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Research on AZ61 Magnesium Alloy by Electromagnetic Stirring and Force Field Analysis

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Abstract: The microstructure and the corrosion property of AZ61 magnesium alloy stirred by permanent magnet (PM) were investigated. Based on the principle of electromagnetic field and magnetohydrodynamics, the force field of liquid metal in a PM field was analyzed. As a result, liquid metal in a PM experiences radial and tangential forces that are cyclically variational both in direction and magnitude. This phenomenon, namely electromagnetic vibration, influences matrix microstructure, subsequently affects corrosion property of the matrix.

Key words: permanent magnet; electromagnetic stirring; magnesium alloy
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1 Introduction

Electromagnetic processing of materials is an important technology developed by combining the magnetohydrodynamics (MHD) and the casting engineering to improve the properties and performances of materials[1,2]. MHD is a subject concerning flow pattern of fluid under electromagnetic field, making use of the action between the electromagnetic field and the fluid, which is widely investigated. It is well known that the most important characteristic of magnetic field is its capacity to inject thermal and mechanical energy into materials without contact between the materials and the power source[3], which can produce driving, stirring, purifying, transmitting or shape-control etc. Electromagnetic stirring (EMS) is one of the important MHD applications[4].

Fluid flow during alloy solidification is known to be important to affect the melt distribution and solidification microstructures. EMS can control melt flow pattern to improve solidification microstructures. In recent years, the magnetic energy of magnetic materials has been increased obviously. High magnetic field can be produced by permanent magnet (PM)[5], and it is possible to control the flow of liquid metal by PM stirring.

The present study analyzes the force filed in PM field, and investigates the microstructure and corrosion property of AZ61 magnesium alloy.

2 Experimental Apparatus and Procedure

The schematic of the experimental apparatus is shown in Fig.1. Ferromagnetic material, NbFeB permanent magnet (PM), for which $(BH)_{max}$ can reach 400 kJ/m^3, was chosen and arranged as shown in Fig.2, and driven by electric motor. The height of PM is 20 mm.

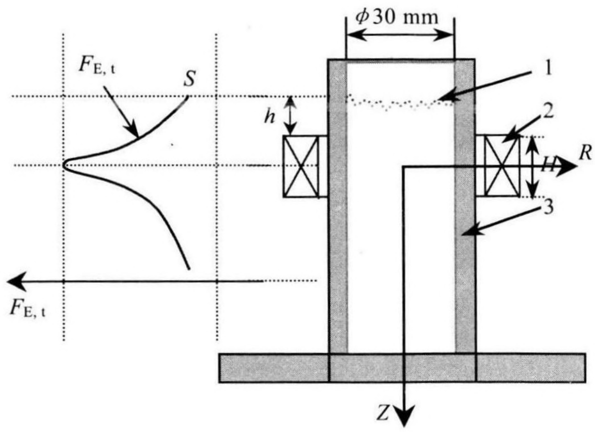

Fig.1 Schematic of permanent magnetic force driving apparatus and its principle: (1) molten metal surface position, (2) permanent magnetic force driver, and (3) stainless steel mold

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The inner container is made of stainless steel, which was preheated to 400℃. Commercial AZ61 magnesium alloy was investigated and its chemical composition is shown in Table 1. The alloy was melt, and then cast into the container at 730℃~740℃. At the same time, electric motor started, and the rotative velocity of PM was controlled at 15 r/s, 10 r/s and 0 r/s, respectively. The ingots were air cooled, with a diameter of 30 mm and height of 100 mm.

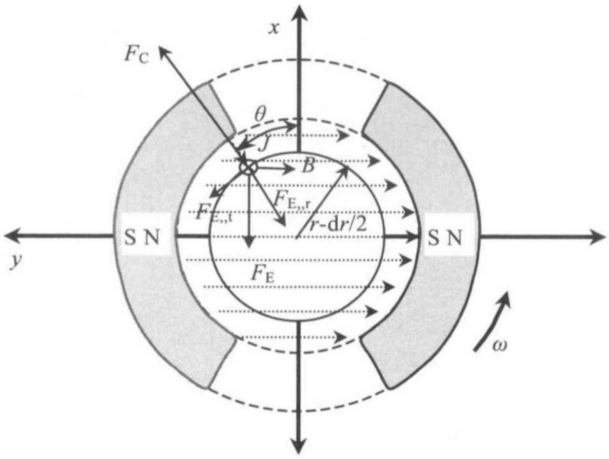

Fig.2 Calculation model of PM stirring magnetic force in molten metal

Table 1 Chemical composition of AZ61 alloy (ω/%)

Al	Zn	Fe	Si	Cu	Ni	Mg
5.7	0.98	0.008	0.009	0.009	0.003	Bal.

The solidified specimens were taken from the ingot at the position the PM applied. The microstructure was observed by optical microscope and electron probe using a Shimadzu EPMA-1600 microprobe. Potentiodynamic polarization curves were measured using an electrochemical measurement system, Potentiostat & Galvanostat Model CP6. Test solution was $Mg(OH)_2$ saturated 3.5% NaCl solution, which was exposed to the air. The scan rate was 60 mV/min.

3 Theoretical Analysis of PM Drive

Stirring of the permanent magnet changes the magnetic field at the domain of the molten metal pool. The changing magnetic field produces an induced current. As a result, the interaction of the induced current and the magnetic field will generate an electromagnetic body force (Lorentz Force) which moves the liquid metal. Under the MHD approximation, the Maxwell's equations (1) to (3) and Ohm's equation (4) are shown as follows[6]:

$$\nabla \times E = -\mu(\partial H / \partial t) \tag{1}$$

$$\nabla \times H = J \tag{2}$$

$$\nabla \cdot H = 0 \tag{3}$$

$$J = \sigma(E + \mu V \times H) \tag{4}$$

where E—the electric field H—the intensity of magnetic field, t—time, μ—the magnetic permeability ($4\pi \times 10^{-7}$ for SI units) and J— the electric current density.

After solving Eqs (1) to (4), the electric and magnetic fields can be obtained. Then the electromagnetic body force F_E can be derived by using Eqs(5).

$$F_E = \mu J \times H = J \times B \tag{5}$$

Fig.2 shows the calculating model of PM stirring magnetic force. Because the arc radian and the volume of PM body are adequate, the magnetic field in the liquid metal can approximately be regarded as steady magnetic field. From Eqs. (1) to (5), the electromagnetic body force applying to the liquid metal can be written in term of the following equation (6) due to the relative motion between PM and liquid metal, in which the direction of the electric current density J is always perpendicular to the magnetic flux density B.

$$F_E = JB\sin\beta = \sigma\omega r B^2 \sin\omega t \tag{6}$$

where σ-the electric conductivity of liquid metal;ω-the angular velocity of the PM drive; r-the radius of local melt.

Its orientation on the left side of x-axis is negative, positive on the right side of x-axis. So the melt experiences electromagnetic body force that is cyclically variational in orientation and magnitude.

3.1 Infinitesimal analysis of radial force

The liquid metal experiences the co-effect of electromagnetic and centrifugal forces produced by rotational PM. For the distance r, infinitesimal volume experiments the radial force obtained by superimposed force.

An infinitesimal volume $(r - dr/2)d\theta dr dz$ is selected as shown in Fig.2. Its mass center is located at the arc whose radius is $r - dr/2$. When the infinitesimal volume revolves as the PM revolution, it generates centrifugal force[7]

$$dF_C = \rho\left(r - \frac{dr}{2}\right)^2 \omega^2 d\theta dr dz \tag{7}$$

The radial component force of electromagnetic force the infinitesimal volume experiments is given by

$$\begin{aligned} dF_{E,r} &= F_{E,r} \cdot \left(r - \frac{dr}{2}\right) d\theta dr dz \\ &= -\frac{1}{2}\sigma\omega B^2 \left(r - \frac{dr}{2}\right)^2 \sin 2\omega t d\theta dr dz \end{aligned} \tag{8}$$

With $r >> dr$, the radial pressure intensity produced by the infinitesimal volume can be expressed as,

$$dp_r = \frac{dF_r}{r d\theta dz} = \frac{dF_c + dF_{E,r}}{r d\theta dz}$$

$$= r(\rho\omega^2 - \frac{1}{2}\sigma\omega B^2 \sin 2\omega t)\mathrm{d}r \qquad (9)$$

The radial pressure intensity of center of circle is equal to zero. Integrating (9) from center of circle to r, (9) becomes

$$p_r = \frac{1}{2}(\rho\omega^2 - \frac{1}{2}\omega B^2 \sin 2\omega t)(r^2 - r_0^2) \qquad (10)$$

Because variation of $F_{E,r}$ is cyclic in orientation and magnitude, F_r varies cyclically as shown in Fig.3a. But due to F_c is higher than $F_{E,r}$, the orientation of P_r is invariant.

3.2 Infinitesimal analysis of tangential force

In this condition, the tangential force F_t is only one, namely the tangential component force of electromagnetic force

$$F_t = F_{E,\,t} = F_E \sin\theta = \sigma\omega r B^2 \sin^2 \omega t \qquad (11)$$

F_t takes positive valve due to its rotation direction same as ω. Its direction is invariable. Its magnitude, however, varies cyclically (see Fig.3b).

Based on the above analysis, it can be considered that infinitesimal volume experiences the effect of radial and tangential forces that vary cyclically, namely electromagnetic vibration. This effect will influence the flow pattern of liquid metal and solidification process.

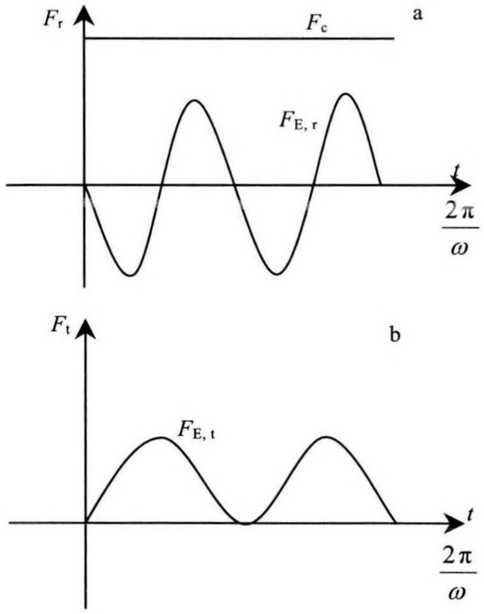

Fig.3 Forces acting on volume element of liquid metal in direction of (a) radius and (b) tangent

4 Results and Discussions

4.1 Microstructural observations

The microstructures of the magnesium alloys stirred using PM are shown in Fig.4. The as-cast AZ61 alloy is characterized by a solid solution structure α with eutectic $\alpha+\beta$ and β ($Mg_{17}Al_{12}$) phase at grain boundaries. At different ratating speeds, the grain sizes at specimen edge are smaller than those at the center, and more β-$Mg_{17}Al_{12}$ phases precipitate relatively. The PM stirring results in decreasing of grain size, increasing and uniformly distributing β phase. From quantitative metallographic analysis, there is 17.68 percent of β phase in sample a, 28.26 percent in sample b and 15.41 percent in sample c. This indicates that PM stirring favors microstructure refinement and precipitate of β phase. But the amount of β phase precipitates decreases when the speed of PM rotation increases from 10 r/s to 15 r/s. The reason is, with increasing of rotation velocity of PM, the influence of $F_{E,r}$ on F_c decreases. In other words, the strength of electromagnetic vibration is reduced.

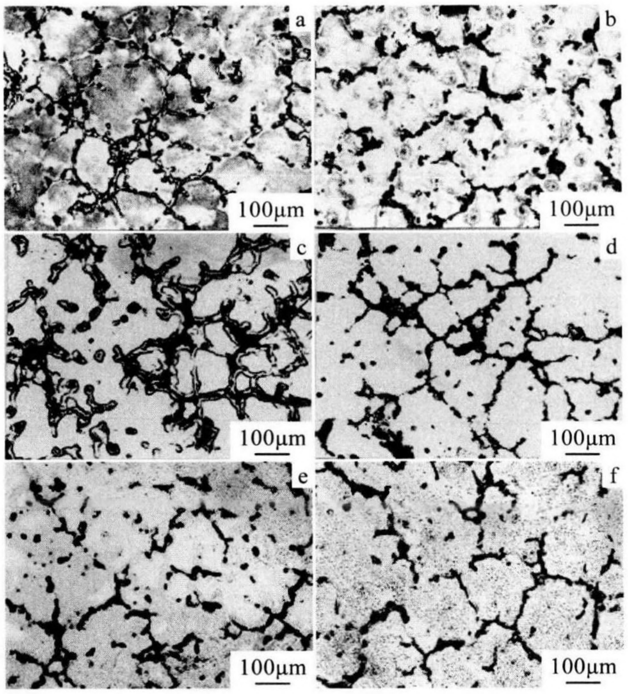

Fig.4 Optical micrographs of AZ61 magnesium alloys stirred by permanent magnetic: (a) the edge of specimen, 15 r/s; (b) the center of specimen, 15 r/s; (c) the edge of specimen, 10 r/s; (d) the center of specimen, 10 r/s; (e) the edge of specimen, 0 r/s; (f) the center of specimen, 0 r/s

4.2 Electrochemical behavior

The uniformity and more precipitation of β phase have great effects on the properties of magnesium alloys. In Mg-Al alloy, β-$Mg_{17}Al_{12}$ phase plays a dual role in corrosion according to its content: the β phase can act either as a barrier or as a galvanic cathode[8]. Fig.5 shows that the cathodic hydrogen evolution rates under these three conditions increases in the following order b

< c < a. From Fig.4, the β phase precipitate increases in the order: c < a < b. This phenomenon can be explained that a little increase of β phase will accelerate the corrosion of the matrix by a galvanic effect. Because of the existence of large amount of β phase in sample b, the β phase acts as a barrier influence, and improves the corrosion resistance of the matrix. In other words, the precipitation amount of β phase does not increase with increasing of speed of PM rotation, and the increase of the content of β phase does not imply that the matrix has a better corrosion resistance.

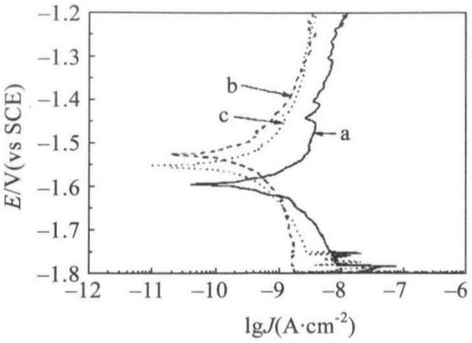

Fig.5 Polarization curves for samples (a), (b), and (c) in 3.5 mol/L NaCl, respectively

5 Conclusions

1) Be consistent with the type of PM stirring casting, the theoretical infinitesimal analyses of radial and tangential forces experienced by liquid metal have been conducted.

2) There is strong correlation between materials microstructure and PM stirring. Moreover, microstructure has an influence on matrix corrosion property.

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AZ61 镁合金电磁搅拌的研究及力场分析

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摘　要：采用永磁体搅拌的方法制备了 AZ61 镁合金，对其组织和腐蚀性能进行了研究。以电磁场和磁流体动力学原理为基础，分析了旋转永磁体磁场内液态金属的受力。结果表明：液态金属在永磁体搅拌过程中，受到大小和方向周期变化的径向力和切向力；在这一效果（即电磁振荡）的作用下，凝固组织发生变化，进而影响到基体的腐蚀性能。

关键词：永磁体；电磁搅拌；镁合金

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