The segregation of copper and silicon in Al–Si–Cu alloy during electromagnetic centrifugal solidification

Yuansheng Yang*, Qingsheng Zhang, Youliang He, Zhuangqi Hu

Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhu Road, Shenyang 110016, People’s Republic of China

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Abstract

The present paper investigates the segregation of copper and silicon in an Al–1wt%Cu–1wt%Si alloy solidified under the co-action of centrifugal and electromagnetic forces. The reasons for the solute segregation and the effect of electromagnetic force on segregation are discussed. Tubular samples cut from the solidified alloy are analyzed, the results showing that the segregation of copper and silicon occurs along the normal direction of the samples and that the electromagnetic field has a remarkable influence on the segregation of both copper and silicon. As the exciting current increases, the segregation of copper decreases, while the segregation of silicon first increases and then decreases. The migration of solute atoms in the melt depends not only on the density difference between the solute and aluminum atoms, but also on the strength of the electromagnetic force. The magnetic force changes the rotation velocity of the melt, reduces the migration velocity of copper and causes the reduction of copper segregation. Because of the difference of the electrical conductivity between the solute and the aluminum melt, the reductions of velocity are not equal. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

It is well known that the electromagnetic field has a great influence on the segregation of elements in alloys during electromagnetic stirring (EMS) solidification processes [1,2]. In some cases EMS reduces segregation, but in other cases it does not. In past researches [3,4] it has been considered that EMS forces the liquid in front of the solid/liquid interface to flow and changes the migration of the solutes in the melt. However, this can not exactly explain the mechanism of the reduction in segregation. In fact, electromagnetic force not only causes convection in the liquid metal during solidification, but also has a direct influence on the movements of solutes in the liquid metal. In the authors’ previous investigation [5], it was found that there is different segregation behavior between copper and silicon in an Al–Cu binary alloy and an Al–Si binary alloy, and it was pointed out that the reduction in segregation of solute atoms in both alloys is the result of the changes of the migration velocity of the solutes, which depends on the electromagnetic properties of the solutes and the flow velocity of the melt.

In order to further explore the reason for the segregation in view of solute movement, this paper investigates solute atom segregation in an Al–1wt%Cu–1wt%Si alloy solidified under the co-action of electromagnetic and centrifugal forces. This study is necessary for electromagnetic centrifugal casting [6], because the liquid metal in the process is subjected to both electromagnetic and centrifugal forces.

2. Experiments

2.1. Materials

The experimental material was an Al–1wt%Cu–1wt%Si alloy made from electrolytic aluminum, electrolytic copper and pure silicon.

2.2. Apparatus and procedure

The electromagnetic centrifugal solidification of the alloy is conducted in the set-up shown in Fig. 1. The melt rotated with the rotating mold due to the viscosity effect of the liquid metal and the mold wall in a DC magnetic field after it was poured into the mold. The rotation speed of the mold was 1600 rpm and the pouring temperature was 600°C. The intensities of the exciting currents are 0, 6, 15, and 30 A, respectively.

Tubular samples were produced after the liquid alloys had...
solidified and they were cut into ring specimens. The solute segregation of the as-cast alloy was measured by means of chemical analysis on the cross-sections of the specimens. The analytical positions of the specimens, layer 1 to layer 5, are shown in Fig. 2.

3. Experimental results

The experimental results show that the magnetic field intensity has a remarkable influence on solute segregation in the alloy. Fig. 3(a) shows that, without a magnetic field ($I_e = 0$), the concentration of copper atoms is clearly higher in the outer region and much lower in the inner region of the tube compared with the nominal composition of the alloy. In the presence of a magnetic field, the solute segregation is changed, and the contents of copper in the outer region of the tube falls with increase of exciting current. In other regions the segregation of copper is increased although the degrees of increase are different. Fig. 3(b) shows that the segregation of silicon changes with the exciting current, but it does not decrease with increase of exciting current. As the exciting current increases, segregation becomes more serious until the exciting current is up to 30 A.

The segregation in different positions of the specimens with various levels of exciting current, is analyzed. Fig. 4(a) shows that in the outer region of the alloy (layer 1) the copper concentration decreases with increase of the exciting current, in the inner region (layers 4 and 5) it keeps at a low level (between 0.86 and 0.91 of the nominal composition) all along, whilst in the middle region it varies only a little with the exciting current. The concentration of copper in the whole section is more uniform when the exciting current is 15 A.

Fig. 4(b) shows the silicon concentration in different positions with increase of the exciting current. The segregation of silicon in all of the layers of the specimen increases with exciting current. It fluctuates more obviously in the inner and outer layers. It is especially noted that the solute segregation of silicon is reduced when the exciting current is 15 or 30 A.

4. Discussion

When the alloy melt rotates with the mold, the atoms in the melt migrate in the radial direction under the centrifugal force. The segregation in centrifugal casting arises from the different migration velocities between solute and solvent atoms. According to the Stokes equation [7], the migration velocity of solute atom clusters is as follows:

$$\frac{dr}{dt} = \frac{D^2}{18\eta r} \left(\rho_s v_{bs} - \rho_l v_{bl}\right)$$  \hspace{1cm} (1)

where $D$ is diameter of the solute atom, $r$ is the radial coordinate, $\eta$ is dynamic viscosity of the alloy melt, $\rho_s$ and $\rho_l$ are densities of the solute and solvent, respectively, and $v_{bs}$ and $v_{bl}$ are the tangential components of the rotation velocities of the solute and solvent, respectively. Therefore, the migration velocity of the solute depends not only on the density difference but also on the rotation velocity difference between the solute and solvent.

If there is no electromagnetic force, the solute atoms rotate at the same velocity as the solvent, so $v_{bs} = v_{bl}$. The migration velocity of the solute is determined by the density difference of the solute and solvent, and the solute atoms with higher density move towards the periphery of the melt tube. In this case, $\rho_{Cu} > \rho_{Al}$, hence, the copper atoms migrate outward to form the segregation as shown in Fig. 3 when $I_e = 0$.

In the presence of the electromagnetic field, the melt is subjected to electromagnetic and centrifugal forces, and gravity also as shown in Fig. 1. The electromagnetic force in cylindrical coordinates is:

$$f_e = f_r + f_\theta = -\frac{1}{2} \sigma B^2 v_\theta \sin 2\omega t - \sigma B^2 v_\theta \cos 2\omega t$$ \hspace{1cm} (2)

The radial and tangential components of all of the forces acting on the melt can be written as:

$$F_r = -\frac{1}{2} \sigma B^2 v_\theta \sin 2\omega t - \rho g \sin \omega t + \rho r \omega^2$$ \hspace{1cm} (3)

$$F_\theta = -\sigma B^2 v_\theta \cos 2\omega t - \rho g \cos \omega t$$ \hspace{1cm} (4)
where $B$ is the magnetic flux density, $\sigma$ is the electrical conductivity, $\rho$ is density, $g$ is acceleration due to gravity, $r$ is radius, $\omega$ is angular velocity, $t$ is time, and $v_\theta = r\omega$ is tangential rotation velocity of the melt.

It is mentioned that the tangential component of the electromagnetic force is always opposite to the rotation direction of the mold. Thus it causes the liquid in front of the solid/liquid interface to flow against the rotation direction of the mold, which will decrease the rotation velocity of the melt. The solute and solvent are subjected to the effect of both electromagnetic and centrifugal forces, where the tangential component of the electromagnetic force acting on the melt runs against the rotation direction of melt, so that the electromagnetic force decreases the rotation velocities of the solute and solvent. However, the velocity drops of the solute and solvent are different because
the electrical conductivity is not equal. Hence, the rotation velocities of the solute and solvent are not equal, i.e. $v_{\text{solute}} \neq v_{\text{solvent}}$. Therefore, the migration velocity $\left(\frac{dr}{dt}\right)$ of the solute will be changed based on Eq. (1). Furthermore, the higher the electrical conductivity, the larger the electromagnetic force, and the more the velocity reduction.

For copper and aluminum, the electrical conductivity has a relation $\sigma_{\text{Cu}} > \sigma_{\text{Al}}$, so $v_{\text{Cu}} < v_{\text{Al}}$. According to Eq. (1), the value of $\rho_{\text{Cu}}v_{\text{Cu}} - \rho_{\text{Al}}v_{\text{Al}}$ becomes smaller than that in
the absence of the electromagnetic field. This effect decreases the outward radial migration speed of copper.

As for silicon, this has a more complex segregation behavior than copper. The reason may be that silicon is a semiconductor element and the density differences of silicon and aluminum is less than that of copper and aluminum.

5. Conclusions

1. The electromagnetic force has remarkable influence on solute segregation in Al–1wt%Cu–1wt%Si alloy solidified during electromagnetic centrifugal casting. Without the electromagnetic force, copper atoms accumulate in the outer area of the as-cast sample, depending on the difference between the densities of copper and the aluminum. The solute concentration copper is decreased under the action of the electromagnetic force. The segregation of silicon has a complex behavior under the action of the electromagnetic force.

2. The reduction of the segregation of copper in the alloy is the result of change in the migration velocity of the copper due to the electromagnetic force. The copper migration velocity is affected by the electrical conductivity difference between the solute and aluminum atoms as well as their density difference. Because the electrical conductivity of copper is larger than that of aluminum, it moves inwards under the electromagnetic force.

Acknowledgements

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