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Abstract
2024 aluminum alloy slabs were horizontally cast under low-frequency electromagnetic fields. The results showed that when the frequency of the magnetic field is kept at 30 Hz, the α-Al grain size becomes smaller with increase of the intensity of magnetic field, indicating that high intensity of the magnetic field is beneficial to the grain refinement. When the intensity of magnetic field is kept at 15000 At, 30 Hz is confirmed as the favorable frequency for obtaining fine α-Al grains. Furthermore, high intensity and relatively low frequency are more effective to inhibit the gravity segregation of Cu element.

Key words : horizontal direct chill casting; aluminum alloy; electro-magnetic field; grain refinement; macro-segregation

Introduction

Alternating current electromagnetic field (EMF) has been successfully applied to the technique of direct chill (DC) casting of aluminum alloys. In 1970s, Getselev [1] developed electromagnetic casting (EMC) on the basis of conventional DC casting of aluminum alloys. In his design, a high frequency (2000-3000Hz) alternating magnetic field was applied. During the casting, the molten metal was not confined by a mold but by the magnetic pressure. This pressure results from the induced Lorentz force which balances the metallostatic pressure. EMC remarkably improved the surface quality of the ingots so that they can be rolled without scalping. In the end of 1980s, Vivès [2] developed CREM (Casting, Refining, Electromagnetic) technique. Different from Getselev, he applied an alternating current magnetic field with a commercial frequency (50Hz) during the DC casting of aluminum alloys. The results indicated that compared with the ingots by conventional DC casting method the solidified structures were refined and the surface qualities of the ingots also improved. In the later 1990s, on the basis of CREM, Vivès et al. [3] developed electromagnetic vibration technique where a steady direct current and an alternating current magnetic field were applied simultaneously. Under both of the stirring and magnetic vibration effects, much finer structure than that under CREM was obtained. In the 21st century, Cui et al. developed a Low-Frequency Electromagnetic Casting process [4]. They applied alternating current magnetic fields with frequencies of 15-30 Hz during the direct chill casting of aluminum alloys. The results showed that LFEC could effectively promote the solution of alloying elements, refine the microstructures and helped reduce the macro-segregation and cracks of the ingots.

It is known that DC casting process usually consists of two forms — vertical and horizontal direct chills (VDC and HDC). Compared to VDC, HDC process has advantages of lower investment cost, higher flexibility, longer casting times, etc [5]. However, the disadvantages are also obvious, such as inhomogeneous microstructures and macro-segregation resulting from gravity difference between top surface and bottom surface. Considering the noticeable influence of EMFs mentioned above, it is of practical interest to apply an EMF to the horizontal direct chill process.

In such a context, two 2024 aluminum alloy ingots were produced by a HDC process, during which LFEMFs with different intensities and frequencies were applied. The microstructures and macro-segregation were studied carefully in this paper.

Experimental

Two slabs of 2024 aluminum alloys (the nominal chemical composition is shown in Table 1) were produced by a HDC casting process. The casting configuration is schematically illustrated in Fig. 1(a).

The equipment mainly consists of a mold (inner size: 200×80 mm) and an induction coil (100 turns). The 2024 alloy was melted in an induction furnace. When the temperature reached 760 °C, the melt was poured into an electrical resistance furnace, and then degassed, slag-removed and refined. After kept for 20 min at 710 °C, the melt was introduced into the tundish to produce a 200×80 mm cross-section slab at a casting speed of 110 mm/min. During the casting process, the EMFs were applied as follows. For the first slab, the frequency was kept at 30 Hz, the intensity of the EMF varied from 0 to15000 At (0, 5000 At, 10000 At and 15000 At) (At is the abbreviation of ampere turns). For the second slab, the intensity of the EMFs was kept at 15000At, the frequency varied from 10 to 50 Hz (10 Hz, 20 Hz, 30 Hz and 50 Hz).

Slices obtained under different EMFs were cut transversely to the casting direction, and then three specimens (T-top, M-Middle and B-bottom) were further cut from each slice for microstructural observation, as schematically shown in Figure. 1(b). The copper compositions in the primary α-Al matrix at positions of T, M and B were detected by EPMA-1600/1610 electron probe microanalyzer (EPMA).

Table 1 Chemical composition of 2024 aluminum alloy

Elements	Composition (wt. %)
Cu	4.5
Mg	1.5
Mn	0.55
Al	Balance

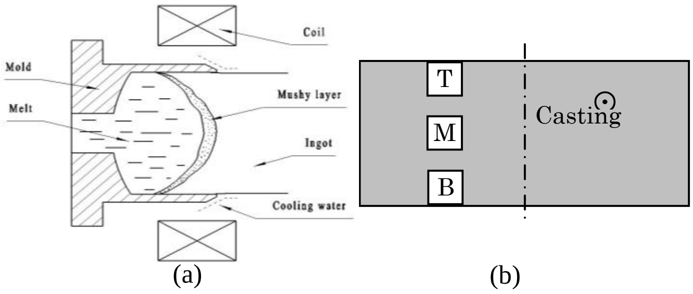

Fig. 1: Schematic illustration of (a) the HDC process with a LFEMF and (b) the positions for microstructural observations in the cross section of the slab. T, M and B represent top, middle and bottom positions, respectively.

Results and discussion

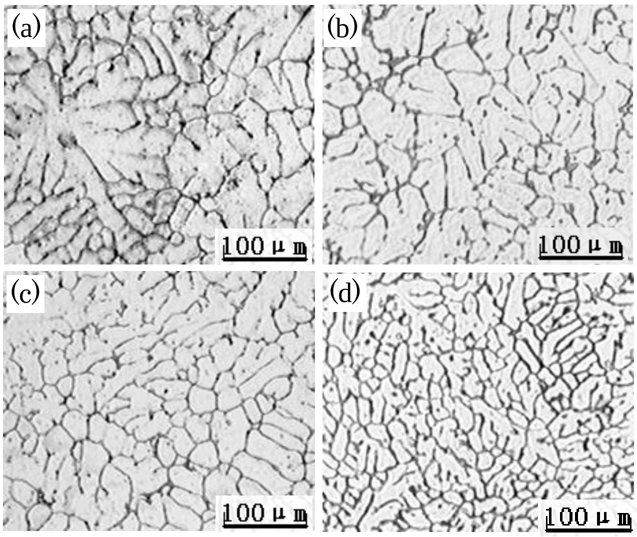

Fig. 2: Microstructures at the M positions of the slices with different intensities of the EMFs when the frequency was kept at 30 Hz: (a) 0 At, (b) 5000 At, (c) 10000 At and (d) 15000 At.

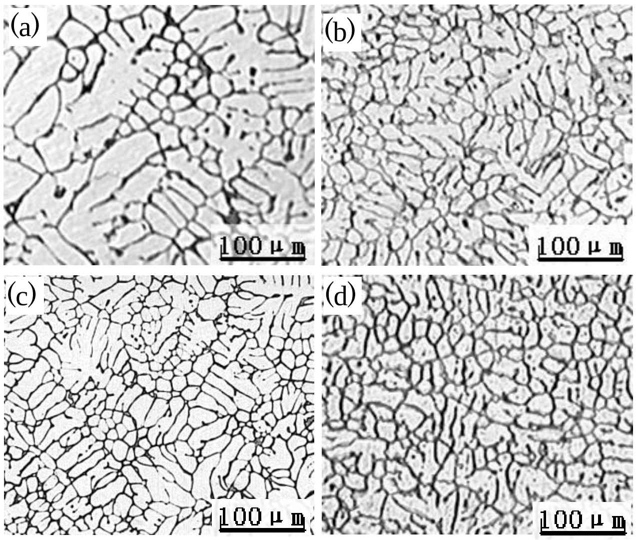

Fig. 3: Microstructures at the T and B positions of the slices with different intensities of the EMFs when the frequency was kept at 30 Hz: (a) 0 At, T (b) 15000 At, T, (c) 15000 At, B and (d) 15000 At, B.

Figs. 2(a)-(d) show the microstructures at the M positions of the slices with intensities of the EMFs of 0, 5000, 10000 and 15000 At (the frequency was kept at 30 Hz), respectively. It can be observed that without the application of the LFEMF the α-Al grains are coarse. With the increase of the intensities of the EMFs, the sizes of the α-Al grains are decreased gradually. When the intensities of the EMFs reach 15000At, the α-Al grains reveal quite fine dendritic morphology. These results indicate that the application of an EMF can effectively help refine the grains.

To show the effect of the EMF on the homogenization of the microstructures, Figs. 3(a)-(d) display the microstructures at the T and B positions of the slices without and with intensities of EMFs of 15000At (the frequency was kept at 30 Hz). It can be seen that without the application of EMF the α-Al grains at the T positions of the slices (Fig. 3(a)) are coarser than those at the B positions (Figs. 3(c)). However, when the LFEMF is applied, the α-Al grains at both positions almost have the same sizes. This suggests that the LFEMF facilitates uniform microstructures in the cross sections.

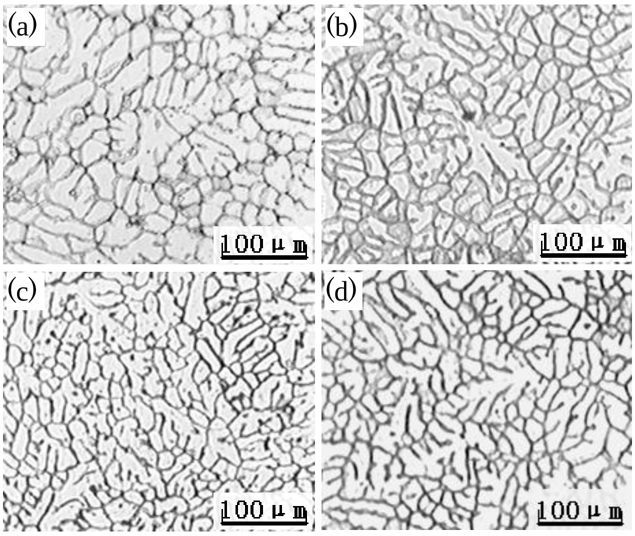

Fig. 4: Microstructures at the M positions of the slices with frequencies of the EMFs of (a) 10 Hz, (b) 20 Hz , (c) 30 Hz and (d) 50 Hz (the intensity was kept at 15000At).

Further, the microstructures of the alloy are also affected by the frequencies of the EMFs. Figs. 4(a)-(d) show the microstructures at the M positions of the slices with frequencies of the EMFs of 10, 20, 30 and 50 Hz (the intensity was kept at 15000At), respectively. As can be seen, 30 Hz is the most favorable frequency for the refinement of the α-Al grains.

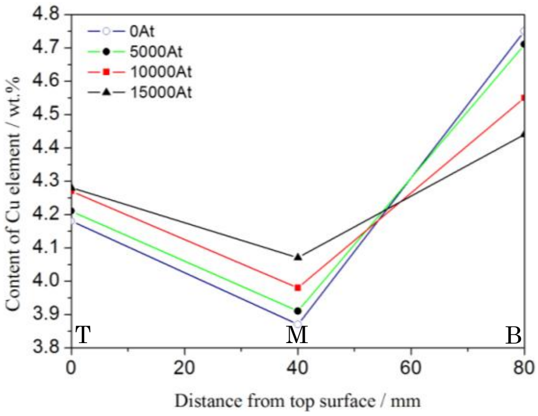

Fig. 5: Cu concentration profiles under different intensities of EMFs when the frequency was kept at 30 Hz.

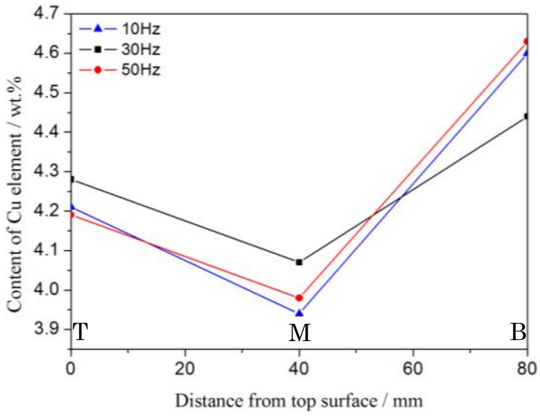

Fig. 6: Cu concentration profile under different frequencies of EMFs when the intensity was kept at 15000 At.

In addition to the microstructures, the EMFs also show a noticeable effect on the macro-segregation of Cu element. Fig. 5 shows the Cu concentration profiles under different intensities of EMFs when the frequency was kept at 30 Hz. It can be observed that in all cases the distribution of Cu element in the α-Al matrix shows a macro-segregation, the concentration varying according to B > T > M positions. However, with the increase of the intensities of EMFs the distribution of the Cu element tends to be homogenized — the Cu content differences between B, M and T positions are gradually reduced. Similarly, Fig. 6 shows the Cu concentration profiles under different frequencies of EMFs when the intensity was kept at 15000 At. Obviously, 30 Hz is the most preferred frequency to inhibit macro-segregation of Cu element.

Different from the VDC casting, the microstructures of HDC cast slabs are strongly affected by gravity [6, 7]. Due to the gravity, the contacting pressure between the bottom mold and ingot surface is larger than that between the top mold and ingot surface, which results in a higher cooling intensity of the bottom surface than that of the top surface. Moreover, high-temperature melt tends to rise towards the top surface while low-temperature melt tends to descend towards to the bottom surface. Both the high cooling intensity and low temperature melt contribute to the nucleation of α-Al grains. As a consequence, the sizes of the α-Al grains at the B position are smaller than those at the T positions. In addition, also due to the gravity, the Cu element tends to descend towards the bottom surface. This results in that the Cu concentration at the B position is larger than that at the T position.

When the time varying EMF is applied, currents will be generated in the melt within the mold. Thus, the melt is subjected to electromagnetic body forces due to the interaction of the induced currents and the magnetic fields. The electromagnetic body force F is the so-called Lorentz force and usually expressed as follows [2]:

$$F = J \times B = \frac{1}{\mu}\left(B\nabla\right)B - \frac{1}{2\mu}\nabla B^2 \tag{1}$$

where B and J are the magnetic induction intensity and current density generated in the melt, and μ is the permeability of the melt. The first term of the equation leads to a forced convection and flow in the melt, i.e. stirring effect, whereas the second term is balanced by static pressure of the melt. The forced convection and flow tend to mix the high- and low-temperature melt and thus homogenize the temperature field in the melt. Meanwhile, they can also prompt the mass transportations, and thereby reduce the solute concentration difference between upper and bottom melt. Therefore, the application of a EMF can help uniform the microstructure and reduce macro-segregation of the Cu element. When the intensities of the EMFs are increased, the stirring effect is enhanced correspondingly. Therefore, the distribution of the Cu element tends to be homogenized with the increase of the EMFs. Furthermore, the enhanced stirring effect promotes fragmentation of the dendrites and subsequent crystal multiplication during solidification. Therefore, the sizes of the α-Al grains are decreased gradually with the increase of the intensities of the EMFs.

It is known that the magnitude of magnetic field decreases as a function of distance into the liquid metal, which is usually described by the so-called skin depth δ as follows:

$$\delta = \sqrt{\frac{1}{\sigma\mu\pi f}} \tag{2}$$

where σ and μ are the respective conductivity and permeability of the melt, and f is the frequency of the LFEMF. From this equation, it can be inferred that when f is high the induced Lorentz force will be concentrated near the surface of the melt. When f is too low, the distribution of magnetic flux density tends to be uniform and thus weakens the Lorentz force [7]. &&Therefore, an intermediate value exists to maintain a strong stirring effect in the melt. In this work, 30 Hz just corresponds to this value. Therefore, with this frequency the microstructure has the most refined grains and the macro-segregation of Cu element shows the best inhibition effect.

Conclusions

The effects of an EMF on the microstructure and macro-segregation of HDC cast 2024 aluminum alloy slabs were investigated. It is found that

1) when the frequency was kept at 30 Hz, the α-Al grains tend to become fine and uniform, and the distribution of the Cu element tends to be homogenized with the increase of the intensities of the EMFs.
2) when the intensity was kept at 15000At, 30 Hz is the most favorable frequency to refine the α-Al grains and to inhibit macro-segregation of Cu element.

All these results are related to the Lorentz force in the melt due to the interaction of the induced currents and the magnetic fields.

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