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Development of regular structure of the monotectic alloys under a magnetic filed

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It is generally difficult to produce the regular structure through solidification for monotectic alloys, since the liquid / liquid interface initiating convection exists and density difference between the two liquid phases causes the gravitational segregation. The high static magnetic fields reduced the convection around the liquid/liquid interface and the movement of the small immiscible liquid drops during solidification, leading to the uniform microstructure. For Al-Bi alloys, the imposition of the magnetic field up to 10T enhanced the engulfment of the liquid Bi drops into the solidifying Al matrix. Consequently, the Bi particles were uniformly distributed in the Al matrix. In the case of the unidirectional solidification of Al-In alloy, the rod-like In phase were regularly aligned in the growth direction when the magnetic fields more than several T were imposed.

Key words; monotectic reaction, segregation, regular structure, particle engulfment

1. INTRODUCTION

Monotectic alloys have been examined to use as free machining materials, superconducting materials, battery grids and bearing materials [1]. The wide solidification range and the large density difference between the constituent phases cause difficulty to produce the castings with high quality. It is generally recognized that solidification processing under 1G involved much effort to produce homogeneous casts.

Effect of the gravity on the monotectic solidification has been investigated in order to produce the homogeneous microstructure [2,3,4,5]. For example, the homogeneous Al-Pb-Bi alloys was achieved under the microgravity condition on the space shuttle [2]. The microgravity environment promoted good superconducting properties in the cold-worked wire made of the Al-Pb-Bi alloys. From a view point of engineering, it is expected to develop alternative processing without the gravity control.

Magnetic fields has been recognized to have potential to produce functional microstructures such as the aligned structure and to control fluid flow [6]. For the fluid flow control, the Lorentz force operating conducting materials is significantly enhanced by the high magnetic field. Thus, it is interesting to investigate the effect of the magnetic field on the casting defect formation such as the gravitational macrosegregation and the nonuniform distribution of the minor phase.

This paper presents the effect of the static magnetic field on the solidified structure of the Al-In monotectic alloys.

2. EXPERIMENTS

Figure 1 shows the phase diagrams of the Al-In alloy system [7]. For the hypermonotectic Al-10mol%In alloy used in the present study, solidification of Al follows the two liquid phase separation. Average radius of the minor phase particles (In in Al-In alloys) was evaluated from the solidified structure.

Induction furnace in the superconducting magnet was used for melting the monotectic Al-In alloy specimens in a short time to avoid the macrosegregation during melting procedures. Cooling rate of the specimens measured by an inserted thermocouple was approximately 7-10 K/s when the specimens were cooled by He gas. Dimension of the specimen was 8 mm in diameter and 15 mm in length.

Unidirectional solidification was performed under magnetic fields. The furnace was inserted into a room

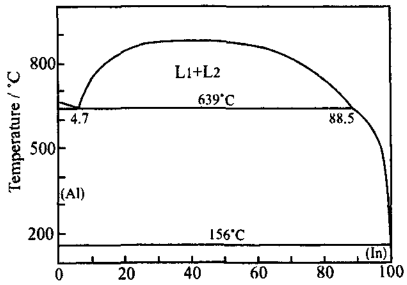


Figure 1 Phase diagram of Al-In system

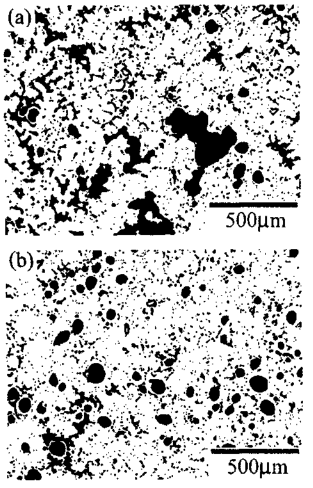


Figure 2 Microstructre of Al-10at%In alloys solidified under 0T and 10T

temperature bore of the superconducting magnet. The furnace was not brought into contact with the bore wall and the magnet body in order to avoid any vibration of the cryocooled magnet. Direction of the magnetic field was vertical direction that is parallel to growth direction. The applied magnetic field was up to 10T. The unidirectionally solidified specimens were polished and etched. Microstructure was observed by an optical microscope.

3. RESULTS AND DISCUSSION

Figure 2 shows the microstructure of the Al-In alloy cast under 0T and 10T. Difference in the distribution of the In particles was observed between the two specimens. In the case of the magnetic field, 0T, the In particles tended to segregate at the grain boundary of the Al matrix or between the Al dendrite arms. The microstructure indicated that the liquid In particles are pushed by the solidifying front.

On the other hand, the imposition of the magnetic field, 10T, most of the In particles with diameter less than 100 μm tended to distributed within the Al grains. Shape of the In phases was rather spherical. The microstructure solidified under 10T suggested that the In particles were not pushed by the solidifying front and were engulfed, keeping the spherical shape formed during the liquid-liquid separation. Furthermore, the imposition of the magnetic field reduced size of the In particles.

The present results proved that the high magnetic field more than several T can reduce the movement of the In liquid drops leading to the uniform distribution, and promoted the engulfment into the Al matrix. It is interesting to consider how the static magnetic field contributed to development of the uniform solidified structure in the Al-In monotectic alloys.

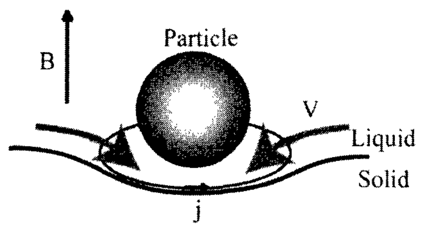


Figure 3 schematic illustration of the aprticle engulfment into the solidifying front under a magnetic field

Studies on engulfment and pushing of the immiscible particles at solidifying front without the magnetic fields have been performed to understand inclusion behavior in steel making process or fine distribution of the ceramic particles in MMC materials [8-16]. Figure 3 shows the schematic illustration of the particle engulfment at the solidifying front, including the magnetic effect. Interfacial energy causes repulsive force due to interfacial energy difference. Melt flow into the gap between the particle and the solidifying front occurs when the solidifying front pushes the particle. The fluid flow in the narrow gap resulted in the viscous drag force. Under the magnetic field, the eddy current loop behind the particle is induced by the interaction between the melt flow and the magnetic field imposed in the vertical direction. The Lorentz force operates as resistance to the melt flow. Consequently, the particles tends to be trapped by the solidification front, as the static magnetic field increases.

The drag force due to the static magnetic field was discussed for the rising particle in the metallic melt by using the magnetohydrodynamics [17-19]. The magnetic-field dependence of the drag force and the terminal velocity of the particles provides useful information, although the present configuration is slightly different from the configuration assumed in ref [17-19]. The drag force was analyzed as a function of the Hartman number, Ha. The Ha is defined by

$$Ha = Ba\sqrt{\frac{\sigma}{\eta}} \tag{1}$$

Here, σ and η are the electrical conductivity and the viscosity, respectively. B is the magnetic flux density and a is the diameter of the particle. The drag force were approximately given by,

$$D = 6\pi\eta rU\left[1 + \frac{3}{8}Ha + O(Ha^2)\right] \tag{2a}$$

$$D = 6\pi\eta rU\frac{Ha}{3}[1 + O(Ha)] \tag{2b}$$

Equation (2a) is valid for Ha<<1, while eq(2b) for

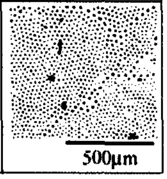
	H=0T	H=10T
Al-10at.%In V=2.7μm/s		

Figure 4 Cross section of the Al-10at%In alloys grown by unidirectional solidification under 0T and 10T. Black part corresponds to the In phase.

Ha>>1. The effect of the magnetic field becomes significant when Ha is much larger than unity. The Hartmann numbers of the In drops in Al melt under 10T is estimated to be the orders of 10^0 and 10^2, for the particles with 10 μm and 100 μm in diameter, respectively. The Hartman number becomes less than 1 if the intensity of the static magnetic field is less than 1T that is typically obtained by the electromagnets. Therefore, it is required to impose the high magnetic field such as several tesra in order to improve the solidified structure though the monotectic reaction. The experimental results shown in Fig. 2 indicated that the magnetic filed of 10T was sufficiently large to increase the drag force for the engulfment of the In particles with 50-100 μm in diameter. The promotion of the particle engulfment into the Al matrix is also expected to improve the microstructure produced by the unidirectional solidification, i.e. regular structure like the eutectic structure.

Figure 4 shows the cross section of the unidirectionally solidified Al-10at%In alloys at the growth rate of 2.7μm/s. Black part correspond to the In phase. In the case of 0T, the In liquid phase was pushed by the solidifying front. Consequently, rather large In particles are distributed in the Al matrix. On the other hand, the In phase was easily engulfed into the Al phase and cooperatively grew with the Al matrix. The cooperative growth of the Al and the In phases resulted in the regular structure which is similar to the eutectic structure.

CONCLUSION

Monotectic solidification of the Al-10mol%In alloy were investigated. Imposition of the high magnetic fields contributed to production of homogeneous microstructure for the Al-10mol%In alloys. The immiscible particles became smaller by imposition of the magnetic field (10T). The magnetic field promoted the engulfment of the immiscible particles into the solidifying front, leading to uniform distribution of the spherical In phase in the Al matrix. The hydrodynamic analysis suggested the critical condition, Ha >> 1 is needed to realize the effect of the magnetic field. In the case of Al-In alloys, the static magnetic field more than several tesra was required to satisfy the condition. In the high magnetic field, unidirectional solidification for the Al-10at%In alloys produced the regular structure like the eutectic structure.

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