



Microstructure and mechanical properties of Mg–Al–Zn alloy under a low-voltage pulsed magnetic field

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ABSTRACT

Effect of a low-voltage pulsed magnetic field on the solidified microstructure and mechanical properties of Mg–Al–Zn alloy has been investigated. When the low-voltage pulsed magnetic field is applied during solidification, the as-cast microstructure is significantly refined and α -Mg is modified from developed dendrite to fine rosette. This morphology modification is caused by the accumulation of Joule heat on the dendrite tip. The yield strength is improved with the application of the low-voltage pulsed magnetic field under normal casting and semi-continuous casting conditions. The ultimate tensile strength is decreased slightly under normal casting condition due to the occurrence of plenty of shrinkage under the low-voltage pulsed magnetic field. The shrinkages are removed and the yield strength and ultimate tensile strength are increased under semi-continuous casting condition with low-voltage pulsed magnetic field.

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1. Introduction

More and more attention is paid to magnesium alloys due to the excellent specific strength and lowest density among the commercially structural materials [1–5]. For magnesium alloys, an important drawback to limit the application on a large scale is the low strength compared with other metal materials [6–8]. Recently, pulsed physical fields have gained increasing attention to refine the as-cast structure of metal materials [9–11].

Extensive studies have been carried out to investigate the effect of electric current pulse on the solidification behavior of alloys [6, 8, 10, 12–14]. Flemings et al. [8] found that grain refinement in Sn–Pb alloy can be achieved and the solidified structures were modified from dendritic to global under pulse electric discharging. The size of the eutectic colony in Sn–Pb alloy can be reduced by a high density electric current pulse [12]. However, application of electric current pulse on the melt is very difficult and the melt may be contaminated. Thus, pulsed magnetic field is developed to refine the solidified structure without touching the melt [15–17]. The grain of 2024 aluminum alloy was refined with a strong pulsed magnetic field [15]. It was found that strong magnetic field can decrease the eutectic spacing and alternating magnetic field facilitated the transformation from columnar to equiaxed during semi-continuous casting [18–19]. However, for strong magnetic field, it is difficult to control and unsafe to utilize due to the high voltage. Recently, we found that significant grain refinement effect in AZ91D alloy and superalloy can be achieved

under a low-voltage pulsed magnetic field (LVPMF) [20–22]. This opens up a new area to refine the as-cast structure of metal materials.

However, previous works are only confined to the analysis of the effect of LVPMF on the microstructure [20–22], and few works have referred to the effect on the mechanical properties. In the present letter, the effect of the LVPMF on the microstructure and mechanical properties of Mg–Al–Zn alloy is discussed.

2. Experimental procedure

A commercial AZ 80 alloy with a composition of 8.2Al–0.54Zn–0.12Mn was used. The experimental apparatus is composed of pulsed magnetic field generator, cooling water system, heat insulation refractory, and graphite mold 60 mm in inner diameter and 140 mm in height. In the experiments, the alloy was heated to 993 K under a mixed atmosphere of SF₆ and CO₂.

LVPMF was applied immediately to the melt after pouring until the solidification is completed. The frequency of the excitation current is 5 Hz, and the voltage is 200 V. The solidification microstructures were analyzed by optical microscopy (OM). The tensile tests were carried out using an INSTRON 5582 electro-universal testing machine at room temperature (RT) with an initial strain rate of 1.0 mm/min. The specimen gauge length was $\Phi 5 \times 25$ mm. The fracture surface of the tensile specimen was observed by scanning electron microscopy (SEM).

3. Results and discussion

The as-cast macrostructure consists of coarse grains in the center and fine grains at the surface without LVPMF, as shown in

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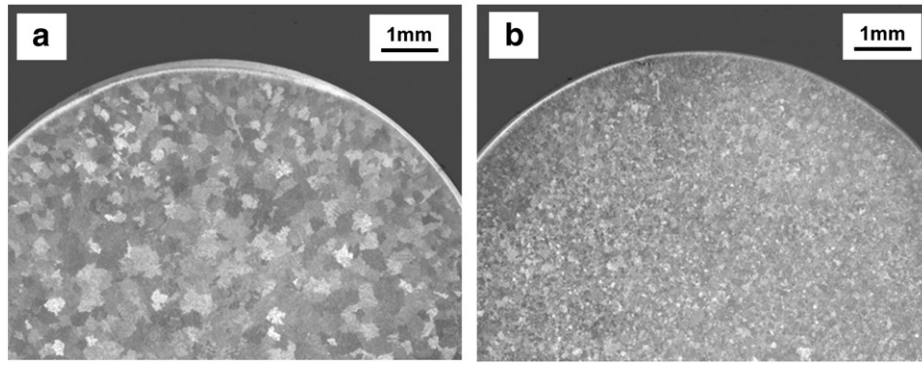


Fig. 1. As-cast macrostructures of Mg–Al–Zn alloy. (a) Coarse grain without LVPMF, (b) fine and uniform grain with LVPMF.

Fig. 1(a). When the LVPMF is applied, the grains are refined and more uniform, as shown in Fig. 1(b). From Fig. 1, it is concluded that fine and uniform structures of Mg–Al–Zn alloy can be obtained with LVPMF.

The α -Mg is coarse equiaxed dendrite with developed branches and sharp dendrite tip without LVPMF, as shown in Fig. 2(a). When the LVPMF is applied, coarse α -Mg dendrite is shortened, and the dendrite tip tends to be rounded, as shown in Fig. 2(b).

According to LMK marginally stable theory [23], the relationship between the growth rate and tip radius can be obtained as

$$V \cdot \rho^2 = \frac{2D_L d_0}{\sigma^*} \quad (1)$$

where D_L is the diffusivity, $d_0 = \Gamma / m_L C_0 (k_0 - 1)$ is the chemical capillary length, Γ the Gibbs–Thomson coefficient, m_L the slope of the liquidus, C_0 the initial composition of the alloy, k_0 the equilibrium partition coefficient, and σ^* is stability constant. From Eq. (1), the product of the growth rate and square of the dendrite tip radius is a constant during dendrite growth. The cross-sectional area of the dendrite tip is much smaller than the dendrite trunk. Under LVPMF, Joule heat will concentrate on the dendrite tip and cause local melting at the dendrite tip. Thus, the dendrite tip is rounded and the dendrite tip radius is increased. Based on Eq. (1), the melting of the local dendrite tip can decrease the growth rate of the dendrite. Therefore, α -Mg dendrites become shorter and shorter during dendrite growth under LVPMF.

As shown in Fig. 3, the values of ultimate tensile strength and elongation of Mg–Al–Zn alloy without the LVPMF are 169 ± 3

MPa and $7.7 \pm 4\%$, respectively. The ultimate tensile strength and elongation of Mg–Al–Zn alloy under LVPMF are 149 ± 5 MPa and $5.1 \pm 5\%$, respectively. Compared with the mechanical properties of the alloy without LVPMF, the ultimate tensile strength and elongation are both decreased when the LVPMF is applied. The yield strength is increased from 80 MPa to 95 MPa with the LVPMF.

The ultimate tensile strength is decreased slightly when LVPMF is applied, which is not expected from the Hall–Petch relationship. To make out the factors which impair the ultimate tensile strength under LVPMF, the fracture surface of the tensile specimen was examined by SEM. Without LVPMF, a number of cleavage planes and steps are present in the fracture, as shown in Fig. 4(a) and (b). This fracture characteristic indicates that the as-cast Mg–Al–Zn alloy is brittle rupture.

Fig. 4(c) and (d) is the fracture with the application of LVPMF. Neither typical cleavage plan nor dimple is observed. Instead, plenty of shrinkage porosities occur in the fracture. The grain is surrounded by some shrinkage porosities, which make the profile of the grain very clear. Apparently, the fracture characteristics in Fig. 4(c) and (d) denote that the specimens are fractured when no enough deformation is achieved during tensile tests. This type of fracture is resulted from the occurrence of a great quantity of shrinkage porosities under LVPMF. The fracture always occurs at the location of shrinkage porosity, which impairs the ultimate tensile strength.

In order to remove the shrinkage porosity to improve the mechanical properties under LVPMF, semi-continuous casting experiments with LVPMF were carried out. The yield strength is increased to 109 ± 3 MPa, and the ultimate tensile strength is increased to 182 ± 5 MPa, as shown in Fig. 3. Furthermore, the shrinkage

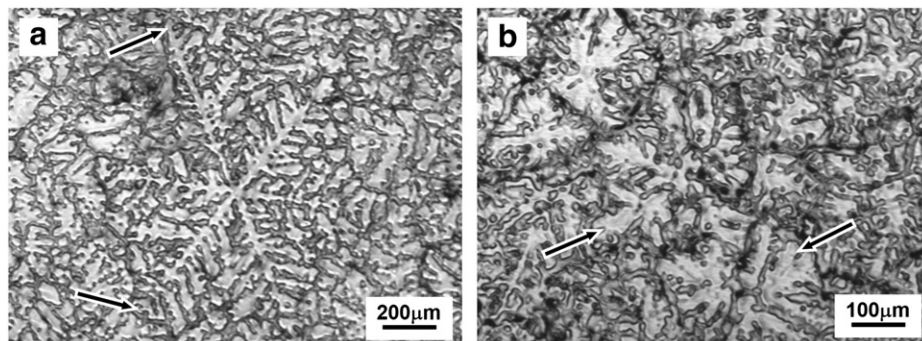


Fig. 2. As-cast microstructures of Mg–Al–Zn alloy. (a) Developed α -Mg dendrite with thin dendrite tip (denoted by arrows) without the application of LVPMF, (b) rosette α -Mg dendrite with rounded dendrite tip (denoted by arrows) with the application of LVPMF.

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