Solidification Structure of Al–Cu and Sn–Cu–Sb Alloys Obtained by Casting through Induction Stirring Using Permanent Magnet*1

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Permanent magnetic stirring is superior in terms of cost and operability compared with electromagnetic stirring. However, it is applied only to melting furnace. In this study, attempts were made to apply permanent magnetic stirring molten metal, and the effects of the stirring on grain refinement, increase in hardness, and suppression of porosity were investigated. We used a stirring device developed by ourselves and two alloys with different solidification morphologies and specific gravities (\(\rho\)). Results showed that needlelike crystals were cut off in Sn–Cu–Sb alloy (\(\rho = 7.4\)). On the other hand, the growth of columnar crystals was inhibited, and grain refinement and a region growing with equiaxed crystals were observed in Al–Cu alloy (\(\rho = 2.7\)) due to the stirring. Furthermore, increased hardness and suppression of porosity were confirmed with the increase in the rotating velocity of magnets in both alloys. Theoretical calculations showed that the molten metal near the mold was directly stirred by Lorentz force, but other regions were indirectly stirred by the flow of force from the directly stirring.


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1. Introduction

Refinement of a cast structure, improvements in mechanical properties and suppression of inner defects are expected through the stirring of molten metal poured into a cast mold. In recent years, electromagnetic stirring has been widely used for improvements of cast materials.1,2) However, electromagnetic stirring has problems; adjustment of the stirring rate is difficult and high electrical power is necessary to form a magnetic field. Therefore, the development of stirring is necessary to improve these disadvantages. A new stirring method to form magnetic fields by turning a permanent magnet along the wall of a melting furnace was proposed.3) This method has several excellent features; electricity consumption can be reduced by 10% and the adjustment of the stirring velocity is easy, but it is difficult to apply the stirring to products with large diameters compared with electromagnetic stirring. This method is used for the melting furnace to melt raw material rapidly and to homogenize chemical composition. There is no report thus far that this method has been applied to the refinement of the grain size, strengthening and quality stabilization. In this study, the effect of refinement of grain size, improvements in mechanical properties and reduction of porosity in castings through stirring with a permanent magnet were investigated.

2. Principle

Figures 1 and 2 show the top view of the stirring device and the cross-section of the mold, respectively. Rotation of the permanent magnet gives rise to eddy currents inhibiting magnetic flux penetrating for unit time by Lorentz’s law in the mold. Lines of magnetic force occur at each location accompanied by eddy current generation. Applying Fleming’s left-hand law using lines of magnetic force and the eddy current, the Lorentz force of repulsion and attraction act in the forward and reverse directions of the magnet, respectively. Thus, molten metal is stirred in the direction of magnetic rotation in the mold.

3. Experimental Procedure

3.1 Stirring device using permanent magnet

A schematic drawing of the device used is shown in Fig. 3.
The rotary device of the magnet was prepared in-house by us. A neodymium magnet in the shape of a cube with 15 mm side turns along the mold. The magnet is rotated at a 20 mm height from the bottom of the mold and different magnetic poles face each other.

3.2 Specimen

Sn-4%Cu-6%Sb and Al-2%Cu (in mass%) alloys were used for the casting. These alloys have different solidification morphologies and specific gravity (\( \rho \)) values. The structures of Sn-Cu-Sb (\( \rho = 7.4 \)) and Al-Cu (\( \rho = 2.7 \)) alloys consist of some phases and an almost dendritic single phase, respectively. An alumina crucible was prepared for the mold with inner diameter, wall thickness and total height of 36, 8 and 100 mm, respectively. Casting ingot heights of the Sn-Cu-Sb and Al-Cu alloys are 55 and 50 mm, respectively. The maximum rotating velocity of the magnet for the Sn-Cu-Sb and Al-Cu alloys was 1100 and 1200 rpm, respectively.

3.3 Cooling curve

The temperature of the outside and center regions at 20 mm height from the bottom of the ingot was measured by thermocouples. The solidification time was defined as the time until the temperature fell below the solidification temperature after reaching the solidification temperature.

3.4 Observations of structure

The microstructure of the Sn-Cu-Sb alloy ingot was observed along the longitudinal section after etching with aqua regia. The macrostructure of the Al-Cu ingot was observed along the longitudinal sections and cross sections at 12 mm height from the bottom after etching with a 50 vol% NaOH solution. The center regions at 2, 12 and 22 mm heights from the bottom of the ingot are termed the bottom, center and upper regions, respectively. The region near the surface of the ingot at 12 mm height from the bottom is called the outside region.

3.5 Hardness tests and porosity measurements

Hardness was evaluated by a Vickers hardness tester. The hardness was averaged for the hardness numbers obtained from eight regions of equal distance. Tests for Sn-Cu-Sb and Al-Cu alloys were carried out under 0.1 and 0.2 kgf weights, respectively. Also, the porosity measurement was applied using the JIS-G-0555 method from the microstructure images of the outside and center regions of the alloys (Sn-Cu-Sb alloy: magnifications of \( \times200 \) and Al-Cu alloy: magnifications of \( \times40 \)).

4. Result and Discussion

4.1 Sn-Cu-Sb alloy

Figure 4 shows cooling curves of the Sn-Cu-Sb alloy from molten metal at 703 K. The solidification time decreases from 100 to 70 s at the center region under stirring at 1100 rpm. Also, it is seen that the cooling rate under stirring at 1100 rpm on the outside region was high compared with no stirring. Furthermore, the solidification time had a tendency to decrease with increasing stirring rate supporting the result under stirring at 900 rpm. This is because the molten metal cools rapidly due to improvement in the thermal conduction of the molten metal to the mold by the stirring through the rotation of the magnet.\(^4\)

Figure 5 shows the microstructures of the center and outside regions solidified under stirring at 0 and 1100 rpm in the Sn-Cu-Sb alloy. Coarse needle-like primary crystals (Cu6Sn5) are observed in the whole area of the alloy under stirring at 0 rpm (Figs. 5(a) and 5(c)). On the other hand, a lot of short needle-like crystals are observed in the center region under stirring at 1100 rpm (Fig. 5(b)). The fraction of granular crystals was higher in this case compared to no stirring (Fig. 5(b)). This indicates that the dividing of crystals occurring by collision among crystals and the collision of crystals with the mold through stirring are responsible for this. Furthermore, it was found that needle-like crystals are hardly observed in the outside region and the granular crystals were dispersed in the matrix (Fig. 5(d)).
Figure 6 shows microstructures of the upper and bottom regions under stirring at 0 and 1100 rpm in the Sn–Cu–Sb alloy. Coarse needle-like crystals, similar to the results shown in Fig. 5, are observed in the bottom and upper regions under no stirring (0 rpm) (Figs. 6(a) and 6(c)). A granular structure is hardly observed under the stirring at 1100 rpm in the bottom region, different from the center and outside regions of the mold (Fig. 6(b)). This result suggests that the time was not sufficient to obtain the effects of the stirring because of rapid solidification in the bottom region of the mold. Furthermore, the same tendency as the center region was observed in the upper region (Fig. 6(d)). This indicated that the stirring had an effect on regions without direct stirring (without the outside region) as well. It was found that the effect of the stirring was the greatest in the outside region. Also, the effect became weak in order of the center and upper regions. Furthermore, the effect is hardly seen in the bottom region. Therefore, the area affected by the stirring with the permanent magnet is local in the Sn–Cu–Sb alloy.

Figure 7 shows micro-vickers hardness values of the Sn–Cu–Sb alloy. The hardness of the Sn–Cu–Sb alloy increased with increasing rotating velocity regardless of the measuring region. Hardness increased remarkably in the outside and bottom regions. Figure 8 shows the porosity in the Sn–Cu–Sb alloy. The porosity of the Sn–Cu–Sb alloy decreased with increasing rotating velocity in the center and outside regions. Furthermore, porosity in the outside region decreased remarkably compared with the center region under the same velocity of the rotation. This indicates that molten metal is supplied rapidly by the stirring. Therefore, it seems that hardness increases due to decreasing porosity, rapid cooling rate in the outside region and accumulation of granular crystals in the bottom region. It is concluded that hardness and porosity are greatly dependent on the rotating velocity of the magnet, thereby affecting the stirring.

4.2 Al–Cu alloy
Figure 9 shows cooling curves from the molten metal at 1023 K in the Al–Cu alloy. The solidification time decreased from 8 to 5 s in the center region and the cooling rate increased in the outside region at 0 and 1200 rpm rotation.
This was the same tendency as in the Al–Cu–Sb alloy. Also, the solidification time decreased with increasing rotating velocity in the thermal analysis at 300 and 600 rpm.

Figure 10 shows macrostructures on the cross-section (Figs. 10(a) and 10(d)) and its schematic drawings (Figs. 10(e) and 10(f)) in the Al–Cu alloy under stirring at 0, 300, 600 and 1200 rpm. Long columnar crystals were grown from the surface of the ingot and coarse equiaxed crystals were formed in the center area of the ingot in the alloy under no stirring (0 rpm) (Figs. 10(a) and 10(e)). On the other hand, columnar crystals were grown forward to the inversion direction of the magnet with gradient to the outside region and the columnar crystals became shorter in the stirred ingot (Figs. 10(b) through 10(d) and 10(f)). This is the same result as in the previous reports of electromagnetic stirring.5,6) Therefore, from the results in this study, it was confirmed that sufficient stirring of the molten metal occurred by the stirring of the permanent magnet.

Figure 11 shows the macrostructures of the longitudinal section in the Al–Cu alloy under stirring at 0, 300, 600 and 1200 rpm (Figs. 11(a) through 11(d)). A long columnar and coarse equiaxed structure similar to the structure of the cross-section (Fig. 10(a)) was observed in the area with rotation of the magnet at 0 rpm (Fig. 11(a)). It is seen that equiaxed crystals became finer with increasing rotating velocity and the area of the equiaxed crystals were enlarged in the stirred alloy (Figs. 11(b) through 11(d)). This indicates that the dendrites that formed in the early stage of solidification were broken by the flow due to the stirring and subsequently became the nuclei of the crystal. The formation of equiaxed crystals in the Al–Cu alloy depends on the heat flux and flow in the solid–liquid coexistence state.4) Also, the refinement of equiaxed crystals in this study depends on increasing the temperature gradation due to the stirring. Refinement of equiaxed crystals was observed in the upper region where the melt was not directly stirred. However, the effect of the refinement is hardly observed in the bottom region of the Al–Cu alloy, which is similar to the case of the Sn–Cu–Sb alloy. Therefore, it is found that the effect of the stirring in the Al–Cu alloy extends to the whole volume except for the bottom region. Also, a shrinkage cavity has a tendency to become larger with increasing rotating velocity.

Figure 12 shows micro-vickers hardness values in the Al–Cu alloy. The hardness increased in the alloy by stirring. Figure 13 shows the porosity in the Al–Cu alloy. The porosity decreased with increasing rotating velocity and decreased remarkably in the outside region, which is also similar to the case of the Sn–Cu–Sb alloy. Thus, the hardness depends on the fraction of porosity. This means that increasing the cooling rate in the outside region by increasing the rotating velocity of the magnet yields the increased hardness.
4.3 Magnetic flux density in mold and force affecting molten metal

4.3.1 Calculation for force by magnet flux

The magnetic flux density was calculated by eq. (1) when an Nd–Fe–B magnet (506 mT) with the same shape was set on opposite sides across the mold.\(^7\)

\[
B(X) = \frac{B_r}{\pi} \left[ \tan^{-1} \left( \frac{AB}{2X\sqrt{4X^2 + A^2 + B^2}} \right) \right. \\
- \left. \tan^{-1} \left( \frac{AB}{2(L + X)\sqrt{4(L + X)^2 + A^2 + B^2}} \right) \right]
\]

Here, \(B_r\) is the magnetic flux density of the permanent magnet; \(A, B\) and \(L\) represent the size of the permanent magnet; and \(X\) is the distance from the center of the mold. First, 506 mT was substituted for \(B_r\). 0.015 m was used for \(A, B\) and \(L\), and \(X\) was substituted by \(-0.026\) to \(0.026\) m.

The Lorentz force affecting the tangential and radial directions of the molten metal in the mold was calculated by eqs. (2) and (3) using the magnetic flux density calculated using eq. (1).\(^5\)

\[
F_t = \frac{1}{2} \sigma \omega r B^2 
\]

\[
F_r = \frac{1}{8} \sigma \omega^2 r^3 \mu_r B^2
\]

Here, \(F_t\) and \(F_r\) are the Lorentz forces affecting the tangential and the radial directions for the molten metal in the mold, respectively. Also, \(\sigma\) is the electrical conductivity of aluminum, \(\omega\) is the rotating velocity of the magnet, \(r\) is the distance from the center of the mold, \(B\) is the magnetic flux density, and \(\mu_r\) is the kinematic viscosity of aluminum. In this study, 5 Hz (300 rpm), 10 Hz (600 rpm), and 20 Hz (1200 rpm) were used for \(\omega\). Also, values of \(37.2 \times 10^6 \Omega \cdot m^{-1}\) and \(0.2 \times 10^{-6} m^2/s\) were used for \(\sigma\) and \(\mu_r\), respectively.\(^9\)

The magnetic flux density, \(B\), depending on the distance from the center of the mold was calculated by the change in \(r\), and \(F_t\) and \(F_r\) were obtained using \(B\).

4.3.2 Calculated results

Figure 14 shows the magnetic flux density as a function of distance from the center of the mold. The magnetic flux density in the mold decreases abruptly at 2 mm distance from the surface of the mold in the central direction and subsequently decreases gradually. Therefore, a higher magnetic flux density affects the molten metal in the mold when the thickness of the mold wall and the inner diameter of the mold become smaller.

Figure 15 shows the force affecting the molten metal in the cylindrical mold as a function of the distance from the center. Lorentz forces increase with increasing rotating velocity of the magnet, whereas Lorentz forces decrease with a shift.
from the outside to the center according to the Lorentz force ($F_\theta$) affecting the tangential direction for the molten metal in the mold (Fig. 15(a)). The Lorentz force ($F_r$) affecting the molten metal in the mold in the radial direction (Fig. 15(b)) shows a tendency similar to the Lorentz force ($F_\theta$) in the tangential direction. However, the degree of the force was small, about $1/1000$ of the force ($F_\theta$). Therefore, the Lorentz force affecting the radial direction hardly contributes to the molten metal so that the effect of stirring using the permanent magnet on the molten metal is not expected. Furthermore, the resultant force ($F = F_\theta + F_r$) of the Lorentz force affecting the tangential and the radial directions shows a tendency similar to the Lorentz force affecting the tangential direction (Fig. 15(c)). Consequently, the effect of the stirring depends remarkably on the Lorentz force affecting the tangential direction. It is concluded that the Al–Cu alloy is stirred directly by the Lorentz force in the outside of the molten metal near the rotating magnet. On the other hand, the alloy in the upper, central and lower regions far from the magnet is stirred indirectly by fluidity generated at the outside region. Also, indirect stirring is difficult in the Sn–Cu–Sb alloy compared with the Al–Cu alloy because of the large specific gravity ($\rho = 7.4$). The effect of stirring appeared markedly only in the outside region near the magnet, as shown in Figs. 5–8. It is clear that the effect of the stirring using the permanent magnet depends on the specific gravity of the molten metal in addition to the magnet flux and the rotating velocity of the magnet.

5. Conclusions

A stirring device using a permanent magnet was designed and was prepared in-house by us. Stirring of the melted metal was carried out during casting. The influence of the stirring using the permanent magnet on ingots having different solidification morphologies and specific gravity values was studied. The following conclusions were obtained.

(1) Stirring of the molten metal brings about shortening of the solidification time.

(2) When the Sn–Cu–Sb alloy was stirred, the primary lath crystal was broken to become granular crystals.

(3) When the Al–Cu alloy was stirred, fine equiaxed crystals were formed in the whole ingot and its area was extended.

(4) Hardness increased with increasing rotating velocity of the magnet and porosity decreased in the alloys.

(5) The molten metal is stirred directly in the outside region near the magnet. On the other hand, the molten metal far from the magnet is stirred indirectly by fluidity generated in the outside region.

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