Microstructure character of AZ80 magnesium alloy ingots cast under electromagnetic vibration

*GUO Shi-jie, LE Qi-chi, ZHAO Zhi-hao, CUI Jian-zhong

(Key Laboratory of Electromagnetic Processing of Materials, Ministry of Education, Northeastern University, Shenyang 110004, P. R. China)

Abstract: Microstructure evolutions of an AZ80 magnesium alloy ingot with 300 mm in diameter cast with and without the electromagnetic vibration was investigated. The microstructures of the ingot cast with the conventional DC exhibited relatively fine dendritic grains at the surface area, but coarse dendritic grains at the 1/2 radius and large equiaxed dendritic grains at the center. However, under the electromagnetic vibration casting condition, the microstructures of the ingot is significantly refined, especially those at the surface and at the center.

Keywords: DC cast; electromagnetic vibration; AZ80 alloy

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Magnesium alloy has attracted many researchers in recent years, particularly due to the increasing application in the automotive and electronic industries [1, 2]. Presently, magnesium components are mainly manufactured by hot forming and die casting [3-5]. Due to the advantage of the better mechanical properties of the magnesium components produced by metal forming technologies, an increasing interest in possible bulk scale of its production can be noticeable.

Direct-chill (DC) casting was invented in the 1930s and found its practical application as a procedure to produce the billets for subsequent processing [6]. This technology had been further developed since it was applied to aluminium alloys. As to the magnesium alloys, the DC cast process was firstly applied in Germany and USA to produce magnesium alloy billet [7].

It is well known that the processing properties of the billets depend strongly on the structures of its grains. The microstructure refining of the alloys has been the subject of numerous researchers in the field of metallurgy. A number of the research subjects can be found in the literature. One of the examples is that vibration forces have been applied to induce fluid flow during solidification in order to refine the structure and improve the properties. The studies were mainly focused on the ultrasonic treatment of the melt [8-10]. It has been reported that the introduction of high intensity ultrasonic vibration into the melt has the effect on the suppression of undesirable dendritic zone and refines the equiaxed grains. However, due to the difficulty in building its apparatus with high frequency required, the ultrasonic vibration is not widely applied in the continuous DC casting.

An effective alternative for application of the vibration forces in the DC casting process was proposed by Mr. Vives, who introduced two electromagnetic fields to generate the forced vibration forces during the freezing of the alloy and successfully applied it to the continuous casting of aluminium alloys [11-14]. Satisfactory results had been obtained. Unfortunately, since the electromagnetic vibration technology has been put forward, there is little work done for the magnesium alloys. In this article, the results of the application of the electromagnetic vibration on an AZ80 magnesium alloy ingot during solidification were presented.

1 Experimental procedure

The nominal composition of the AZ80 magnesium alloy employed in the present work is given as follows: Al 7.6 wt.%, Zn 0.7 wt.%, Mn 0.13 wt.%, Be 0.0005-0.001 wt.% and Mg balance. At first, the AZ80 Mg alloy was melted out in a resistance furnace in the lab with a steel crucible and protected by CO₂+0.5% SF₆. Then, the melt was transferred to a semi-continuous casting machine at 923 K and poured into ingot mold with the diameter of 300 mm at the velocity of 80 mm/min.

The experimental apparatus for the electromagnetic vibration was shown in Fig. 1. The mold is made of stainless steel that is resistant to the magnetic field. The electromagnetic vibration is produced by the simultaneous application of a stationary magnetic field and a variable magnetic field. The stationary magnetic field is generated by the direct current (DC) in the induction coil. A ring of the pole is embedded in the upper coil.

*GUO Shi-jie

Male, born in 1979. Graduate student of Professor CUI Jian-zhang Research interest: magnesium alloy DC casting Contact E-mail: guoshijie8834@163.com Tel: +86-24-83681742 Received date: 2005-10-25; Accepted date: 2006-10-25
to increase the stationary magnetic field. The variable magnetic field is created by another induction coil below the top of the mold, which is induced by an alternating current (AC). These magnetic fields are nearly parallel to the vertical axis of the ingot. An induced current is generated inside the melt by the variable magnetic field. The interaction between the induced current and the applied magnetic fields, including stationary magnetic field and variable magnetic field, generates both vibration and forced convection inside the melt [14].

In the experiments, the pouring temperature was maintained at 650°C and the intensities for the static and the variable magnetic fields were at 10 000A-turns and 13 000A-turns, respectively. When the steady state was reached and a required length of the ingot was cast, the magnetic fields were shut off and the AZ80 ingot was cast at the conventional conditions with all the casting parameters unchanged.

The samples were taken at the surface region (10 mm from the surface), at 1/2 radius and at the center of the ingot, respectively. They were polished and etched with a solution of 50 mL ethylene glycol, 30 mL glacial acetic acid, 2 mL concentrated acid and 18 mL water. The microstructure was observed under optical microscope, Leica DMR.

2 Results and discussion

2.1 Vibrating ripples on the liquid metal surface

During the vibration casting, both convection and vibration occurred inside the melt simultaneously. Under the effect of the variable magnetic field, an induced current was generated inside the melt. By the interaction between the induced current and the variable magnetic field, a forced convection was generated. Moreover, considering the static magnetic field the melt was also subject to vibrating Lorentz force by the interaction between the induced current and the static magnetic field. The melt was forced to be vibrated during solidification and its convection generated by the variable magnetic field was partly suppressed. In this way, the surface of the liquid metal rippled during cooling and solidification of the melt, as shown in Fig. 2.

2.2 Microstructures of AZ80 ingot under electromagnetic vibrations

Figure 3 (a) to 3(c) show the structure evolution of the ingot cast in the conventional DC casting conditions. The results show that the ingot exhibits relatively fine dendritic grains at the surface area, coarse dendritic grains at the 1/2 radius and large equiaxed dendritic grains at the center of the ingot, respectively. The dendritic grains at the ingot center are very large due to the large ingot diameter and the low cooling rate at that region.

However, the ingot exhibits different microstructure evolution under the condition of the electromagnetic vibration casting. Figure 4 (a) to 4 (c) show the results. The grains at the surface are greatly refined, shown in Fig. 3 (a). Compared with the microstructures at the 1/2 radius of the ingot, the microstructure of the ingot under the electromagnetic vibration is slightly refined, as shown in Fig. 4 (b). However, at the center, Fig. 4 (c), it can be noticed that no large dendritic grains were observed at all and the average grain size was significantly reduced, which is considerably different from that in the conventional casting.

The mechanism of the grain refinement of the ingot cast under the electromagnetic vibration is probably due to both the dendritic fragment and the increase of the nucleate particles. The electromagnetic vibration is generated by simultaneous application of a stationary magnetic field and a variable magnetic field in the molten metal during solidification. Under the effect of the alternating current at certain frequency, the coils generate a variable magnetic field \( B \), in turn, produce an induced current \( J \). The time-mean electromagnetic body force \( F \) resulted from the interaction of the induced current \( J \) and the variable magnetic field \( B \), is expressed in equation (1) as follows [15]:

\[
F = J \times B = - \nabla \left( \frac{1}{2} \mu B^2 \right) + \frac{1}{\mu} \left( B \cdot \nabla \right) B
\]

Where \( B \) and \( J \) are the induced magnetic intensity and the current density generated inside the melt, \( \mu \) is the permeability of the melt. The electromagnetic body force \( F \) can be resolved into a radial component (principally irrotational) and a vertical component (principally rotational), respectively. The rotational forces are responsible for an electromagnetic stirring inside the melt. Furthermore, the combined action of the collinear fields generated vibrations in the metal pool. The principle of the electromagnetic vibration is shown in Fig. 5 [14], which is of dual
Fig. 3 Microstructures of the ingot cast in the conventional DC casting conditions

Fig. 4 Microstructures of the ingot cast in the electromagnetic vibration casting conditions

Fig. 5 Space principle of the origin of the electromagnetic vibration

The vibrating forces mainly originate at the skin area and are propagated throughout the melt, owing to the medium elasticity. Therefore, the initial solidifying grains on the mold surface have more possibilities to be detached into the undercooled melt than that in the conventional conditions. These solid particles inside the melt are subject to vibration forces and are transported by the fluid flow. As the magnetic-field intensity and the amplitude of the vibrating electromagnetic pressure is very small, heterogeneous nucleation induced by cavitation phenomenon hardly happens \(^{[11]}\). Therefore, the fragmentation of the dendrite is believed to be the mechanism of the grain refinement. In the mushy zone, due to the big difference in electrical conductivity between the liquid and solid phase \(^{[5]}\), the solidified grains are subject to larger magnitude of electromagnetic vibrating forces, compared with the melt surrounding them. The dendritic grains are forced to be vibrated more intensely by the Lorentz force. That is favorable to the remelting of the secondary dendrite arms. The broken fragmentations may act as supplying the large numbers of effective nucleation particles (i.e., effective nuclei), which may contribute to increase the nucleation rate. Moreover, the vibration of the liquid metal disturbs the melt surface, as shown in Fig. 2. In this way, the dendritic grains that are attached to the liquid surface will be dispersed into the undercooled melt. During solidification, the forced convection is partly suppressed by the imposed stationary magnetic field and the dendritic grains or the nucleation particles would deposit to the ingot centre, which may contribute to the grain refinement at the ingot centre. With the increasing of intensity of the electromagnetic vibration, the melt would subject to larger Lorentz forces and lead to the increased extent of the grain refinement accordingly. However, the increase of the magnetic fields also results in intensely liquid flow and raises the possibilities of the entrapped oxides within the melt, which is harmful to the properties of the AZ80 ingot in subsequent forming process.

3 Conclusions

The electromagnetic vibration was applied during the continuous DC casting of AZ80 magnesium alloys ingots with the diameter of 300 mm. In the conventional casting, the ingot exhibited relatively fine dendritic grains at the surface region, coarse dendritic grains at the 1/2 radius and large equiaxed dendritic grains at the center. Under the electromagnetic vibration, the microstructure of the ingot is significantly refined, especially at the surface region and the center. The mechanism of the grain refinement of the ingot cast under the electromagnetic vibration is considered to be from both the dendritic fragment and the increase of the nucleate particles inside the melt.
References


