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Effects of transverse magnetic field during directional solidification of monotectic Al-6.5wt%Bi alloy

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Monotectic Al-6.5wt%Bi alloy was directionally solidified in the presence of a transverse static homogeneous magnetic field up to 2.0 kG to determine if gravity-induced convection effects could be reduced or eliminated. Growth rate V was varied over the range 1 to 100 μm/s, while temperature gradient at the liquid-solid interface was 120 K/cm. The microstructures of Al-6.5wt%Bi alloy is characterized by regular, aligned Bi fibres or Bi droplets under given growth conditions. Morphological, thermal and magnetic analyses were carried out on sample grown with and without an applied magnetic field. Results indicated that spacing and diameter of Bi fibres decreased in a transverse magnetic field, and the microstructure became more homogeneous, which means that transverse static homogeneous magnetic field can effectively reduce or eliminate gravity-driven and thermal convection during directional solidification of Al-Bi monotectic alloy.

1. Introduction

The monotectic systems are a kind of extensive alloys, some of them have good physical and chemical properties, such as Al-Pb and Cu-Pb alloys are regarded as good wear-resistant materials, Al-Bi and Al-In alloys are regarded as useful materials for light and soft *in situ* superconductors [1].

The monotectic systems consist of elements with different physical properties. The homogeneous liquid L_1 having a monotectic composition transforms to the A solid and B-rich liquid L_2 simultaneously through the monotectic reaction at a constant monotectic temperature. The monotectic alloys have such proprietary characteristics that both A and B elements are almost insoluble in each other in the solid state, liquids L_1 and L_2 have very different densities, and the alloy has a liquid miscibility gap which is very wide in the diagram in hypermonotectic alloys. So it is never easy to obtain a homogeneous alloy melt, and alloys having compositions within the liquid immiscible range solidify, accompanied by heavy gravity segregation before monotectic solidification begins [2–4].

These problems have delayed the utilization of monotectic alloys as industrial materials and systematic work on the solidification of monotectic alloys [5–7]. The main effects to cause coarsening of microstructure of monotectic alloys is gravity induced thermal and solute convection on ground [8].

Several methods are presently known to control gravity induced thermal and solute convection [9]. Generally, the methods can be placed in three broad categories and are: (a) altering the magnitude of gravity-forced buoyancy either by significant reduction in ampoule size, changing the solidification direction with respect to the gravity vector, or reducing the magnitude of gravity through low-gravity processing, (b) applying a compensating Coriolis-type force; and (c) applying either a magnetic field gradient or a homogeneous, static magnetic field. Many of these methods have inherent limitations for application to practical solidification processing. For example, reduction in ampoule size, usually places small diameter ($\leq$0.1 cm) constraints on the size of materials to be solidified; changing the solidification direction so as to minimize solute convection is not possible if the rejected solute has a lower density than the bulk fluid; applying a compensating Coriolis-type force has significant engineering related, practical difficulties and frequently introduces unwanted fluid perturbations, and application of a nonuniform magnetic field gradient can introduce magneto-thermal convection if applied in the presence of thermal gradient. These difficulties suggest that, at present, either processing in low gravity or processing in a homogeneous static magnetic field offers the greatest promise for controlling and minimizing gravity related effects.

In past decades, many experiments on materials processing under microgravity in space had been done, and investigation on the melting, solidification and growth of monotectic systems had been carried out under microgravity in which gravity segregation didn't seem to occur. In hypermonotectic alloys, however, specimens solidified under microgravity showed extreme inhomogeneous structure [10–12]. In this present work, detailed directional solidification experiments on hypermonotectic Al-6.5wt%Bi alloy were investigated in uniform static magnetic fields to determine whether magnetic field can reduce or eliminate gravity and surface tension given convective effects and thermal convection.

2. Experimental procedures

Hypermonotectic Al-6.5wt%Bi alloys were prepared from 99.99mass% purity Al and 99.99mass%purity Bi. The alloys were melted under argon atmosphere in high purity alumina crucibles. The rod-like specimens with a diameter of 5.0 mm and 120 mm long were placed in an Al_2O_3 crucible tube. The specimens were processed in a Bridgman furnace. The maximum temperature gradient is 120 K/cm. Growth rate could vary from 1 μm/s to 100 μm/s. Unidirectional solidification was achieved by driving the alumina crucible downward out of the induction coil at a given rate, which would ensure the solid/liquid interface unmovable. When the monotectic growth front reached the given position, the electric furnace was pulled up quickly as soon as possible, and the solidifying alloy was quenched into Ga-In alloy together with the alumina crucible.

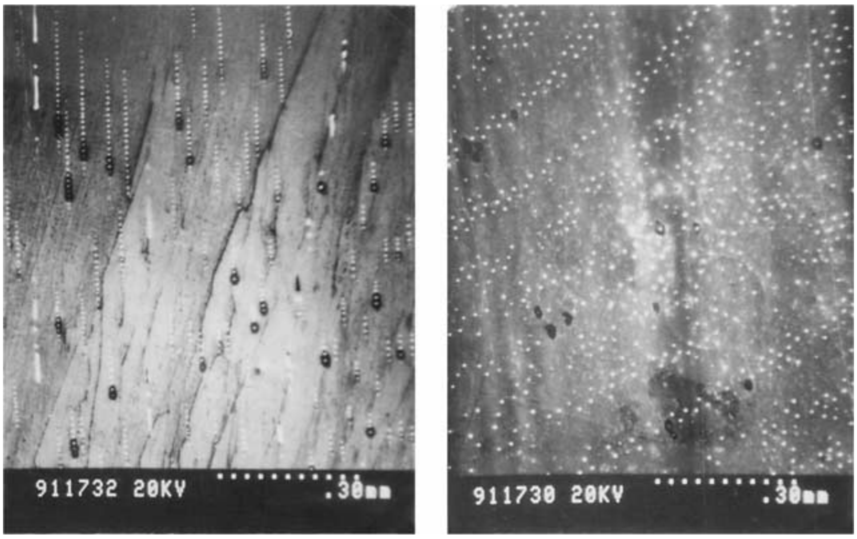
The processed specimens were prepared metallographically parallel and perpendicular to the direction of solidification. The polished specimens are etched with Tucker's reagent. Scanning electron imagings were made for microstructure observation.

The magnetic field strength between the pole faces was calibrated to determine uniformity. A Hall probe with a model TST-21 gaussmeter was used to measure field strength vs. current and voltage with and without the furnace assembly present. The furnace, consisting largely of nonmagnetic material, had negligible effect on field uniformity. Any ferromagnetic parts were far enough from the pole faces not to disturb field strength or shape. By taking the transverse section of the solidified structure, the diameter and spacing of fibres were measured by XQF-2 Image Processing and Analysis System.

3. Results

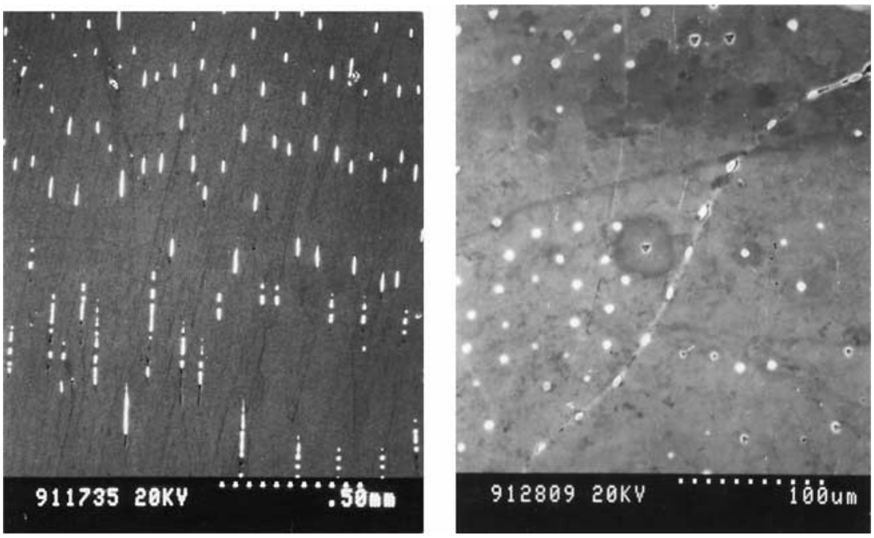
In order to study the effects of the transverse static uniform magnetic on the solidified structure of hypermonotectic Al-Bi alloys, the contrastive experiments were done with and without an applied magnetic field under the same growth conditions. Fig. 1 shows that the directionally solidified microstructure of Al-6.5wt%Bi alloy when the growth rate is 2.1 μm/s at temperature gradient 120 K/cm with 2 kG magnetic field. The black matrix is α-Al, and the bright fibres or arrays are the second phase Bi. Fig. 2 shows the microstructure of this alloy under the same growth rate and temperature gradient conditions, but without magnetic field. Note that the microstructure with magnetic field is similar to that obtained without field under higher temperature gradient and lower growth rate, the microstructure is aligned fibres or regular arrays of Bi droplets. When growth rate is more than 7.21 μm/s at temperature gradient 120 K/cm, the microstructure becomes irregular.

Table I gives the measurement result of the diameter and spacing of Bi fibres or arrays, where λ and d is average fibre spacing and diameter respectively. It can be obtained from Fig. 3a and b, which is plotted from the data in Table I, that the diameter and spacing of Bi fibres or arrays became smaller with magnetic field than that without magnetic field under the same growth condition (same growth rate and temperature gradient), and that the effect become much more marked with the growth rate increase.



(a) (b)

Figure 1 Microstructures of Al-6.5wt%Bi alloy under $B = 2.0$ kG, $G = 120$ K/cm and $V = 2.1$ μm/s (a) longitudinal section and (b) transverse section.

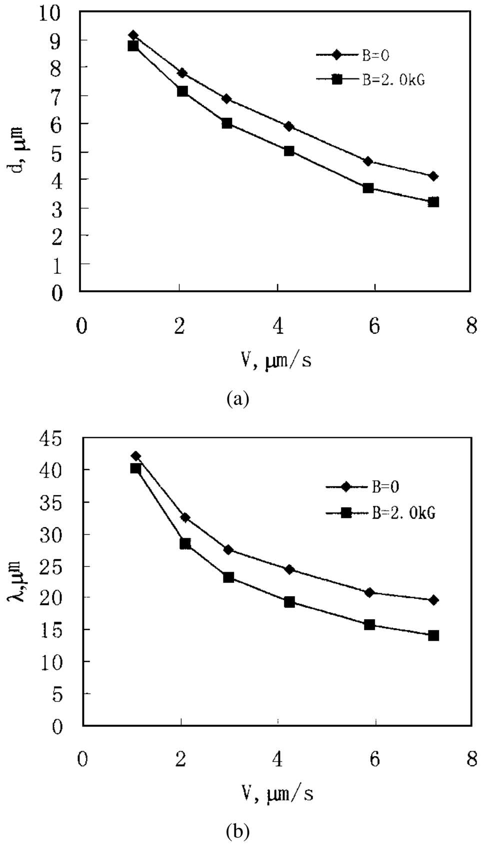


(a) (b)

Figure 2 Microstructures of Al-6.5wt%Bi alloy under $B = 0$, $G = 120$ K/cm and $V = 2.1$ μm/s (a) longitudinal section and (b) transverse section.

TABLE I Spacing and diameter of Bi fibres

B (kG)	V (μms^{-1})	λ (μm)	d (μm)
0.0	1.10	42.20	9.12
0.0	2.10	32.54	7.78
0.0	3.00	27.55	6.84
0.0	4.26	25.03	5.91
0.0	5.89	20.78	4.64
0.0	7.21	19.69	4.10
2.0	1.10	40.13	8.78
2.0	2.10	28.47	7.13
2.0	3.00	23.30	6.02
2.0	4.26	19.43	5.13
2.0	5.89	15.87	3.67
2.0	7.21	14.15	3.17



(b)

Figure 3 Effects of magnetic field on spacing and diameter of Bi fibres.

4. Discussion

Fig. 4 is a schematic representation of transverse field configuration using an electromagnet. Since the components of Al-Bi melt are conductive, an externally imposed, constant magnetic field will interact with the fluid flow generated Lorentz force in the melt. The Lorentz force is proportional to the current density [13]

$$F = J \times B \tag{1}$$

Where F is the Lorentz force, J the current density and B the magnetic.

Dissipation is taken into account through the extended form of the phenomenological Ohm's law [14]:

$$J = \sigma(E + V \times B) \tag{2}$$

Where σ is the electrical conductivity of the fluid, V the vector flow velocity and $E = 0$ the electric field strength. Thus the magnetic field serves to redirect the flow field via the cross-product term. Magnetic suppression of turbulent flow has been well documented [15, 16]. The magnetic force dominates the liquid viscosity when the Hartmann number, N_{Ha}, as defined by

$$\begin{aligned} N_{\mathrm{Ha}} &= BL(\sigma/\mu)^2 \\ &= \text{magnetic viscous force/ordinary viscous force} \end{aligned} \tag{3}$$

is larger compared to unity. Here, L is characteristic length; μ is viscosity of the melt. A plot of the Hartmann number versus magnetic field for Al is given in Fig. 5 for two melt temperatures and the plot displays weak temperature dependence. Physical parameters of Al-Bi alloy used during calculation are list in Table II. Thus,

TABLE II Physical parameters of Al-Bi alloy

Symbol	Unit	Value	Reference
σ	$\Omega^{-1}\text{m}^{-1}$	4.03×10^{6}	[17]
β	K^{-1}	2.65×10^{-6}	[17]
μ	$\text{N}\cdot\text{s}\cdot\text{m}^{-2}$	1.15×10^{-3}	[17]
ν	$\text{m}^{2}\text{s}^{-1}$	1.74×10^{-4}	[17]
ΔT	K	82	[17]
K_{L}	W(mK)^{-1}	98.71	[17]
g	ms^{-2}	9.8	[13]
C'	$\text{Jg}^{-1}\text{K}^{-1}$	1.08	[17]

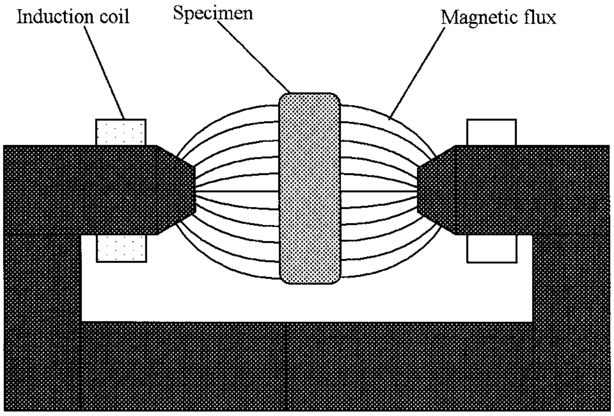


Figure 4 Transverse field configuration using an electromagnet: schematic representation.

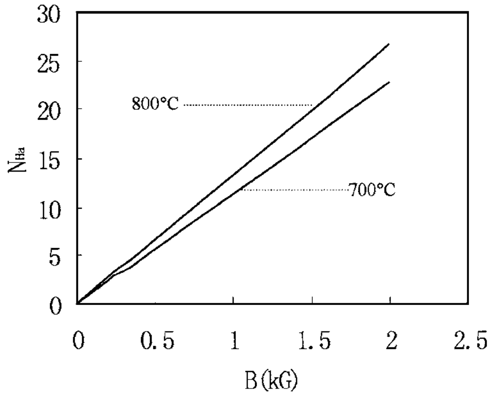


Figure 5 Relationship between N_{Ha} and B.

for an applied field of 2.0 kG, magnetic viscosity should dominate where we are operating in the region.

A measure of the intensity of convection is provided by the magnitude of the Rayleigh number, N_{Ra}, which is the vatio of buoyancy force to viscous force [18]:

$$N_{\text{Ra}} = \frac{L^{3}\beta g \Delta T c' \mu}{\nu^{2} K_{\text{L}}} \tag{4}$$

where β is coefficient of thermal expansion, g acceleration of gravity, ΔT temperature difference, c' specific heat, K_{L} thermal conductivity of liquid, ν kinetic viscosity. For $N_{\text{Ra}} \gg 1$, convection effects dominate. By calculating, $N_{\text{Ra}} = 3.24 \times 10^{4}$, for the processing conditions used, which means that there exists strong convection in the ampoules under this condition. One of the effects of thermal convection is to accelerate the transmission of solute atoms in the front of solid-liquid interface, which will decrease the thickness of the solute boundary layer. Another important effect is to introduce thermal gradient, which will increase the temperature gradient in the liquid side of the solid-liquid interface. The third important effect is to induce temperature wave. When the temperature wave reaches the solid-liquid interface, it will lead to unstable movement of the interface. If the amplitude increases, the average growth rate will increase after the suppression of the convection by the transverse magnetic field, which will make the spacing of Bi fibres decrease. The effects of magnetic field become much stronger under higher growth rate condition, because higher growth rate creates higher fluid (i.e., convection) rate. As the convection velocity increases, the effects of the magnetic field become enhanced due to the Lorentz force ($\propto V \times B$). On the other hand, due to the suppression of thermal convection by the application of a transverse magnetic field, solute atoms are only transferred in the form of pure diffusion, so its growth ability decreases, which leads to Bi diameter decreases too.

5. Conclusions

The directionally solidified microstructure of Al-6.5wt%Bi alloy is similar with and without magnetic field. However, note that spacing and diameter of Bi fibres become smaller in the case of magnetic field than that of without magnetic field. The effects of magnetic field on microstructure become more remarkable under rapid growth condition. The distribution of the second phase Bi fibers or regular aligns becomes more homogeneous under an application of a transverse magnetic field.

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