Microstructure and properties of Al-Si alloys under intermediate frequency electromagnetic field

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Abstract

The intermediate frequency electromagnetic (IFEM) field was applied to treat Al-1%Si (high-purity) and Al-8%Si alloys during direct chill (DC) casting process. The ingot was studied by means of metallographic examination and mechanical tests. The results showed that compared to the conventional casting, both Al-1%Si and Al-8%Si alloys processed under IFEM field exhibited superior refinement as well as an enhancement in the mechanical properties, especially the elongation. Si element segregation of high purity Al-1%Si alloy had effectively improved under IFEM field. Numerical simulation was used to better understand the role of IFEM field, that showed the inducing forced convection and the subsequent achievement of a uniform temperature field of IFEM field during the solidification could be accounted for the experimental observations.

Keywords: Al-Si alloys; Intermediate frequency electromagnetic field; Solidification Microstructure; mechanical properties.

1. Introduction

Al-Si alloys are extensively used owing to their low density and excellent mechanical properties. For instance, Al-1%Si (All compositions quoted are in wt.% unless otherwise stated) is an important deformed alloy, it can be used as the bonding wires of electronic packaging and the functional thin film for integrated circuit. Thus high purity and elemental homogeneity are always required. As the Si content increases to 7-8%, it is widely applied in auto-making, ship building and aircraft manufacturing as casting alloy. However, the coarse grain, Si segregation and subsequent performance degradation are serious constraint to its application and development[1].

It is generally considered that grain refinement is an effective way to restrain segregation and to improve the mechanical properties. Electromagnetic field[2-4] is a common method to modify the solidification structure, and widely used in the production of Al alloy ingot, for example, the DC casting process. It has a significant influence on grain size and surface quality. However, in the past years, the intermediate frequency electromagnetic (IFEM) field has been rarely employed in DC casting. The skin depth in case of IFEM field is relatively shallower, which is regarded as a beneficial factor as it leads to the fragmentation of the columnar structure.

In the present study, an IFEM field (with frequency of 1.1 KHz and incoming current of 125A) was applied during the DC casting process of Al-1%Si (high-purity) and Al-8%Si alloys. The effects of IFEM field on the solidification structure and mechanical properties were studied. The numerical simulation of the physical model has been utilized to explain the necessary physical phenomena.

2. Experimental methods

The circular ingot of Al-1%Si and Al-8%Si alloys with diameter of 160 mm was prepared by a vertical DC casting installation. The experimental setup mainly consists of the mold, pouring system, cooling water system, and electromagnetic unit. The ingots were prepared with the casting velocity of 50 mm·min⁻¹ and the cooling water flow rate of 1000 L·h⁻¹. The electromagnetic effect was generated by
a variable magnetic field with frequency of 1.1 KHz, and induced by copper induction coils arranged inside the mold with cooling water.

The composition of Al-1%Si alloy is Si 1.07%, and Al in balance. It was prepared by high purity Al (>99.995%) and Si (>99.997%). In order to prevent element segregation, the master alloy Al-20%Si was made of high purity Al and Si by induction smelting with water-cooled copper crucible, then was used for the preparation of Al-1%Si. The composition of Al-8%Si is as followed, Si 7.9%, Fe 0.2% and Al balance, made by commercial purity Al and Al-20%Si master alloy. In this experiment, as experimental procedure shown in Fig.1a, about 30 kg of Al-1%Si alloy (Al-8%Si) was melted in a resistance furnace at 780 °C (750 °C for Al-8%Si) under Ar gas protection. Then the melt was poured into the mold through the pouring system at 720 °C (680 °C for Al-8%Si), about 60 °C higher than the liquidus temperature. The starting head began to draw out when the solidification shell was formed. Meanwhile the IFEM field of power 47.5KW was applied till the experiment was over.

After the ingots were prepared completely, the top and bottom parts were cut down. Then the cross section was ground and etched to observe the macrostructure. The samples for microstructure observation and mechanical testing were taken from different positions (as illustrated in Fig. 1b). The tensile test (sample size in Fig.1c) was performed in a universal test machine with a strain rate of 2 mm·min⁻¹. The component detection of Si in Al-1%Si was carried out by inductively coupled plasma (ICP, Optima 2000DV, Perkinelmer).

**3. Results**

Figure 2 shows the macrographs and microstructure of Al-1%Si and Al-8%Si ingots with or without IFEM field. It is obvious that IFEM field has a distinct influence on the macrostructure and grain size. For the conventional Al-1%Si, the cross-section structure is not uniform, the average grain size of edge is 800µm while that in the center increases to 2000µm. When under IFEM field, the macrostructure transforms to uniformity, with an average grain size of approximately 350µm. For Al-8%Si ingot, macro segregation is not observed neither with nor without IFEM field. The cross section of conventional ingot is characterized by coarse grains which have size more than 1200 µm. Under IFEM field, the macrostructure is finer, and the average grain size decreases to less than 500 µm. Based on both Al-1%Si and Al-8%Si ingot, it is worth noting that the deviation in grain size under IFEM field is relatively smaller, indicating that the IFEM field causes the structure not only refined, but also uniform.

By microstructure refinement, Si element segregation of high purity Al-1%Si alloy has effectively improved. Under conventional condition, the content of Si in the edge, R/2 and center part is 1.61%, 1.37% and 0.91%, respectively. While under IFEM field, the content at the same position turns to 1.22%, 1.10 % and 1.05%, respectively. The grain refinement also leads to an enhancement of mechanical properties. The average tensile strength and elongation with IFEM field increase 65.8% (from 64.1 MPa to 106.3 MPa) and 44.8% (from 21.2% to 30.7%), respectively, compared with that
without IFEM field. The application of IFEM field improves the ultimate tensile strength of Al-8%Si ingot with enhancement of 15.6%, 18.0% and 10.2% from edge to center, respectively. The elongation for the corresponding positions is 27.1%, 29.7% and 19.1%, respectively. These results indicate that the application of IFEM field during DC casting process is beneficial for the structure refinement and improvement of mechanical properties in the whole ingot.

| Cross-section | Edge | R/2 | Center |
|---------------|------|-----|--------|
| Al-1%Si       | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| with IFEM     | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| Al-8%Si       | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |
| with IFEM     | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |

Figure 2 Macrostructure and microstructure of Al-1%Si and Al-8%Si ingot under different condition

4. Discussions

When the coil is energized with an alternating current, an electromagnetic volume force is generated by magnetic field and induced current in the melt. The calculated distribution of this electromagnetic force is displayed in Fig. 3a, suggesting that the Lorentz force is not uniform along the longitudinal direction and achieves a maximum value at the horizontal mid-plane of coils. The electromagnetic force causes a forced convection, and further fluid flow, mass and heat transfer in the melt. It can be seen from the flow velocity distribution that the IFEM field generates fluid circulations in the melt. The forced convection provides efficient homogenization of temperature field. Figure 3b presents the temperature distribution. Under IFEM field, a more uniform temperature field is obtained in the melt. Moreover, the temperature gradient from center to edge is reduced as well.

During DC casting process, there is always an obvious temperature gradient along the radius due to the cooling effect of water-cooling mold. This is conducive for dendrites growth. When IFEM field is applied, the operating range of electromagnetic field is determined by its frequency. For the IFEM field in this experiment, the skin depth is 8 mm. It implies that the influence of IFEM field is mainly concentrated on the edge of ingot, subsequently causing fragmentation in the columnar structure.

The forced convection induced by IFEM field also assists in dendrite fragmentation and abscission of the secondary dendrite arms during solidification[3, 5]. In the presence of forced convection, the initially solidified dendrites near the cold mold wall are easily broken off, then, are dispersed to the inner melt by the fluid flow, serving as nuclei during solidification. Moreover, the forced convection causes not only mass transfer, but also heat transfer. The peripheral melt with low temperature is transferred to the center, while the internal melt with high temperature is taken to the periphery. This
provides a homogenized temperature field and subsequently a lower temperature gradient, which is favorable for the equiaxed grain growth. All of these conditions mentioned above facilitate the grain refinement and then enhance the mechanical properties.

Fig.3 Calculated results of distribution of (a) time-average electromagnetic volume force and flow velocity and (b) temperature field under IFEM field of 125 A current magnitudes

5. Conclusions
In this paper, the effect of the IFEM field on DC casting of Al-1%Si (high-purity) and Al-8%Si alloys was studied. The following conclusions can be drawn from the study:

(1) The application of IFEM field with 125A current during the DC casting process is beneficial for the grain refinement and improvement of mechanical properties.

(2) Si element segregation of high purity Al-1%Si alloy had effectively improved under IFEM field.

(3) Based on the numerical simulation, the IFEM field brings about fluid flow, mass and heat transfer in the melt, and thus influences the nucleation as well as growth process.

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