by TEMC during directional solidification of an Al–Cu alloy in a static magnetic field. As shown in Fig. 2, the motion of a fragment near the liquid/solid interface gave direct evidence of the presence of TEMC. Note also that the liquid motion due to the TEMF can also induce a Lorentz force which will, in turn, brake such motion. This was evidenced in some experimental studies. Recently, Li et al. theoretically predicted the competition between the Lorentz force and TEMF in affecting convection at different length scales. As shown in Fig. 3, the flow initially increased with increasing magnetic flux density (TEMF-driven) and then decreased after reaching a peak (Lorentz force-suppressed), although the peak and corresponding magnetic flux density were different for different length scales.

2.1.3. Magnetic Force-modified Convection

Although phenomena resulting from a magnetic force have been known for many years, convection driven by magnetic forces had been almost neglected until super-conducting magnets, which can produce magnetic fields as large as 10–20 T, became available. If the magnetic field gradient coexists with the magnetic susceptibility gradient in a fluid, the
convection in the fluid can be controlled by the induced magnetic force. Unlike the Lorentz force, it does not require the material to be electrically conductive and possibly applies to insulating fluids. For a paramagnetic fluid whose magnetic susceptibility is in accord with Curie’s law, the gradient of the magnetic susceptibility caused by the temperature gradient in the fluid can create a fluid motion dependent on the magnetic force; for a diamagnetic fluid whose magnetic susceptibility is dependent on the density, the gradient of the magnetic susceptibility caused by the density gradient can also modify the convection in terms of the magnetic force. Studies were initially focused on paramagnetic gases and liquids. For example, Uetake et al.31) put a ceramic tube in a high magnetic field and heated one part of the tube to produce a thermal convection of air (paramagnetic, the magnetic susceptibility at room temperature is $0.38 \times 10^{-6}$). By adjusting the position of the heating center in the magnetic field to control the direction of magnetic force acting on the air, the thermal convection flow was either accelerated or suppressed. Braithwaite et al.32) investigated convection in a solution of gadolinium nitrate (paramagnetic, the magnetic susceptibility at room temperature is $1.63 \times 10^{-7}$ m$^3$ kg$^{-1}$) in a system comprising a horizontal fluid layer heated from below (Rayleigh-Bénard system) in a magnetic field. They produced both the enhancement and suppression of the buoyancy-driven convection due to the magnetic field gradient. In regard to convection in diamagnetic fluids, several theoretical studies33–35) modeled the magnetic force by considering magnetic susceptibility as a function of density which is dependent on the temperature or concentration, and predicted that the convection can be either enhanced or suppressed by a magnetic force. Recently, this prediction has been confirmed by experimental studies. Nakamura et al.36) configured a system of a horizontal fluid layer heated from below (Rayleigh-Bénard convection) to investigate the effect of the magnetic field on convection in water (diamagnetic, the magnetic susceptibility at room temperature is $-9.1 \times 10^{-9}$ m$^3$ kg$^{-1}$). By measuring the temperature difference using thermocouples and observing images of convection patterns using the shadowgraph technique, they found evidence that convection in diamagnetic fluids can be either suppressed or enhanced depending on magnetic force direction. Figure 4 shows the shadowgraph images of convection patterns near the onset of convection driven by the magnetic force.

2.2. Controlling Diffusion

Solute diffusion plays an important role in affecting crystal growth and solidification. Some effort has been made to investigate the effect of high magnetic field on solute diffusion in both liquid metals and in solid/liquid interfaces.

2.2.1. Diffusion in Liquid Metal

Mathiak and Frohberg37) measured the diffusion coefficient in an In-Sn liquid system in various high magnetic fields by a capillary method. The measurement results indicated that the application of the magnetic field can suppress the diffusion in horizontal capillaries and has little effect on that in vertical capillaries. The diffusion coefficient measured in transversal magnetic fields higher than 3 T was consistent with that measured in microgravity. Using a similar method, Miyake et al.38) investigated the temperature dependence of interdiffusion coefficient of In-Sn with and without a 4-T magnetic field. Their results confirmed a decrease in diffusion under an applied magnetic field (Fig. 5). Botton et al.39) measured the diffusion coefficient of an impurity in liquid metals in the absence and presence of a magnetic field using a shear cell method. Results also showed a decrease in the diffusion coefficient with magnetic field. Furthermore, they predicted that a field of around 2.5 T would be enough to suppress diffusion in liquid metals to the same extent as that measured in microgravity. Their prediction agreed with the experimental results obtained by Mathiak and Frohberg.37) Indeed, the decrease in the diffusion in liquid metals by magnetic field can be mainly attributed to suppressing convection, which causes additional mass transfer, but the effect of magnetic fields on the atomic

![Fig. 4. Shadowgraph images of convection patterns near the onset of convection. The number in each square is the value of $\Delta T$ ($^\circ$C) across the fluid. Convective patterns appear at large $\Delta T$ under the upward magnetic force but at small $\Delta T$ under the downward magnetic force.36)](image)

![Fig. 5. Temperature dependence of the interdiffusion coefficient for the In-Sn alloy with and without a 4-T magnetic field.38)](image)
mobility in liquid metals should be weak.40)

However, for diffusion at solid/liquid interfaces such as in directional solidification of alloys or in solid/liquid interdiffusion couples, changes in the solute diffusion by the application of magnetic field are more complex owing to the presence of TEMC. For example, Youdelis and Dorward19) investigated the effect of high magnetic field on the solute diffusion during directional solidification of Al–Cu alloys by comparing the solute concentration between the formed solid and the bulk liquid (effective partition coefficient). The experimental results indicated that the solute diffusion in liquid phase decreased with magnetic field at low pulling rates and low alloy compositions, but increased at higher pulling rates, indicating that a TEMC was induced at higher pulling rates and caused additional mass transfer. Li et al.29,41,42) and Wang et al.28) characterized the interdiffusion behavior of various solid/liquid interdiffusion couples in high magnetic fields and found out that there is competition between a decreasing effect from the Lorentz force and an increasing effect from TEMF on the solute diffusion depending on the solid/liquid system. For example, in a liquid Bi/solid Bi0.4Sb0.6 interdiffusion couple, the effective diffusion coefficient decreased with increasing magnetic flux density, indicating that the solute diffusion was suppressed by the magnetic field in terms of the Lorentz force which can suppress the convection in the liquid.41) However, in a liquid Al/solid Cu system, the effect of the magnetic field on the solute diffusion was strongly dependent on the magnetic flux density. Figure 6 shows the magnetic-field dependence of the thickness of diffusion layers in liquid Al/solid Cu interdiffusion couples. The thickness of diffusion layers initially decreased with increasing magnetic flux density but increased sharply at about 8.8 T and then decreased again. The authors argued that the TEMC at about 8.8 T was large enough to enhance solute diffusion, but was dampened by magnetic field suppression with fields higher than 8.8 T.28)

2.3. Control of Phase or Solute Migration

The migration of precipitated phases or solute elements in alloy melts has a strong influence on their distribution in the solidification microstructure and hence is important for the properties of the alloys. With the development of superconducting magnet technology, which makes it easier to access high magnetic fields, it is necessary that the magnetic force acting on the particle-like phases is more effective in controlling their migration in alloy melts. Recently, attempts have been made to control this distribution and their product phases in the melt during solidification using high magnetic field gradients.

2.3.1. Particle-like Phase Migration

Fujiwara et al.43,44) have predicted that if the magnetic energy is larger than the thermal energy of a solvent atmosphere, a magnetic force would be necessary to control the migration of particles. Based on this prediction, they successfully controlled the migration of a series of para- or diamagnetic metal ions (the radius is less than 1 μm, Table 1 shows the magnetic susceptibility of typical metal ions at room temperature) which were dispersed in a solution using magnetic field gradients at room temperature and achieved the separation of these ions. In all cases, the migration depended on the magnetic force acting on the metal ions. Takayama et al.45) also attained control of the migration of nonmagnetic particles in a liquid matrix using high magnetic field gradients. In their studies, the migration depended on the dipole-dipole interactions induced in the particles and the magnetic force derived from the field gradient. As seen in Fig. 7, diamagnetic gold spheres (the radius is 0.5 mm, the magnetic susceptibility at room temperature is $-3.45 \times 10^{-5}$) suspended in a paramagnetic solution were driven at room temperature to form a triangular lattice in the plane perpendicular to the magnetic fields.

Recently, research has been extended to high temperature processes such as solidification. Liu et al.46) heated a hypoeutectic Mn–Sb alloy to a semi-solid state to produce a mixture comprising a liquid matrix and paramagnetic

![Fig. 6](image1)

**Fig. 6.** Magnetic-field dependence of the thickness of diffusion layers in different magnetic fields at 973 K.20)

![Fig. 7](image2)

**Fig. 7.** Triangular lattice of the gold spheres formed by the combination of the dipole-dipole interaction and magnetic force. The inset gives a close-up view of the crystal.45)

<table>
<thead>
<tr>
<th>Metal ions</th>
<th>Ca²⁺</th>
<th>Ag⁺</th>
<th>Al³⁺</th>
<th>Fe³⁺</th>
<th>Co²⁺</th>
<th>Cr³⁺</th>
<th>Zn²⁺</th>
<th>Cd²⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic susceptibility, $\times 10^{-6} (\text{cm}^3/\text{mol})$</td>
<td>1 500</td>
<td>-24</td>
<td>-2</td>
<td>15 000</td>
<td>9 500</td>
<td>6 200</td>
<td>-10</td>
<td>-22</td>
</tr>
</tbody>
</table>

Table 1. Magnetic susceptibility of some metal ions at room temperature.43,44)
MnSb particles. After holding the mixture for a period of time in a high magnetic field gradient, the distribution, i.e., the migration, of the MnSb particles in the alloys were successfully controlled. Figure 8 shows the volume fraction distributions of the MnSb particles along the depth from the lower surface of the alloys. Such control was dependent on the direction of the magnetic field gradient, the value of $|\frac{dB}{dz}|$, and holding time. Using a similar experimental procedure, Lou et al.\textsuperscript{47} suppressed the strong segregation of the TiAl\textsubscript{3} particles in an Al/Si melt by a negative magnetic field gradient.

### 2.3.2. Solute Migration

To achieve control of phase migration, the phases should possess large sizes so that the magnetic energy is comparable with the thermal energy especially at high temperature. Generally, it is hard to control the migration of alloying elements by magnetic forces because such forces from a field of about 10 T cannot drive the particles at the atomic scale. However, for a particle/liquid system in a magnetic field gradient, the magnetic influence of the surroundings (liquid) should be taken into account. Thus, an enhanced magnetic force acting on the particles, i.e., the magneto-Archimedes buoyant force coined by Ikezoe et al.\textsuperscript{48}, will be produced.

In terms of this force, Liu et al.\textsuperscript{49} experimentally determined that it is possible to control the solute migration in alloy melts using high magnetic field gradients. They held a Mn(paramagnetic, the magnetic susceptibility in the liquid state is $882.62 \times 10^{-6}$)/Sb(diamagnetic, the magnetic susceptibility in the liquid state is $-1.0048 \times 10^{-6}$) alloy melt in high magnetic field gradients for a period of time and then quenched the melt. By characterizing the distribution of the MnSb phase in the quenched microstructure, they were able to characterize the migration behavior of Mn in the melt. Figure 9 shows typical microstructures of the alloys quenched in various magnetic field gradients. The magnetic field gradient-dependent distribution of the MnSb phase indicates that the magneto-Archimedes buoyant force from a magnetic field of about 10 T acting on the Mn clusters is large enough to control the solute migration in alloy melts. Further experiments suggested that such control was dependent on the direction of the magnetic field gradient, the value of $|\frac{dB}{dz}|$, holding temperature, and holding time.

### 3. Effect of Field-modified Transport Phenomena on Solidification

The effects of convection, together with solute diffusion and solute or phase migration, are of utmost importance when developing solidification microstructures of alloys. Following the research on understanding the evolution of the above-mentioned transport phenomena at high magnetic fields, particular interest has been centered on exploring this development of alloys with these magnetic field-modified transport phenomena.

#### 3.1. Effect of Field-modified Convection

##### 3.1.1. Suppression of Convection

Although it has long been recognized that magnetic fields can be used to improve the quality of semiconductor crystals, the research on the effect of changes in convection on the solidification microstructure of alloys produced new findings. From the suppression by the Lorentz force of the thermal convection in alloy melts, nucleation, phase distribution, solute segregation, and grain growth have been found to be obviously modified. Liu et al.\textsuperscript{50} characterized the nucleation behavior of Ni-90 at.%Cu alloys and pure Sb in high magnetic fields during ingot solidification. An obvious increase in undercooling before nucleation in both materials was observed in the presence of an 11.5-T magnetic field (Fig. 10). Accordingly, an obvious grain refinement was obtained in the Ni–Cu alloys (Fig. 11). The increase in undercooling was attributed to Lorentz-force suppression of melt convection, which can delay the formation of oxides needed for the heterogeneous nucleation. Similar behavior also occurred in glass-fluxed Sb\textsuperscript{51} and Cu\textsuperscript{52} melts solidified in various high magnetic fields. Furthermore, in glass-fluxed Sn melts, the
magnetic force produces additional effects on nucleation behavior.\(^{51}\)

The effect of a vertical magnetic field on the phase distribution and solute segregation in alloys was investigated by theoretical analysis and observations of their solidification microstructure. The migration of the solid phases in the alloy melt is strongly affected by natural convection. In some theoretical studies,\(^{53,54}\) by taking into account that the Lorentz force still has a vertical component with the imposed magnetic field and exhibits a similar effect to that of viscous resistance, the terminal velocity of the solid phases was deduced in terms of the Hartman number. Such quantitative description has been used to characterize the solidification processes for Cu–Pb monotectic\(^ {53}\) and Al–Ni eutectic\(^ {54}\) systems in high magnetic fields. Some experimental studies\(^{55,56}\) suggested that movement of solid phases in the melt was remarkably restrained because the Lorentz force suppressed the natural convection. Thus the sedimentation of the phases in some alloys was obviously inhibited and more homogeneous microstructures were obtained.

Similarly, gravitational segregation of the alloying elements was reduced in some alloys. For example, the segregation of Cu at the lower part of an Al–Cu alloy and Mg at the upper part of an Al–Mg alloy was suppressed more or less by the application of high magnetic fields. The associated efficiency was dependent on the physical properties of the elements such as density and electrical conductivity.\(^{57}\) In addition to natural convection, a high magnetic field was also found to reduce the local flows around the solidifying front caused by solute rejection and thermocapillary effect. Yasuda \textit{et al.}\(^ {58}\) applied a high magnetic field on the directional solidification of an Al-In hypermonotectic alloy to reduce the melt flow near the solidifying front and to enhance engulfment of the In droplets by the Al matrix. An aligned rod structure, generally formed in eutectic systems, was thus fabricated.

3.1.2. Thermo-electromagnetic Convection

Research into the effect of TEMC on the solidification microstructure originates from work on the effect of magnetic fields on directional solidification processes in alloys. During the early years, in an attempt to explore the microstructure evolution with TEMC, Tewari \textit{et al.}\(^ {59}\) directionally solidified a Pb–Sn alloy with and without a 0.45-T transverse magnetic field. As shown in Fig. 12, at low pulling rates, the cellular array was found to be severely distorted with freckles perpendicular to the magnetic field direction. However, they attributed this phenomenon to one of the components of the natural convection being suppressed by the applied magnetic field. Following their work, Lehmann \textit{et al.}\(^ {26}\) directionally solidified a Cu–Ag alloy in a horizontal configuration with and without a transverse magnetic field. Without magnetic field, the microstructure featured a eutectic border at the lower part of the specimen, but with magnetic field the border appeared at the upper part of the specimen. They suggested that this microstructural change was due to TEMC which inverted the direction of convection in the mushy zone. Recently, Li \textit{et al.}\(^ {30,60}\) carried out a series of experimental studies to investigate the influence of TEMC on the morphological instability of the growth interface of Al–Cu alloys during directional solidification. The results obtained indicated that the presence of TEMC destroys the interface shape and the cellular and dendritic morphology.

3.2. Effect of Field-modified Solute Diffusion

During solidification of eutectic alloy systems, the decrease in solute diffusion in the liquid phase induced by high magnetic field has been found to produce obvious effects on the growth of the dendrite and eutectic. Liu \textit{et al.}\(^ {61}\) solidified a hypoeutectic alloy and a near eutectic Al–Si alloy in various high magnetic fields at different cooling rates to investigate the evolution of the secondary dendrite arm spacing (SDAS) of the primary Al dendrites and the lamellar spacing (LS) of the eutectics with the field. The
application of the magnetic field was found to decrease both the SDAS and LS. Furthermore, the magnetic field effect decreased with increasing cooling rate. They attributed this decrease to the weakness of the solute diffusion in front of the growth interface of the dendrite and eutectic. A similar decrease was also observed in the growth of the Al–Al$_2$Cu and MnSb–Sb eutectics and the SDAS of the $\alpha$ dendrites in an Al–Li alloy.

Incorporated with other magnetic field effects such as magnetic orientation, the change of the solute diffusion induced by the magnetic field has also been suggested to modify the growth of the materials with a magnetically anisotropic behavior. By solidifying alloys either from a semi-solid state or melting state in a high magnetic field, various aligned microstructures were produced. For example, in the hypoeutectic Al–Ni alloy solidified from the melting state in a high magnetic field, the primary AlNi$_3$ was observed to be aligned with its long axis perpendicular to the applied field direction. Also, in the dilute Mn–Bi alloy solidified from the semi-solid state in a high magnetic field, the primary MnBi was found to align along the applied field direction. In particular, during the ingot solidification of a Tb–Dy–Fe alloy in the presence of a 4.4-T magnetic field, the cellular grains consisting of (Tb,Dy)Fe$_2$ and (Tb,Dy)Fe$_3$ were highly aligned along the magnetic field direction. Such aligned microstructures are generally formed in directionally solidified alloys and can strongly enhance the magnetic property of Tb–Fe alloys. As shown in Fig. 13, the highly aligned alloy exhibits obvious magnetic anisotropic behavior (Fig. 14(c)).

3.3. Effect of Field-Modified Phase or Solute Migration

3.3.1. Phase Migration

In earlier studies, Al–Si alloys were frequently chosen as model materials to investigate the migration behavior of primary Si in the Al–Si melt. Wang et al. applied high magnetic field gradients during solidification of a hypereutectic Al–Si alloy and successfully controlled the segregation of the primary Si particles. A similar phenomenon was also observed by Jin et al. Using the same procedure, Wang et al. characterized the evolution of the solidification microstructure of a Mn–Bi alloy in high magnetic field gradients. Because the alloy undergoes a paramagnetic to ferromagnetic transformation, the MnBi grains aggregated strongly at one side of the specimen with a varying distribution throughout to form a highly aligned microstructure. Recently, Sun et al. has extended the research to metal-ceramic systems. A graded microstructure with the oxide particles varying throughout the specimen was also produced. In these cases, the particle assembly was governed by the applied magnetic force, magnetic dipole-dipole interactions, and chain-chain interaction. Recently, Liu et al. extended this research to other binary and multi-alloy systems, such as Bi-11.8 wt.%Mn and Al-12Si-11.8Mg-6.5Ti, respectively. During the solidification of Bi-11.8 wt.%Mn alloys in high gradients, there are three typical structures, i.e., primary MnBi, primary Mn and MnBi/Bi eutectic in the alloys whereas for Al-12Si-11.8Mg-6.5Ti alloys, there are five typical structures, i.e., Mg$_2$Si, (Al,Si)$_3$Ti, (Al,Si)$_3$Ti–Ti$_5$Si$_4$ coupled phase, Al/Mg$_2$Si eutectic and Al/Si eutectic in the alloys. Depending on the magnetic susceptibility and density of these structures, their distributions in the alloys were successfully controlled by high magnetic field gradients.

3.3.2. Solute Migration

If the distribution (migration) of alloying elements prior
to alloy solidification can be well controlled, the solidification behavior of the alloys will be altered so that novel microstructures are created. This has support from some experimental results. One of the most significant microstructures arises in one alloy with the simultaneous presence of two primary phases and eutectics. Wang et al.\textsuperscript{74} and Liu et al.\textsuperscript{75} performed a series of solidification experiments of Mn–Sb alloys with various alloy compositions in various magnetic field gradients to characterize microstructure evolution with changes in solute distribution. By changing the direction of the field gradients, a varying distribution of solutes throughout the alloys prior to solidification was produced (Fig. 15 shows for example distributions of alloying elements in eutectic Mn–Sb melts). Depending on alloy composition, the alloys solidified to form different microstructures. For alloys of near eutectic composition,\textsuperscript{74,75} coexistence for both primary MnSb and Sb phases with a continuous change in volume fraction was established in one specimen (Fig. 16). Primary phase locations depended on the direction of the field gradients. For alloys of far-from-eutectic compositions,\textsuperscript{75} the primary MnSb or Sb was segregated to one side of the specimen thus exhibiting a continuous change in volume fraction. Furthermore, the evolution of the microstructure was strongly dependent on alloy composition, specimen dimension, cooling rate, and the $|\beta dB/dz|$ value.\textsuperscript{75}

4. Summary

This review covered the progress on high magnetic field-controlled transport phenomena and their effects on solidification microstructure. Based on Lorentz force, thermo-electromagnetic, and magnetic forces, the application of a high magnetic field was found to be a powerful means to control convection, solute diffusion, and phase or solute migration in liquids. Also evident is the fact that these magnetic field-modified transport phenomena can have a profound impact on the development of solidification microstructure. It is possible to use high magnetic fields to control processes related to transport phenomenon like solidification.

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