Original Article

Strain induced dynamic recrystallization nucleation of ZA21 magnesium alloy during compression process at low and medium temperatures

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Abstract

Dynamic recrystallization (DRX) behavior of ZA21 magnesium alloy during compression process was investigated through uniaxial compression tests at 110 °C and 210 °C with an initial strain rate of 0.01 s⁻¹. Based on OM and detailed TEM characterization, preferential nucleation position of DRX grains at different compression temperatures were identified. The DRX grains preferential nucleation position under the conditions of low and medium temperatures are in grains and at grain boundaries, respectively. This is mainly caused by the inconsistency between intragranular strength and grain boundary strength. Grain boundary strength is higher than the intragranular strength at low temperature. But the intragranular strength is higher than the grain boundary strength at medium temperature. This leads to a difference in the ability to resist deformation between them, so that the site of the DRX priority nucleation is different.

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1. Introduction

Magnesium alloys are the lightest (ρ ~ 1.74 g/cm³) materials of all structural metals, significantly lighter than steel alloys (ρ ~ 7.9 g/cm³), titanium alloys (ρ ~ 4.51 g/cm³), and aluminum alloys (ρ ~ 2.7 g/cm³) [1–6]. Considering the shortage of traditional metal resources and serious energy consumption, magnesium and its alloys are the most potential structural materials in the world to replace steel and aluminum alloy products [7–9]. Therefore, magnesium alloys are being considered for structural application in aerospace, automobile, and electronic industries [2,10,11]. However, because of the poor room temperature strength and plasticity of magnesium alloys due to their hexagonal closed-packed (HCP) crystal structure, especially for the as-cast magnesium alloys, the application of magnesium alloys is limited [12–15].

Grain refinement is a method to improve strength and ductility at the same time. In the process of plastic deformation, dynamic recrystallized (DRX) grains will be produced and the grain structure of magnesium alloy will be refined [16–18]. Therefore, plastic deformation is one of the main methods to refine grains and improve mechanical properties of mag-
nesium alloys [19–21]. There have been many reports on the mechanism of microstructure evolution during the plastic deformation process in magnesium alloys especially on the mechanism of DRX. The effect of twinning on DRX behavior of Mg-Gd-Y alloy during hot compression was investigated by Lu, and the results showed that the twin boundary at the junction of twins can provide new DRX sites, while the single twin will grow rapidly, which is not conducive to the nucleation of DRX [22]. Another study showed that Mg2Ca and Al2Ca particles in AZ31-0.5Ca acted as a barrier to dislocation motion resulting in the nucleation of DRX in this area during warm rolling process [23]. Although there are many researches on the DRX behavior during plastic deformation of magnesium alloy, the deformation temperature is generally high. The high deformation temperature causes the DRX grains to be coarsened and has a bad effect on the improvement of the mechanical properties. On the other hand, there has been no study on the relationship between the position of DRX preferential nucleation and the original grain boundary. Therefore, the nucleation laws of DRX at medium and low temperature conditions are worth to be studied. In this study, the relationship between DRX nucleation sites and the original grain boundaries was investigated by compression at 110 and 210 °C. And the causes of this phenomenon were expounded.

2. Materials and methods

The material used in this work is ZA21 Mg alloy ingot with a composition of Mg –2.0 wt.% Zn –1.0 wt.% Al. The alloy was synthesized with pure Mg ingot (99.9 wt.%), pure Al ingot (99.9% wt.%), and pure Zn ingot (99.9% wt.%). Low frequency electromagnetic casting method was adopted to obtain the ZA21alloy. Firstly, pure Mg, ingot was put into the resistance melting furnace and heated to melt. Next, add Al ingot and Zn ingot into the melt. Then use MnCl2 to remove Fe from the melt when the melt temperature was about 735 °C. And when the melt was cooled to 690–700 °C, electromagnetic semi-continuous casting was carried out under the protection with a mixed gas atmosphere of CO2 and SF6 (CO2 : SF6 = 99:1, vol%). The obtained ingot was homogenized at 400 °C for 18 h. And then the compression samples were cut from the homogenized ingot. The size of compression samples is Φ10 × 15 mm. Uniaxial compression tests were performed with a strain rate of 0.01 s−1 at 110 and 210 °C using a gleeble-3500 thermal simulation machine. The strains are 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0 or until crack occurs. All compressed samples were water-quenched immediately after compression to preserve the deformed microstructure. True stress-strain curves were recorded automatically from the compression tests. After compression, the surface morphology of the samples was recorded by taking photos. The microstructures of the compressed specimens were investigated by optical microscope (OM) and transmission electron microscope (TEM). For the sake of comparison, the volume fractions of twins and DRX grains were calculated by Image Pro Plus 6.0 (IPP 6.0) software. The areas of twins and DRX grains were measured, firstly. And then the total area was measured. Finally, the area fractions of twins and DRX grains were calculated respectively. Here, the area fraction is equal to the volume fraction.

3. Results and discussions

True stress-strain curves and surface morphology of compressed samples are shown in Fig. 1. The surface of the samples is smooth and crack-free after being compressed at 110 °C when the strain is 0.05–0.4. However, there is an obvious crack in the sample after compression with the strain of 0.6. The crack and compression direction are at an angle of 45°. This is an obvious characteristic of shear fracture. When compression is carried out at 210 °C, no cracks appear in all samples even the maximum true strain reaches 1.0. By comparing the stress-strain curves at these two temperatures, it can be found that the compressive stress-strain curve at 110 °C are relatively flat and the compression curves at 210 °C have a significant downward trend after reaching the maximum value.

The OM microstructures of the samples after compression with different strains at 110 °C are presented in Fig. 2. Horizontal direction is the compression direction (CD). When the compression strain is 0.05, many lamellar twins appear in the original grains. Furthermore, the angle between twins and compression direction is about 45°. When the compression strain is 0.1, the number of twins increased, and the phenomenon of twin-twin intersections appeared. When the compressive strain is increased to 0.2, the number of twin-twin intersections also increases, and the twins are thicken and coalesced to form large twins. As the compression strain continues to increase to 0.4, the number of twin-twin intersections is increased further, and the DRX nucleation begins to occur at the location of twin-twin intersections.

Fig. 3 shows the OM microstructures of the compressed samples with different strains at 210 °C. At the compression strain as low as 0.05, twins and twin–twin intersections appear in the original grains. The shape of the twin is similar to that of the same strain at 110 °C, and both of them are like thin plate. When the compressive strain is less than or equal to 0.2, the twins increase with the increase of strain. When the compressive strain is 0.4, DRX grains begin to appear near the parent grain boundaries, but the number of twins does not increase. As the strain continues to increase, the DRX grains continue to increase, and when the strain is 1.0, the continuous dynamic recrystallization (CDRX) is obvious. Under the condition of 110 °C compression, the DRX grains nucleate preferentially in the original grain, and gradually expand outward with the increase of strain. On the contrary, the DRX grains nucleate preferentially near the parent grain boundaries, and gradually expand inward with the increase of strain when the compression temperature is 210 °C. DRX does not occur at 110 or 210 °C when the compression strain is low. This shows that the occurrence of DRX is induced by strain.

The volume fractions of twins and DRX are shown in Fig. 4. The results show that with the strain increases the volume fraction of twins increases at 110 °C. However, the volume fraction of twins is not varying monotonically when compressed at 210 °C. When the strain is 0.2, the twinning volume fraction reaches the maximum, then decreases with the increase of strain, and when the strain is 1.0, the twinning volume fraction is 0 after compression at 210 °C. When it comes to DRX, the volume fraction of DRX increases monotonously with
the increase of strain during compression process whether at 110 °C and 210 °C. When the strain is constant, the volume fraction of DRX is larger at high compression temperature than low temperature.

In order to deeply understand the microstructure evolution mechanism of the Mg alloy, detailed TEM characterizations are carried out and shown in Figs. 5 and 6. Fig. 5 shows the TEM microstructures of the compressed samples with different strains at 110 °C. From Fig. 5(a), it can be seen that many dislocations occur during compression with strain of 0.05. After compression with a strain of 0.2, twin and high-density dislocation in the twin can be observed as shown in Fig. 5(b). Fig. 5(c) shows an obvious DRX grain nucleation inside the twin. It is further proved that the DRX grains are first formed in twins when deformed at low temperature.

The TEM microstructures of the compressed samples with different strains at 210 °C are shown in Fig. 6. When the strain is 0.05, there are many dislocations in the alloy. From Fig. 6(b), the low-density dislocation region and the high-density dislocation region are located on both sides of the original grain boundary. As the strain increases to 0.1, the dislocation density increases as shown in Fig. 6(c) and (d). When the strain is 0.2, obvious twinning and twin-twin intersections can be observed as shown in Fig. 6(e) and (f). Fig. 6(g) shows that there are many screw dislocations after compression at 210 °C with the strain of 0.4. Meanwhile, DRX grains nucleate near the original grain boundary with dislocation accumulation. After compression with the strain of 0.6, there are several DRX grains with a size of about 0.2 μm. With the increase of strain, the DRX grains increase. With the increase of strain to 0.8, the DRX grains also increased obviously as shown in Fig. 6(j) and (k). The DRX grains are no longer scattered distribution, but become a state of continuous distribution. When the compression strain is 1.0, the continuous distribution of DRX grains can still be
observed from Fig. 6(f). It can be seen from Fig. 6 that when compression is carried out at 210 °C, the DRX grains initially nucleate at the grain boundary where the dislocation accumulation, and gradually propagate to the inside of the initial grains with the increase of strain.

4. Discussions

The two DRX mechanisms discussed above are schematically summarized in Fig. 7. Fig. 7(a) shows the mechanism of DRX at low temperature compression process (110 °C). Step 1 starts

Fig. 3 – Microstructures of the compressed samples with different strains at 210 °C: (a) ε = 0.05, (b) ε = 0.1, (c) ε = 0.2, (d) ε = 0.4, (e) ε = 0.6, (f) ε = 0.8, (g) ε = 1.0.
with the formation of twins, in which some dislocations also appear. With increasing strains, the twin-twin intersections begin to appear. DRX grains gradually nucleate in the twins and twin-twin intersections. With the further increase of strain, the DRX grain increases gradually and begins to expand outward from the inside of the original grain. Fig. 7(b) shows the mechanism of DRX at medium temperature (210°C). In the early stage of deformation, twins are formed in the original grains just as in the low temperature compression. However, unlike the DRX mechanism at low temperature, the DRX grains begin to nucleate around the original grain boundaries with the increase of strain. As the strain further increases, the DRX grain gradually expands to the interior of the original grain. With the further increase of strain, the recrystallized grains gradually expand to the inner of original grains. Eventually, DRX grains with continuous distribution are formed within the original grains. That is, the DRX grains of ZA21 magnesium alloy at low temperature is initially nucleated inside the original grain and then expand outward at low temperature. On the contrary, at medium temperature, the DRX grains of ZA21 alloy is initially nucleated around the original grain boundaries and expand to the inside of the original grains.

This is mainly due to the inconsistency between the intragranular strength and the grain boundary strength. It is well known that grain refinement can improve the room temperature strength of magnesium alloys because the grain boundary strength is higher than the intragranular strength at room temperature. At 110°C, the grain boundary strength is higher than intragranular strength, so the preferential deformation inside the grain produces new distortion. Higher energy from new distortion can easily nucleate new grains. With the increase of temperature, the intragranular strength increases

Fig. 4 – The twin (a) and DRX (b) volume fraction of compressed samples with different strains at different temperatures.

Fig. 5 – TEM microstructures of the compressed samples with different strain at 110°C: (a) ε = 0.05, (b) ε = 0.2, (c) ε = 0.4.
and the grain boundary strength decreases. The decrease of grain boundary strength causes the grain boundary to deform preferentially than in the crystal. Therefore, the DRX grains nucleate preferentially at grain boundaries during compression at 210 °C. As the compression strain increases, the deformation is gradually extended from the grain boundary to the grain interior.

5. Conclusions

The DRX behavior of ZA21 alloy during compression process at low and medium temperatures was studied in this work. Based on OM and detailed TEM characterization, the DRX mechanisms were identified. The following conclusions can be obtained.
(1) The occurrence of DRX is induced by strain during compression process at 110 °C and 210 °C.
(2) The preferential nucleation positions of DRX grains are within grains and at grain boundaries during compression deformation at 110 °C and 210 °C, respectively.
(3) The main reason for the different nucleation positions of DRX grains is the inconsistency between intragranular strength and grain boundary strength.

Conflicts of interest

The authors declare no conflicts of interest.

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