Effects of Uniform and Gradient High Magnetic Fields on Gravity Segregation in Aluminum Alloys

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The effects of uniform and gradient magnetic fields on gravity segregation in Al–5wt%Cu and Al–10wt%Mg alloys are investigated. The results show that high magnetic fields can be used to control the solute distribution and thus control gravity segregation caused by the difference of physical properties such as density and magnetic susceptibility between the bulk liquid and the solute-enriched liquid. The effects of the field can be attributed to performances of Lorentz and magnetic forces.

KEY WORDS: solidification; metals and alloys; Al alloys; gravity segregation; high magnetic fields.

1. Introduction

It is well known that segregation in solidified structure results in poor properties and performances of alloys. For example, core segregation may not only induce the difference in both physical and chemical properties on the scale of grain, but has a great impact upon the mechanical properties of casting on a large area scale as well. Gravity segregation has a detrimental impact on the subsequent processing behavior and properties of cast materials. Therefore, methods for the control of gravity segregation had been constantly pursued, such as solidification under microgravity,¹⁾ rapid solidification,²⁾ addition of alloying elements,³⁾ diffusion annealing⁴⁾ and electromagnetic fields,^{5,6)} etc. However, all these methods have some weaknesses or deficiencies because they are relatively complicated or inefficient.

Nowadays, high magnetic fields have been found to not only largely increase the value of traditional Lorentz force, but also contribute to the likelihood of the use of magnetic force on nonmagnetic materials.^{7–9)} The previous studies show that the high magnetic field can affect the solute distribution during solidification process.^{8,10–12)} Results of experiments using low magnetic fields¹³⁾ and numerical modeling¹⁴⁾ indicate that the magnetic field can suppress gravity segregation in term of Lorentz force. The segregation in solidified structure is associated with both the nature of the solute and the magnetic intensity and gradient. The present investigation is undertaken to examine the effects of both uniform and gradient magnetic fields on gravity segregation of solute in Al–Cu and Al–Mg alloys.

2. Experimental

The materials employed in this study are ZL301 Al–Mg alloy and Al–5wt%Cu alloy which was prepared from pure aluminum (99.94 wt%) and copper (99.97 wt%). The experimental apparatus, as shown in Fig. 1, is based on a superconducting magnet which can generate a magnetic field with a maximum magnetic flux density, $B = 12$ T at the centre of a bore of 100 mm diameter and a maximum value of the product of magnetic flux and its gradient, $BdB/dz = \pm 564$ T²m^{−1} at ± 105 mm from the centre of the bore. A resistance furnace (inner diameter 33 mm), in which the temperature can reach 1 473 K, is installed into the magnet for melting and solidifying the specimens.

For Al–Cu system, a specimen (9 mm in diameter and 30 mm in length) put into an alumina crucible (inner diameter 10 mm; outer diameter 13 mm) were heated to 973 K under an argon atmosphere at a heating rate of 5 K min^{−1}

Fig. 1. Schematic illustration of experimental apparatus and distribution of the magnetic field along the bore axis ($B_{\text{max}} = 12$ T).

and held at the same temperature for 60 min to ensure its homogeneity. The temperature was then cooled down to 500 K at a cooling rate of 5 K min^{-1} and finally cooled to room temperature by turning off the DC power source. For Al–Mg system, the experimental conditions were the same as the case of Al–Cu system, except that the maximum heating temperature was 1023 K. The alloys were also solidified under various high magnetic field conditions. The magnetic field conditions are summarized in **Table 1**, in which Z_0 – Z_5 indicate five positions as shown in Fig. 1, respectively. The distances between Z_1 (or Z_5) and Z_0 , Z_3 (or

Z_4) and Z_0 are 105 mm and 45 mm, respectively. Microstructures of the magnetic field-treated specimens were examined using scanning electron microscopy (SEM) on the longitudinal section. Solute segregation in the specimens was determined using an electron probe microanalysis (EPMA). Each 25 values were measured and averaged separately in the upper and lower parts from the dendrite cores for each specimen. Here, the upper and lower parts are the upside 8 mm length and the downside 8 mm length of the specimens, respectively.

Table 1. Experimental conditions of high magnetic fields.

Magnetic flux density B , T	BdB/dz , T^2/m
Z_0 0	—
Z_1 8.8	-564
Z_0 8.8	0
Z_5 8.8	564
Z_3 11.5	-282
Z_0 11.5	0
Z_4 11.5	282

3. Results and Discussion

Secondary electron photos of Al–5wt%Cu and Al–10wt%Mg alloys and area distribution images of solutes in these two alloys at 0 T and 8.8 T are shown in **Fig. 2** and **Fig. 3**, respectively. At the same time it should be pointed out that some rod-like Mg poor areas were found at the bottom of Figs. 3(c) and 3(d). These Mg poor phases resulted from the impurity contents in ZL301 alloy. The solidified structures of the alloys all consist of α -Al dendritic parti-

Fig. 2. Secondary electron photos of Al–5wt%Cu alloy under a magnetic field of 0 T (a) and 8.8 T (c) and corresponding area distribution images of elements (b) and (d).

Fig. 3. Secondary electron photos of Al–10wt%Mg alloy under a magnetic field of 0 T (a) and 8.8 T (c) and corresponding area distribution images of elements (b) and (d).

cles, with $\alpha + \text{CuAl}_2$ eutectic for Al-5wt%Cu and Al_3Mg_2 for Al-10wt%Mg being distributed at the grain boundaries based on the measurement results of EPMA. During dendrite growth, solidification involves solute redistribution and this causes microsegregation. From Fig. 2 and Fig. 3, it can be found that the application of a high magnetic field has no effect on the microsegregation type in these two alloys. The solutes of Cu and Mg for Al-Cu and Al-Mg alloys, respectively, still segregate at the interdendritic regions, although the extent of segregation may be enhanced or reduced by a high magnetic field as mentioned in previous paper.¹²⁾

In order to evaluate the gravity segregation of the solute in the alloys, an estimate of the extent of segregation can be made by $C_u - C_l$, where C_u and C_l are the average elemental concentrations at the dendrite cores in the upper and lower parts of the specimens, respectively. The measurement for the mean average composition of dendrite cores is given in Ref. 12).

Figure 4 shows the changes of $C_u - C_l$ of solutes in Al-5wt%Cu and Al-10wt%Mg alloys as a function of B , respectively. The negative or positive values in the figures indicate that the elemental concentrations in the dendrite cores in the upper part of the specimen are less or larger than those in the lower part. Gravity segregation mainly results from the movement of liquid, especially from the convection for Al-Cu and Al-Mg alloys which is linked to the difference in density between the bulk liquid and the solute-enriched liquid. From Fig. 4, Gravity segregation of solute for both alloys without the magnetic field can be detected obviously. However, with the application of high uniform magnetic field, the value of $C_u - C_l$ increases (for Al-Cu system) or decreases (for Al-Mg system) gradually with increasing B and tend to be zero at 11.5 T. This indicates that the high uniform magnetic field can reduce remarkably the extent of gravity segregation. When a high uniform magnetic field is imposed on an electrically conducting fluid, the interaction of the electric current which is induced by the movement of the fluid and the imposed field will then generate Lorentz force which will suppress significantly fluid flow. Therefore, gravity segregation associated with the liquid movement can be decreased under a high magnetic field because of the braking effect of the field on the convection.^{8,15)}

The effects of gradient magnetic fields on gravity segregation of Al-5wt%Cu and Al-10wt%Mg alloys are shown in **Fig. 5**. However, in this case, the magnetic flux density B is not constant because of the limits of the experimental apparatus. In other words, the effects of Lorentz force caused by uniform magnetic fields that were mentioned above are also involved in this figure. It can be seen that the values of $C_u - C_l$ for both cases are near zero at the gradient $BdB/dz = -564 \text{ T}^2\text{m}^{-1}$. Following these two values, the $C_u - C_l$ decreases for Al-5wt%Cu or increases for Al-10wt%Mg with increasing BdB/dz . This indicates that the gravity segregation can be decreased for both Al-5wt%Cu and Al-10wt%Mg alloys when the value of BdB/dz changes from positive to negative. According to the Helmholtz free energy which is stored in the flow medium by a magnetic field, the electromagnetic forces acting on the fluid are Lorentz force, $\vec{F}_L$ and magnetic force, $\vec{F}_M$. The

Fig. 4. Changes of $C_u - C_l$ of solutes in Al-5wt%Cu and Al-10wt%Mg alloys as a function of B .

Fig. 5. Changes of $C_u - C_l$ of solutes in Al-5wt%Cu and Al-10wt%Mg alloys as a function of BdB/dz .

latter which is only generated at gradient magnetic fields is considered to be able to act on the solute-enriched liquid and given as $F_M = (\chi/\mu_0)VB(dB/dz)$, where μ_0 is vacuum magnetic permeability, χ is the magnetic susceptibility of the solute-enriched liquid and V is the volume of the solute-enriched liquid. However, the exact magnitude of F_M is hard to obtain due to the lack of above parameters. Under a negative field gradient, Cu-enriched liquid will be acted on magnetic force which is upwards to suppress their settlement because of its negative susceptibility. Consequently, gravity segregation resulted mainly from the density difference between bulk liquid and solute-enriched liquid in Al-5wt%Cu alloy will be, to some extent, decreased, due to the canceling each other of the magnetic and gravitational force. In the case of positive gradients, the magnetic force acting on Cu-enriched liquid is downwards and this will thus enhance gravity segregation. On the other hand, under a negative field gradient, Mg-enriched liquid will be acted on magnetic force which is downwards to suppress their floatation because of its positive susceptibility. As a result, gravity segregation in Al-10wt%Mg alloy will be also enhanced under positive gradients and decreased under negative gradients owing to the density difference and magnetic force.

4. Conclusions

An application of uniform magnetic field decreased gravity segregation of solutes in Al-5wt%Cu alloy and Al-10wt%Mg alloys. Gradient magnetic fields could also decrease gravity segregation in Al-5wt%Cu alloy but increase it in Al-10wt%Mg alloy. The effects of the field can be at-

tributed to performances of Lorentz and magnetic force.

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