Effect of Low-Frequency Magnetic Fields on Microstructures of Horizontal Direct Chill Cast 2024 Aluminum Alloys

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The horizontal direct chill (HDC) casting process is a well-established production route for wrought aluminum alloy ingots. However, the ingots may suffer from heterogenous microstructures due to the unbalanced cooling condition and gravitational effect. In order to minimize the casting defects, a low frequency electromagnetic field was applied in the HDC casting process and its influence on solidified microstructure was studied. The results show that the low frequency electromagnetic field can effectively reduce heterogenous microstructures in HDC ingot; and two main parameters of electromagnetic field, i.e., intensity and frequency, significantly affect the microstructures and solute distribution from the center to the periphery of the ingot. In the range of ampere-turns and frequency employed in the experiments, the ampere-turns of 10000 At and frequency of 30 Hz were found to be optimum.

Keywords: low frequency electromagnetic field, horizontal direct chill casting, microstructure, aluminum alloy

1. Introduction

The casting of aluminum alloys for extrusion and rolling has been principally carried out with the DC (direct chill) casting process. The DC process could be classified into VDC (vertical direct chill) casting and HDC (horizontal direct chill) casting. For many decades, VDC process has played an important role in aluminum alloys ingots production. Only in recent years, the HDC process has attracted the attention of the global aluminum industry.¹

Compared to the VDC process, the HDC process has many advantages such as lower investment cost, higher flexibility and so on.² However, the HDC process has some characteristic technical problems caused mainly by gravitation effect, which often results in macro segregation in the ingots, namely, the bottom part of the horizontally cast ingots are rich in heavier alloy elements. Therefore, finding an effective way to obtain homogeneous microstructures is a challenge for further development of the HDC process.

The application of electromagnetic casting techniques (EMC) for improving production quality has attracted a great deal of attention in recent years, and considerable advances have been achieved. Other than the EMC³,⁴ process, Vivès introduced a new electromagnetic casting technique, the CREM process⁵,⁶ aiming at refinement of the microstructure and improvement of the surface quality of ingots. In this process, an inductor, surrounding the ingot mold, is supplied with a 50Hz alternating current. Under the effect of the AC current, the inductor generates an alternating magnetic field and the melt can be inductively stirred. The constrained effect of electromagnetic forces reduces the contact pressure between melt and mold, which, in turn, reduces the primary cooling intensity. The forced convection due to the electromagnetic field broadens the mushy zone, decreases the height and depth of the sump, promotes heterogeneous nucleation, reduces temperature gradient and weakens the effect of gravity. All these effects result in a significant refinement of microstructures and improvement of solute redistribution in the ingot.⁷,⁸

In light of CREM process, we applied a low frequency electromagnetic field in the HDC process in order to improve the production quality. A systematical study of the effect of low frequency electromagnetic field on the microstructure of the HDC products was carried out.

2. Experimental Procedures

The experimental setup is illustrated schematically in Fig. 1. The inner diameter of the mold is 60 mm and a 50-turn coil is arranged outside the mold. A casting speed of 200 mm/min and a casting temperature of 998 K are held constant throughout the experiment to highlight the influence of the electromagnetic field on the microstructure. In order to investigate the influence of the electromagnetic field, the experimental procedures were divided into two parts. The first part was designed to study the effect of the intensity of the magnetic field on the microstructure and distribution of alloying elements. During experiment, the frequency of the magnetic field was kept at 30 Hz while the coil current varied...
from 0 to 200 A, i.e., the magnitude of ampere turns increases from 0 to 10000 At. The increase of the ampere-turns results in an increase of intensity of magnetic field. The second part is to investigate the effect of electromagnetic frequency on the microstructure and distribution of alloying elements. The magnitude of ampere-turns was maintained at 10000 At and the frequency of alternating current was varied in the range of 10 to 100 Hz during experiment.

The diameter of the billet is 60 mm and the material used for this investigation is a 2024 aluminum alloy. The chemical composition of the alloy is shown in Table 1. The specimens taken from bottom to top surface in the cross-section of the ingot were observed by an optical microscope, Leica DMR following by standard metallurgical preparation. The concentrations of alloying element Cu inside the grains or cells were measured by electron probe microanalysis (EPMA). For investigation of macro segregation, concentration of the alloy elements from the bottom to top surface of the billet was measured by chemical analysis. DAS (Dendrite Arm Spacing) was measured using optical methods for the secondary dendritic arms.9)

### Table 1 Chemical composition of the experimental 2024 alloy (mass%).

<table>
<thead>
<tr>
<th>Elements</th>
<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.25</td>
<td>1.8</td>
<td>0.7</td>
<td>0.25</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

3. Results and Discussion

#### 3.1 Refinement of the microstructures

Similar to VDC hot top process (a kind of VDC process),10) molten metal in the HDC process is surrounded by refractory and the edge of casting mould at the initiating point of solidification (region A which sign in the Fig. 1). Moreover, in contrast to the VDC hot top process, as the metal is pulled out in the horizontal direction, non-uniform tensions are liable to occur on a shell being solidified. Besides, in the vicinity of the mould, the extraction of heat tends to vary between upper and bottom portions due to the unbalanced cooling and gravity difference. If these adverse conditions occur simultaneously, the microstructure of ingot tends to deteriorate and create a thick segregation layer, which, in turn, results in a great reduction in ingot quality.11) However, in the ingots examined in this study, the application of low frequency electromagnetic fields results in a forced convection in the melt. It enhanced the transportation of mass and heat between top and bottom. The flow field and temperature pattern become uniformed and so the unbalanced solidification is reduced.

Figure 2 shows the microstructures of HDC ingots. In conventional HDC process, the grains are heterogeneous and the grain size becomes coarse from the bottom to the top due to the unbalanced cooling.11) The average DAS is about 35 µm in the top and center, and about 16 µm in the bottom. In the condition of electromagnetic HDC, the microstructures are homogeneous and the difference in DAS from the top to the bottom is reduced. The average DAS size in this case is about 12 µm in the center and about 15 µm in the bottom respectively. Comparing with conventional HDC condition, the dendritic structures change from coarser to finer and are more uniform from top to the bottom of the billet as shown in Fig. 2.

Figure 3 shows the distribution of the Cu element from the bottom to the top surface. In the absence of an electromagnetic field, the alloying element is highly enriched at the bottom surface and the average solution concentration differs between the upper and bottom portions, namely, both inverse segregation and gravity segregation took place. In contrast, in the presence of a 10000 At, 30 Hz electromagnetic field, such a macrosegregation is greatly reduced. Besides the reduced macrosegregation, under the electromagnetic field, the solute content inside the crystal grains is also increased. The...
percentage of Cu inside the crystal grains is about 3.04 mass% in the presence of a 10000 At, 30 Hz electromagnetic field, while it is about 2.2 mass% in the absence of an electromagnetic field.

### 3.2 Effect of intensity of magnetic field on the microstructure

Under periodic current, the inductor generates an alternating magnetic field in the melt, and gives rise to an induced current. Thus, the melt is subject to electromagnetic body forces caused by the interaction of the eddy current density vector $J$ and the magnetic field flux density vector $B$. Another characteristic of electromagnetic field is the presence of a fringe effect consisting of a pronounced inclination of the magnetic field lines toward the axis of symmetry of the ingot. Therefore, the Lorentz force density consists of two parts as expressed below:

$$F = \frac{1}{\mu} (B \cdot \nabla) B - \frac{1}{2\mu} \nabla B^2$$  \hspace{1cm} (1)

The first part in the right hand side of eq. (1) is a rotational component, which results in a forced convection in the melt. The transportsations of heat and mass between upper and bottom portions are enhanced leading to a uniform temperature field. The second part is a potential force balanced by a reduced primary cooling and reduced friction force between ingot and mold. As discussed above, the gravity and unbalanced cooling that induced heterogeneous microstructures are greatly decreased by the effects of electromagnetic forces.

With an increase in current intensity, forced convection and the confined effect of the Lorentz force are intensified and the effects are enhanced. The effect of the electromagnetic intensity on the microstructures is shown in Figs. 4(a) and (b). The casting conditions of the ingots varied with the electromagnetic intensities while the frequency was kept the same, i.e., 30 Hz. It can be seen that, increasing the number of ampere-turns from 5000 At to 10000 At, the dendritic grains change from coarser to finer and are more uniform.

It is also noticed that the amount of the alloying elements within grains increases with increasing the current intensity. The alloy melt is a system consisting of atomic nuclei surrounded by negatively charged electrons. The atomic nuclei make irregular thermal motion with a velocity ($\vec{v}$). Under the static electromagnetic field they will do revolution motion around the lines of magnetic field, the revolution radius and angular velocity are as followings:

$$r_c = \frac{mv}{|q|B}$$ \hspace{1cm} (2)

$$\omega_c = \frac{B|q|}{m}$$ \hspace{1cm} (3)

where $r_c$ is the revolution radius of the atomic nuclei in the magnetic field, $q$ is the quantity of charge of a atomic nuclei, $v_i$ is the velocity in the vertical direction of the line of magnetic field, $m$ is the mass of atomic nuclei, $\omega_c$ is the revolution angular velocity. The Al, Cu ions are $\text{Al}^{3+}$, $\text{Cu}^+$. Their revolution radius and angular velocity are different because of the difference in $m$ and $q$. For instant, $m_{\text{Al}}^{3+} < m_{\text{Cu}}^{+}$ and $q_{\text{Al}}^{3+} > q_{\text{Cu}}^{+}$ lead to $r_c_{\text{Al}}^{3+} < r_c_{\text{Cu}}^{+}$. Thus, a relative movement among $\text{Al}^{3+}$, $\text{Cu}^+$ will occur. It is this relative movement of the different atomic nuclei that promotes the entropy of the melt in front of the solid-liquid interface; in order to reduce free energy of the solute elements automatically scatter throughout the melt. At the same time, under the condition that electromagnetic field increases the number of nuclei and decrease the distance that solute elements need to travel, the concentration of solute elements along grain boundaries is low. Both of the two reasons lead to an increase of the content of alloying elements within grains and reduce the grain boundary segregation. With an increase in current intensity, the effects discussed above are enhanced. The relation between the distribution of Cu and the electromagnetic field intensity at the same frequency (30 Hz) are shown in Fig. 5(a). In the ampere turns range of the present study, large-scale heterogenous of alloying elements reduces with increasing the ampere turns. Figure 5(b) shows con-

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**Fig. 4** Optical morphologies of as-cast microstructures in electromagnetic HDC. (a) 5000 At 30 Hz; (b) 10000 At 30 Hz.

**Fig. 5** (a) Cu concentration profile from the bottom to top surface under different intensities of electromagnetic field; (b) Cu concentration profile inside crystal grain under different intensities of electromagnetic field.
centration of Cu element inside crystal grains under various intensities of electromagnetic field; all specimens have been taken from the center of cross-section of ingots. It appears that the stronger the intensity is, the more efficient for promoting solution of alloying elements inside crystal grains.

3.3 Effect of frequency of magnetic field on the microstructure

As a principal parameter, frequency greatly influences the distribution of magnetic flux density in conductive media. In the process of electromagnetic casting, flow pattern and temperature field of the melt can be modified by means of frequency and optimized conditions of solidification can be obtained. The characteristic length, which specifies how the magnitude of magnetic field decreases as a function of distance into the liquid metal is the skin depth:11)

$$\delta = \sqrt{\frac{1}{\sigma \mu \pi f}}$$

where $\sigma$ and $\mu$ are the conductivity and permeability, respectively, of the liquid metal and $f$ is the frequency. Figure 6 shows the distribution of magnetic flux density with various frequencies of coil current. When the frequency is relatively high (50 Hz or more), the skin depth is extremely fleet and the force density significantly concentrated near the surface of the metal. The rapid change in magnetic flux density across a small skin depth means a high gradient of force density, which forms a stronger confined pressure. On the other hand, the stirring effect is also weakened. With the decrease of frequency, the magnetic field, induced currents, and hence Lorentz force density is increased throughout the bulk of the liquid metal, the rotational part became dominant and the forced convection will be enhanced. With a further decrease of frequency (less than 10 Hz), although the magnetic flux density is still increased, the distribution of magnetic flux density is relatively uniform throughout the melt; the rotational force is weakened again. Therefore, under a fixed magnetic intensity, the ideal flow pattern and temperature field can be obtained by application of a proper frequency of electromagnetic field, which, in turn, improves the microstructure to the best effect.7,8)

Figures 7(a) and (b) shows the effect of frequency of the magnetic field on the microstructures. Figure 7(a) shows that the structure is still dendritic and not uniform with a frequency of 100 Hz; Fig. 7(b) shows that the structure is finer and more uniform with a frequency of 30 Hz.

Figure 8(a) shows the distribution of Cu element from the bottom to the top under different frequencies of electromagnetic field at the intensity of 10000 At. In the presence of the electromagnetic field, the inverse segregation and gravity segregation are drastically reduced. The best effect was gained with a frequency of 30 Hz. Figure 8(b) shows the concentration of Cu inside the crystal grains under different frequencies of electromagnetic field. With the decrease of the frequency, the average content of Cu increases. However, when the frequency is lower than 30 Hz, the average content of Cu decrease. It demonstrates that the frequency of 30 Hz is the most efficient for promoting solution of alloying elements inside crystal grains.

Fig. 6 Distributions of magnetic flux density with various frequency of coil current frequency of coil current.

Fig. 7 Optical morphologies of as-cast microstructures in electromagnetic HDC. (a) 10000 At 100 Hz; (b) 10000 At 30 Hz.

Fig. 8 (a) Cu concentration profile from bottom to top under different frequency of electromagnetic field; (b) Cu concentration profile inside crystal grain under different frequency of electromagnetic field.
4. Conclusions

The following conclusions can be drawn based on the present work.

(1) The application of a low frequency electromagnetic field in the HDC process leads to an even and refined cast microstructure and reduce macrosegregation of the alloy elements.

(2) The intensity of electromagnetic field plays a significant role in grain refinement and solute redistribution. With an increase in coil current intensity, the confined effect and stirring effect of electromagnetic body forces increase, which, in turn, change the dendritic structure from coarser to finer, and reduce macrosegregation. The solute content inside the grains is also gradually promoted.

(3) The frequency of electromagnetic field greatly influences the microstructures and segregation of an HDC ingot. The results indicate that at a frequency of 30 Hz an optimum microstructure could be obtained when the intensity of the magnetic field was kept at 10000 At.

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