

Microstructure refinement of AZ31 alloy solidified with pulsed magnetic field

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Abstract: The effects of a pulsed magnetic field on the solidified microstructure of an AZ31 magnesium alloy were investigated. The experimental results show that the remarkable microstructural refinement is achieved when the pulsed magnetic field is applied to the solidification of the AZ31 alloy. The average grain size of the as-cast microstructure of the AZ31 alloy is refined to 107 μm . By quenching the AZ31 alloy, the different primary α -Mg microstructures are preserved during the course of solidification. The microstructure evolution reveals that the primary α -Mg generates and grows in globular shape with pulsed magnetic field, contrast with the dendritic shape without pulsed magnetic field. The pulsed magnetic field causes melt convection during solidification, which makes the temperature of the whole melt homogenized, and produces an undercooling zone in front of the liquid/solid interface, which makes the nucleation rate increased and big dendrites prohibited. In addition, the Joule heat effect induced in the melt also strengthens the grain refinement effect and spheroidization of dendrite arms.

Key words: AZ31 magnesium alloy; grain refinement; pulsed magnetic field; solidified microstructure

1 Introduction

Magnesium alloys are potential candidates for replacing steel and other high density materials due to their low density, high specific strength and excellent machinability. Thus, magnesium related research has surged in recent years[1]. For the alloys generally exhibit limited ductility and strength at ambient temperature, new efforts on grain refinement are devoted to minimize these disadvantages. The method of use of refiners has some problems that the refiner materials are often expensive and the recycling of used materials becomes difficult[2]. The rapid cooling method also has some serious drawbacks that the size or shape of the sample is very restricted due to the necessity of achieving an extremely high cooling rate. The ultrasonic vibration technique also has serious problems such as the dissolution of the transmitter when it is applied at high temperatures and the attenuation of the vibrations in regions remote from the vibrator[3]. Therefore, an alternative method for the development of fine grain magnesium alloys with high strength is desired.

Applying electromagnetic vibration to the

solidification of metals is a new method developed in recent years[4–6]. Pulsed magnetic field (PMF) processing as a new electromagnetic technology has become one of the most promising new techniques to refine solidified structures. BAN et al[7] applied a pulsed magnetic field to 2124 Al alloy solidification and found a remarkable change occurring in the solidified structures. GAO et al[8] studied the structural transformation in pure Al under external PMF. The experiments showed that totally equiaxed grains were produced for pure Al. WANG et al[9–10] researched the grain refinement effect of AZ91 alloy and Mg-Gd-Y-Zr alloy under external PMF. The experimental results showed that the remarkable microstructural refinement was achieved and the grain sizes were refined to 104 μm and 37 μm , respectively, by PMF treatment.

As mentioned above, the PMF process has been studied with different alloy systems, but there has been a lack of investigation on grain refinement mechanism. In this work, the structure refinement of AZ31 alloy by the PMF process is studied and the structure evolution is observed by quenching treatment, furthermore, the refinement mechanism is analyzed and the mechanical properties are investigated.

2 Experimental

The commercial AZ31 alloy was selected as the raw material in this study. Its chemical composition (mass fraction, %) is as follows: Al 3.0, Zn 1.0, Mn 0.2 and Mg Balance.

The experiment was carried out on a self-designed PMF setup and the details of the experimental apparatus are presented in Ref.[11].

The AZ31 alloy was first remelted at 750 °C for 10 min in an electrical resistance furnace using a mild steel crucible, and then the melt for observing the grain refinement effect was poured into a preheated (to 400 °C) graphite mould with a diameter of 50 mm, height of 80 mm and a wall-thickness of 3 mm. The pulsed magnetic field was imposed to the melt until it was completely solidified. Different pulse frequency and fixed discharge voltage of 200 V were used in the experiments. The melt used for the microstructure evolution was poured into a preheated (to 400 °C) graphite mould, in order to achieve the better heat dissipation capacity, with the minor diameter of the mould of 20 mm, height of 50 mm and a wall-thickness of 2 mm. The eutectic temperature (β -Mg₁₇Al₁₂ phase) and the liquidus temperature of the AZ31 alloy are 437 °C and 648.0 °C respectively[12]. Different quenching temperatures of AZ31 alloy were used in the experiments, i.e., 610 °C, 590 °C, 570 °C and 550 °C. The 5 Hz, 200 V PMF was imposed to the melt until it was reached the quenching temperature. Then, the sample with the mould was taken out immediately for water quenching. Both melting and solidification were conducted under a protective atmosphere of 0.5%SF₆+99.5%CO₂ to prevent oxidation.

The specimens for microstructure observation were made from the transverse section of the 1/2 height of the castings. After grinding and polishing, the specimens were etched with a solution of 100 mL ethanol, 5 g picric acid, 5 mL acetic acid and 10 mL water. The average grain size was measured by the linear intercept method.

The compressive specimens with a gauge length of 15 mm and a gauge diameter of 10 mm were made from longitudinal sections of the sample. Compression tests were conducted with an initial strain rate of 10⁻³ s⁻¹ at room temperature.

3 Results

The macrostructures of AZ31 alloy solidified without or with the pulsed magnetic field are shown in Fig.1. Without PMF treatment, the constitution of the morphology in Fig.1(a) is equiaxed grains in the centre and thin columnar grains at the edge. With the 5 Hz, 200 V PMF treatment, totally refined equiaxed grains are

achieved as shown in Fig.1(b). Therefore, the solidification structure of AZ31 alloy can evidently be refined under the effect of a pulsed magnetic field. Correspondingly, the grain size is uniform on the whole surface under PMF casting, which is beneficial to the uniformity of mechanical performance on the whole casting. Namely, the solidification structure of AZ31 alloy could be evidently refined under the effect of PMF.

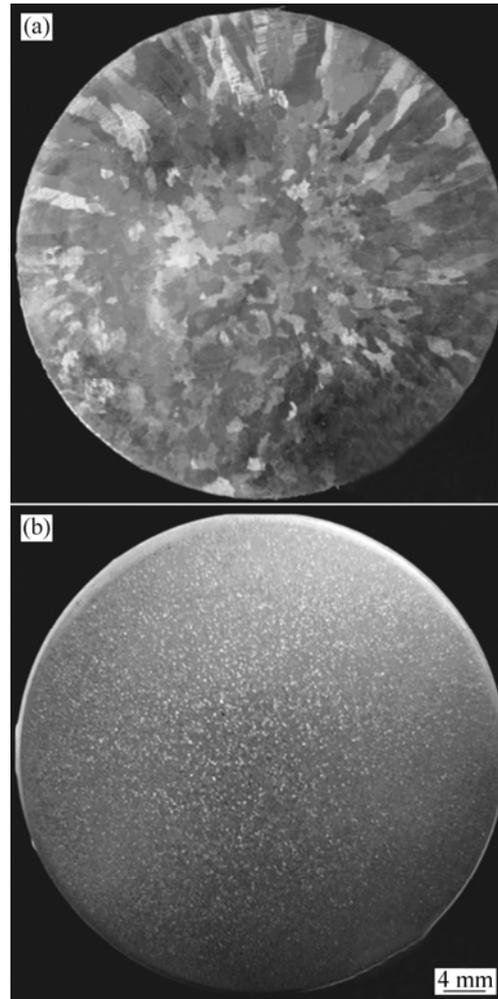


Fig.1 Macrostructures of AZ31 alloy: (a) Without PMF treatment; (b) With 5 Hz, 200 V PMF treatment

Adjusting the pulse frequency can change the effect of grain refinement. Fig.2 presents the solidification structures of AZ31 alloy after the 200 V PMF treatment with different pulse frequencies. The optimized grain refinement effect can be achieved at 5 Hz pulse frequency, as shown in Fig.2(b). The lower or the higher pulse frequency, e.g. 2.5 Hz, 10 Hz and 20 Hz in Figs.2(a, c, d), are not the desirable technological parameters. However, it can also achieve remarkable microstructural refinement effect in contrast to that without the PMF treatment. Fig.3 shows that the average grain size of AZ31 alloy is 2 400, 227, 107, 216 and 274 μm ,

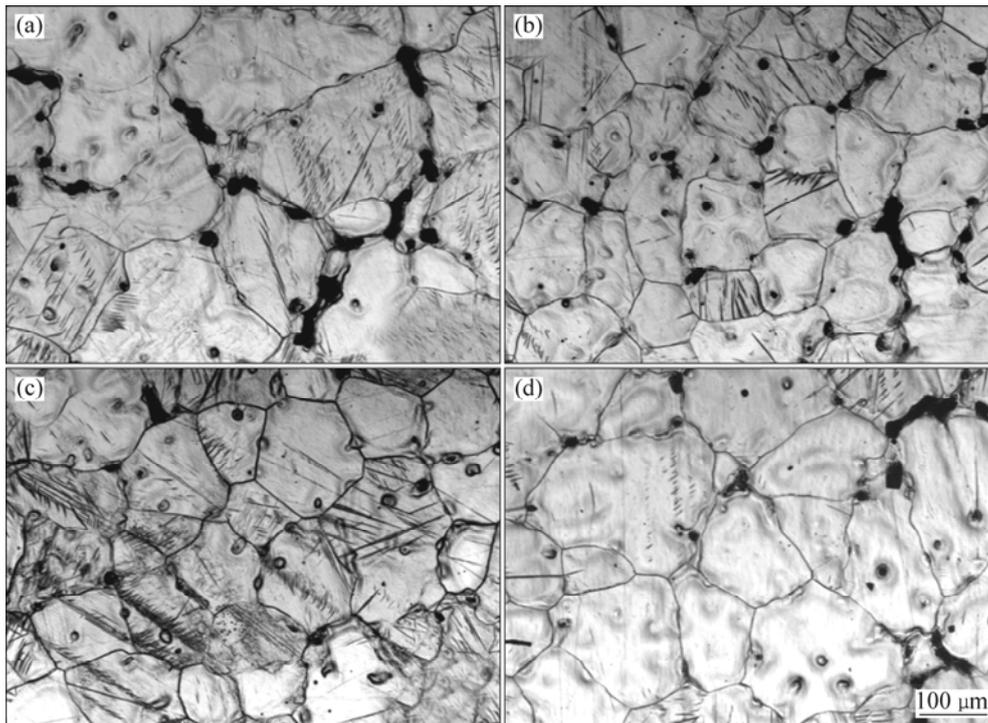


Fig.2 Microstructures of AZ31 alloy solidified with different pulse frequencies of PMF: (a) 2.5 Hz; (b) 5 Hz; (c) 10 Hz; (d) 20 Hz

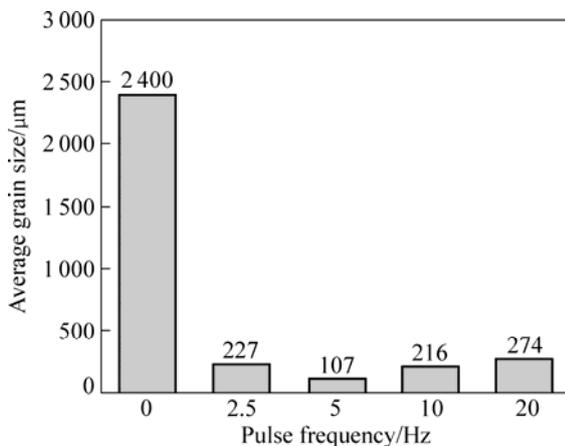


Fig.3 Average grain size of AZ31 alloy solidified with different pulse frequencies of PMF

corresponding to the conditions of without and with 2.5, 5, 10 and 20 Hz PMF treatment, respectively.

In order to reveal the nucleation and growth of the grains of AZ31 alloy with and without PMF treatment, the primary α -Mg microstructures are preserved by quenching the AZ31 alloy during the course of solidification. Fig.4 and Fig.5 show the microstructures of AZ31 alloy quenched during the course of solidification with 5 Hz, 200 V PMF and without PMF. With PMF treatment, the primary α -Mg presents near globular shape at initial stage in Fig.4(a), more near globular shape primary α -Mg in the following stages in

Figs.4(b, c), and with the quenching temperature decreasing to 550 °C, the primary α -Mg presents fully globular shape in Fig.4(d). In contrast, the primary α -Mg presents dendrite morphology in Fig.5(a). This means that the initial small number of grains are in dendrite growth. During solidification, the dendrites continue to grow, as shown in Figs.5(b, c); ultimately, the whole microstructures of the casting are coarse dendrites, as shown in Fig.5(d).

Compressive nominal stress–nominal strain curves of AZ31 alloy produced without and with 5 Hz, 200 V PMF are shown in Fig.6. It is evident that the PMF treatment has a strong influence on the mechanical properties of AZ31 alloy. Without the PMF treatment, the ultimate compressive strength and fracture strain of AZ31 alloy are 157 MPa and 14.1%. With the 5 Hz, 200 V PMF treatment, the mechanical properties of AZ31 alloy are significantly improved. The ultimate compressive strength and fracture strain increase to 337 MPa and 31.6%, which is mainly related to the formation of fine, uniform, non-dendritic grains.

4 Discussion

When PMF is applied to the melt, an electromagnetic force is generated by the coupling of the induction current and the magnetic field in the melt. As a result, the energy density of the magnetic field represents pressure acting orthogonally on the magnetic field and

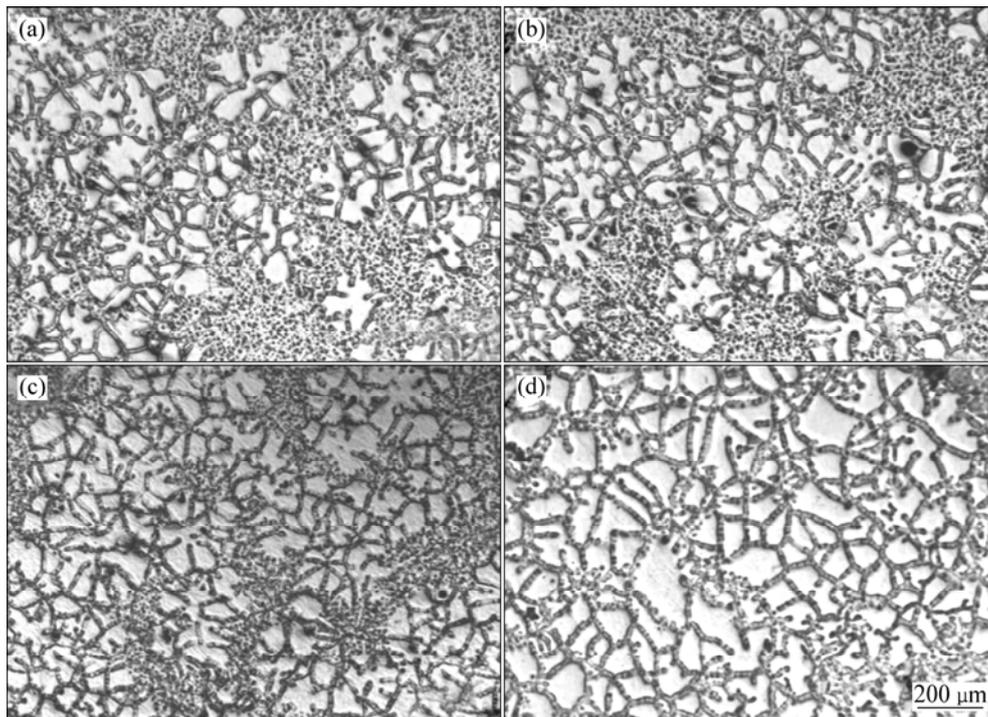


Fig.4 Microstructures of AZ31 alloy quenched during solidification with 5Hz, 200 V PMF at different quenching temperatures: (a) 610 °C; (b) 590 °C; (c) 570 °C; (d) 550 °C

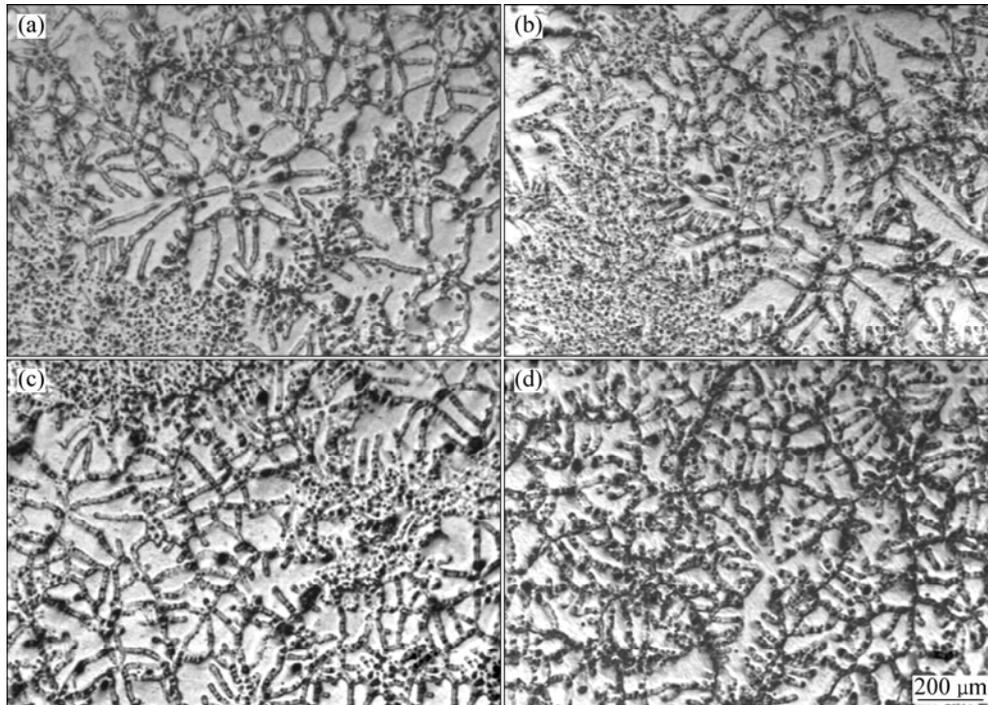


Fig.5 Microstructures of AZ31 alloy quenched during solidification without PMF at different quenching temperatures: (a) 610 °C; (b) 590 °C; (c) 570 °C; (d) 550 °C

towards the centre of the melt[8], so the resulting pressure difference imposed on the melt causes vigorous agitation as soon as the action of the electromagnetic force is felt.

By quenching treatment, the primary α -Mg phase is clearly retained. From the morphologies of primary α -Mg during different solidification stages as shown in Fig.4 and Fig.5, we can see that PMF treatment has

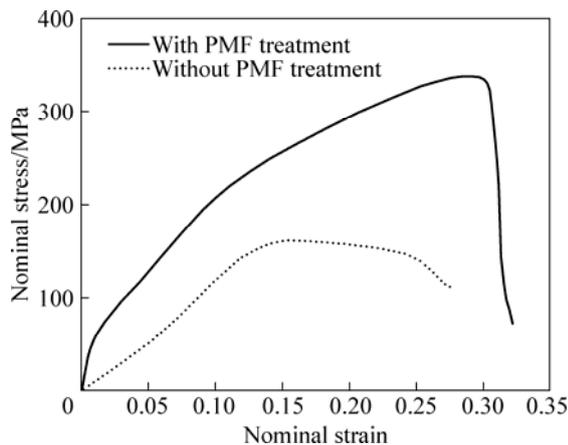


Fig.6 Compressive nominal stress–nominal strain curves of AZ31 alloy solidified without and with PMF

significant effect below the liquidus of AZ31 alloy (See Fig.4(a)), and a strong effect on the following stage of solidification (See Figs.4(b, c, d)). However, the primary α -Mg presents dendrite morphology in Fig.5 in the whole stage of solidification. So, we can safely draw the conclusion that the refinement by PMF treatment is related to the nucleation and growth in AZ31 alloy.

Without the deliberate stirring caused by PMF, the primary dendrites grow up and the secondary dendritic arms develop unrestrainedly, so the solid advances in the form of dendrites to form the coarse grains. However, with the PMF treatment, the electromagnetic force towards the centre of the melt causes the fluid to flow with a high velocity, which produces a high shear stress to the primary and secondary dendrites. The secondary dendritic arms may detach from the primary dendrites and be injected into the melt, and the melt rushes to the top of the primary dendrites at the solid/liquid interface, so that the primary dendrites can be fractured. Therefore, the fractured tips of the columnar dendrites or the broken-off dendrite branches promote the formation of an equiaxed structure with fine grains, and the broken pieces, which are transported into the bulk liquid, act as nuclei.

In addition, there is an extra undercooling caused by the pulsed magnetic field[9]. This undercooling will increase the nucleation rate and make grain refined. Simultaneously, the convection reduces the slope of temperature gradient across the bulk liquid, thus encourages further nucleation and refinement of the primary α -Mg particles within the bulk liquid.

It should be noted that Joule heat induced by the induction current also influences the solidification process. For the skin effect, the Joule heat effect flattens the temperature gradient from the surface to the centre, which reduces the temperature gradient ahead of the solidification front and depresses the growth of

dendrite[13–14]. Meanwhile, as the electrical resistivity of the liquid is about twice as high as that of the solid for AZ31 alloy[15], the electric current difference between the solid and liquid reduces the Lorentz force difference between the two phases, generating an uncoupled movement between them, which favours the refinement.

In addition, the mechanical properties shown in Fig.6 provide a clue to the structure evolution of the AZ31 alloy with PMF treatment. With a 5 Hz, 200 V PMF treatment from pouring temperature 750 °C to room temperature, the AZ31 alloy shows superior mechanical properties to those without PMF treatment. These changes are consistent with the change from coarse dendrites to fine uniform non-dendrite grains. As a result, the mechanical properties of the AZ31 alloy are improved with PMF treatment.

5 Conclusions

1) The large dendrites in solidification structure of AZ31 alloy are changed to near globular structure under action of the pulsed magnetic field. With the optimal pulsed magnetic parameter, the finest as-cast microstructure of the AZ31 alloy is obtained with an average grain size of 157 μm .

2) The grain refinement caused by the pulsed magnetic field is regarded as the electromagnetic vibrating forces and Joule heat effect in the melt. The convection by the electromagnetic vibrating force results in the initiate dendrites fragmentation, and reduces the temperature gradient in front of the interface, which brings about the detachment and spheroidization of dendrite arms together with the Joule heat effect.

3) Superior mechanical properties, ultimate compressive strength of 337 MPa and fracture strain of 31.6% are achieved in the AZ31 alloy produced with a 5 Hz, 200 V PMF treatment.

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