1. Introduction

Grain refining and modification offer substantial benefits to aluminum alloy in casting processes, because finer grains ensure better mechanical properties. Many conventional methods, such as chemical modification, electric current pulse, vibration (mechanical, sonic, ultrasonic) have been used to process light metal. Among these techniques, the application of electromagnetic vibration (EMV) is of particular interest, because the vibration is easy-operated and free from pollution to the melt owing to non-contact between the vibrator and the melt.

Recently, researchers have confirmed the effects of electromagnetic vibration on the solidification of alloy or pure metal, especially on the grain refinement, which was generated by simultaneous imposing of a static magnetic field and an alternative electric current on the whole body of the melt. Among these techniques, the application of electromagnetic vibration (EMV) is of particular interest, because the vibration is easy-operated and free from pollution to the melt owing to non-contact between the vibrator and the melt.

The aim of this paper is to explore the refinement mechanism by conducting experiments in which electromagnetic vibration was imposed on the top of the samples.

2. Experimental Apparatus and Procedure

The experimental apparatus, as shown in Fig. 1, consists of a superconductor (SC) magnet, a furnace, a cylindrical alumina tube, and AC power. A strong static magnetic field can be produced with magnetic flux density up to 14 T in the center of the magnet and a gradient of the field away from the center. The distributions of the magnetic flux density and the parameter \( G_z \) are shown in Fig. 2.

The material used in the experiment was 99.9% Al. It was melted in a vacuum induction furnace, and poured into a graphite mold to produce pure Al rods. The rods were cut into 80 mm long pieces to be used as samples.

After setting the sample in an alumina tube and putting it in the furnace, as shown in Fig. 1, it was heated up to 750°C for melting and kept at this temperature for 30 min to homogenize of melt. Then the power of the furnace was turned off to let the sample cool and the alternative electric current with the frequency of 50 Hz was imposed to the metal through a couple of stainless steel electrodes inserted at the top of the sample. When the temperature of the sample dropped down to 600°C, the AC current was turned off.

The solidification was conducted on the condition of 0–10 T magnetic field coupled with 0–10 A alternative electric current.

Samples obtained from the experiment were cut longitudinally along the center line between two electrodes, and...
then polished to reveal the macrostructure with solution composed of 90 mL HCl, 30 mL HNO₃, 30 mL HF and 50 mL H₂O.

3. Results

Figure 3 compares the macrostructures solidified under several vibration conditions. It is shown that the application of a single 10 T magnetic field or a 10 A current with the frequency of 50 Hz could not refine the structure. While the simultaneous imposition of a 0.5 T magnetic field and an alternating current of 10 A, which generates electromagnetic vibration in the sample, the refined structure [Fig. 3(d)] is gained at the bottom region of the sample. With increasing magnetic flux density to 10 T, the refined structure is gained at the top region of the sample.

In order to explore the formation of the refining structure under electromagnetic vibration, two kinds of experiments were carried out. One was to investigate the refining mechanism of the electromagnetic vibration on the solidification structure of pure aluminum and the other was to investigate the distribution of the refined grains under different experimental conditions.

3.1. Effect of Cooling Rate on Crystal Refinement

In general, the size of the solidified structure is strongly affected by the cooling rate. Sometimes, imposing electric current and magnetic field may influence the heat transfer. In order to clarify this effect of EMV, cooling curves with different experiment conditions were measured with the results shown in Fig. 4.

Form Fig. 4 one can learn that in the case of application of a single magnetic field, a slower cooling rate is observed with a coarse structure (Fig. 3(b)). However, applications of the alternative electric current or the EMV have almost no effect on the cooling rate. Therefore, it is clear that the cooling rate is not responsible to the grain refinement.
3.2. Refining Period during Solidification

To confirm when the structure was refined during the solidification, the imposing period of the alternative electric current was changed while the static magnetic field of 1 T was maintained during all periods of the solidification. The imposing periods of alternative electric current were adjusted according to the cooling curve and its derivative curve of the sample without vibration (Fig. 5). Figure 6 shows the experimental results.

From Fig. 6, it can be noticed that the application of EMV before nucleation has no effect on structure refinement, and the solidification structure can be refined effectively during nucleation. After nucleation, EMV has slight effects on refining of structure (comparing Figs. 6(a) and 6c)). Based on the above experiments, grain refinement by EMV is mainly achieved during nucleation but not at the stage of crystal growth. In other word, dendrite fragmentation due to electromagnetic force isn’t responsible to the refinement in this case.

3.3. The Refining Mechanism under Local Vibration

Classic nucleation theory predicts that a large nucleation rate is a necessary condition for grain refinement, but it is not an only governing factor, because the grain refinement depends also on the survival rate of the nuclei. In the conventional casting processes, heterogeneous nucleation takes place immediately in the undercooling liquid close to the mould wall. The majority of the nuclei are transferred to the overheated liquid region by the convection aroused from mould filling and dissolved. Only a small proportion of the nuclei survives and contributes to the final microstructure, resulting in a coarse and non-uniform microstructure. It is therefore necessary for microstructure refinement that every single nucleus formed during nucleation can survive and grow. The high nuclei survival rate can be achieved by creating the following conditions: (1) more uniform temperature and nucleating sites throughout the entire volume of the liquid alloy; (2) rapid extraction of latent heat to prevent recoalescence. Under such conditions, nucleation will occur throughout the entire volume of the liquid and each nucleus will survive and grow, producing a fine and uniform structure.

The simultaneous imposing a static magnetic field and an alternative electric current on the whole samples, Vibration is the main reason for grains refinement in the case of high frequency and small volume samples. And this technique was applied to the continuous casting processing. While melt flow is the main reason for grain refinement in the case of large ingot and low frequency. However, a lower frequency vibration is imposed to the top of moderate size samples, surface oscillation (melt vibration and melt flow) occurs in the surface, this can be demonstrated in Fig. 7. It makes the nuclei dissociate from the cooled surface of the melt and disperse the nuclei agents. Furthermore, the surface oscillation promotes heat transfer efficiently, avoiding any chance for recoalescence. In addition, the temperature and composition distribution will be more uniform throughout the entire melt in the presence of the oscillation. Therefore, vibration induced surface oscillation is an important approach for achieving crystal multiplication and refined uniform structure.

In order to confirm crystal multiplication induced by the surface oscillation as the main cause for grains refinement, two experiments were carried out. One was to clarify origin of the crystal nucleus from the surface and the other was to confirm that surface oscillation of the sample will improve effective nucleation and crystal multiplication under EMV. For experiment (1), a wire net was set at the middle of sample, which prevents the nucleus to fall to the
bottom, and the temperature distribution was examined by two thermocouples located at the center and top of the sample respectively. For experiment (2), a pair of electrodes was set at the bottom of sample for avoiding surface oscillation. And the results are shown in Fig. 8 and Fig. 9. It is shown that as the temperature being below the liquidus, the nuclei originated firstly on the surface of the melt, which can be confirmed by the temperature distribution (the top temperature is 30°C lower than the center at the same time, as shown in Fig. 8). When simultaneous imposing a static magnetic field (low intensity) and an alternating electric current at the top of the sample, surface oscillation and disturbance were induce by the alternative electromagnetic force, which increase effective nucleation and make the crystal nuclei dissociate from the surface and fall to the bottom of the sample. As a result almost the whole region was refined (Fig. 9(a)). When setting a net in the middle of the sample, refined structure is only obtained above the net while coarse macrostructure is observed below the net, and the wire net is approximately the boundary between these macrostructures (Fig. 9(c)). As application vibration at the bottom of the sample, only coarse structures were obtained (Fig. 9(b)), suggesting no disturbance of the surface by the EMV because of the dissipation of the wave in the melt.

3.4. The Influence of Magnetic Force on the Crystal Refinement

Based on the above experiments, one can learn that the main cause for grains refinement is crystal multiplication under local vibration. Among the process, crystal nuclei dissociating from the surface and falling towards the bottom of the sample, which is called ‘crystal shower’, is the significant step for grains refinement. In other word, controlling crystal shower will affect the crystal multiplication and the refining region. To verify this, an upward effective magnetic force is applied on the crystal nuclei by placing the sample at the position of \( z < 0 \), where the gradient of the magnetic field is positive, and owing to the difference in magnetic susceptibility \( 0 < \chi_x < \chi_z \) between the liquid and the solid aluminum, direction of the magnetic force \( F \) on the solid is upward, which will retard the crystal shower.

Figure 10 shows the structure with the same electromagnetic vibration force but various magnetic forces. As can be seen, under a low magnetic force \( (B=0.5 \, T, B_zdB_z/dz=0.95 \, T^2/m) \), the structure was refined only at the bottom of the sample; and further increase the magnetic force to \( B=2 \, T \) and \( B_zdB_z/dz=8.5 \, T^2/m, \) the refining region was lifted to the top of the sample. Moreover, it can be found that almost all the margins of the samples shown in Fig. 10 are coarse grains structure. This also confirms that most of refining grains are originated from the surface not the wall of the mould. Indeed the above results prove that the application of the magnetic force can restrain the crystal shower and change the distribution of refining region significantly.

Figure 11 shows the structures solidified under the same magnetic field \( B=1.5 \, T \) and \( B_zdB_z/dz=8.5 \, T^2/m \) with different current intensity. It can be observed that all samples were refined completely, and with the increase of the current intensity a decrease in size and increase in number of Al grains took place. This indicates that the gradient field of \( B=1.5 \, T, B_zdB_z/dz=8.5 \, T^2/m \) has offered a positive magnetic force; as a consequence, the crystal shower is restrained partly and the nuclei distribute heterogeneously in the sample, resulting in the refining structure throughout the whole sample.
3.5. The Influence of Electromagnetic Vibration Force on the Crystal Refinement

Since crystal shower has influenced the distribution of the refined grains, in order to investigate the direct effect of the electromagnetic vibration force on the structure, it is necessary to eliminate the effect of crystal shower on the structure. From Fig. 12, it can be learned that the magnetic force under 10 T, $B_z dB_z/ dz = 400 T^2/m$ is enough to restrain crystal shower completely, therefore the structures under the gradient magnetic field of $B = 10 T$, $B_z dB_z/ dz = 400 T^2/m$ and various electric currents (that is various EMV force) were investigated. Comparison of the structures in different conditions as shown in Fig. 12 indicates that with the increase of the electric current, the size of Al grains decreased and the depth of refinement region increased. This means that with the increase of the EMV force, the refining effect is enhanced.

4. Discussion

4.1. Mechanism of Grain Refinement in EMV Processing

The refining mechanism should be attributed to effective nucleation and crystal multiplication due to surface oscillation motion. When simultaneous imposing a static magnetic field and an alternative electric current to the top of molten metal, an alternative electromagnetic force is induced, which behaves as periodic forces of compression and tension and put the liquid metal into oscillatory motion. As the temperature lower than the liquidus, the nuclei originate firstly on the surface of the liquid metal because of higher heat transfer rate there. As mentioned above, the periodic molten metal oscillation induced by the EMV force, which results in a large amount of disturbance in liquid metal and an intensive strike on the surface, the nuclei may dissociate from the surface and fall toward the center and bottom of the samples. The formation of steady solidification shell was postponed by the vibration, resulting in more nuclei dissociate from the surface or crystal shower.

Usually, refinement of crystal in the presence of a vibration is attributed to the cavities effect of the vibration, because the collapse of the cavities will produces shock wave with super high pressure which will promote nucleation. In our case, the vibration pressure is calculated as about $10^4 Pa$, much lower then the threshold pressure of cavitation. Therefore, the shock wave produced by cavitation is not the main reason for grains refinement. Consequently, it is reasonable to attribute the refinement of grains to the crystal multiplication induced by surface refinement and crystal shower.

4.2. Controlling the Refining Structure by Gradient Magnetic Field

Above experimental results indicate that the magnetic force influenced the refining grains region significantly. This should be attributed to the change of the effective gravitation under a gradient magnetic field. A non-uniform magnetic field will produce a magnetic force. In the case of axis-symmetric magnetic systems, the axial component of the magnetic force density at any position can be expressed as Eq. (1)

$$\bar{F}_v = \chi_s - \chi_l \frac{B_z}{\mu_0} dB_z/ dz$$

Where $B_z$ is the axial component of the magnetic flux density, $\mu_0$ is the permeability of the free space, $\chi_s$ and $\chi_l$ are the magnetic susceptibility of the Al particle and the surrounding medium, respectively.

Considering the Archimedes effect, the effective gravitation without magnetic field is:

$$\bar{G}_v = (\rho_p - \rho_l) \bar{g}$$

Thus, the total forces act on Al particles under a gradient magnetic field is:

$$\bar{F} = \bar{F}_v + \bar{G}_v = \frac{\chi_s - \chi_l}{\mu} B_z dB_z/ dz + (\rho_p - \rho_l) \bar{g}$$

This equation indicates that the effective gravitation is modified under a gradient magnetic field. Therefore the application of the non-uniform magnetic field can restrain crystal shower and change the distribution of the refined grains.
5. Conclusions

(1) Refining grains were obtained in the experiments by top imposing EMV. It is suggested that surface oscillation induced crystal multiplication and crystal shower is the dominant mechanism for the grain refinement, with the increase of the electromagnetic force, the size of Al grains decreases and the area of refinement region increased.

(2) Owing to falling of the refined grains during the electromagnetic vibration, the refined structure was normally gained only at the bottom region of the sample. A method was proposed to restrain crystal shower by using an upward magnetic force in a gradient magnetic field.

(3) An uniform refining structure can be achieved under the gradient magnetic field of $B = 1.5 \, \text{T}$, $B_z dB_z/dz = 8.5 \, \text{T}^2/\text{m}$.

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