The Influence of Developed Texture on the Mechanical Anisotropy and Deformation Modes of an As-Extruded Mg-Zn-Zr Alloy

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The texture evolution of an as-extruded ZK60 Mg alloy with different tensile strains has been determined by X-ray diffraction technique. As strain increases, (0002) basal plane of most grains gradually inclines to the tensile direction, which is more pronounced for TD sample. This firmly suggests that the mechanical anisotropy and the difference of deformation modes between ED and TD samples are not only caused by initial basal texture, but also by the developed texture during the tensile test.

Keywords: ZK60 magnesium alloy, texture evolution, mechanical anisotropy

1. Introduction

Recently, it has been reported that the mechanical properties of wrought Mg alloys are superior to those of cast Mg alloys, because the former has a finer grain structure. Generally, wrought Mg alloys having a grain size less than 10 μm, can be easily obtained just through primary processing such as hot rolling or extrusion. However, these procedures generally give rise to a strong basal texture. The critical resolved shear stress (CRSS) for various slip systems in pure Mg has been reported. It indicated that during the deformation at room temperature, the CRSS for prismatic slip was about 100 times higher than that for basal slip. Therefore, the mechanical properties of wrought Mg alloys are greatly influenced by the basal texture. However, previous researches mainly focused on the influence of initial basal texture produced by hot rolling or extrusion on the mechanical properties. In this paper, we show that during the tensile tests, plastic deformation can also cause the reorientation of basal planes. Therefore, it is essential to study the influence of lattice reorientation during tensile tests on the mechanical anisotropy and deformation modes of wrought Mg alloys. Through determining (0002) pole figures of an as-extruded ZK60 Mg alloy with different tensile strains of 0%, 5%, 10% and 15%, two questions: 1) how the initial texture changes during the tensile tests and 2) how the changed texture influences the mechanical anisotropy and deformation modes will be answered in this paper.

2. Experimental Procedures

The material used in the present study was an as-extruded ZK60 magnesium alloy (Zn 5.68, Zr 0.78 and balance Mg, by mass%). The alloy was made by melting high-purity magnesium in an electric resistance furnace, and then 6.3 mass% Zn and 2.0 mass% Zr were added under the protection of SF6 and CO2 mixed gas. After stirring the molten alloy and keeping for 30–40 minutes at 710°C to homogenize it, the molten alloy was cast into cylindrical ingot with 110 mm in diameter, and 500 mm in height. Then the as-cast ingot was extruded into thick plates with cross section of 8 mm × 100 mm at 390°C. The extrusion ratio was 10 : 1.

To accurately determine the texture evolution, the tensile samples with a gauge length of 20 mm and a 4 mm × 20 mm rectangular cross-section were machined. The shape and size of tensile sample are shown in Fig. 1. The axial directions of the tensile samples were parallel to the extrusion direction (ED samples) and parallel to the transverse direction (TD samples), respectively. Tensile tests were conducted on the MTS (858.01M) testing machine with the constant strain rate of 1 × 10⁻³ s⁻¹ at room temperature. Some of the tensile tests were interrupted and reloaded to determine the texture evolution. Pole figures for ED and TD tensile samples with the strains of 0%, 5%, 10% and 15% has been determined by D/Max 2400 X-ray diffractometer (XRD). Generally, pole density decreases remarkably with increasing angle from the center of a pole figure (ND) in an outer part more than 45°. Therefore, the intensity of pole figures must be corrected using a randomly oriented powder sample to make an intensity correction against defocusing. In this work, high-purity Mg powder was used to make the intensity correction of pole figures.

3. Results and Discussion

Typical engineering stress-strain curves are shown in Fig. 2. The yield strength (σ0.2), ultimate tensile strength
orientation of {0002} basal plane changes remarkably. Therefore, only the changes of direction. At the higher strain, the texture evolution for TD basal planes for most grains gradually tends to the tensile strain is basically the same, of pole figures for ED and TD samples with the increase of 2.5 times as high as that of TD sample.

XRD texture analysis indicates that the changing tendency of pole figures for ED and TD samples with the increase of strain is basically the same, i.e. the orientation of (0002) basal planes for most grains gradually tends to the tensile direction. At the higher strain, the texture evolution for TD sample is more pronounced. Therefore, only the changes of pole figures for TD sample during the tensile tests have been selected to analyze, as shown in Fig. 3. It shows that only the orientation of (0002) basal plane changes remarkably. Meanwhile, two peaks at positions of 0 and 30° from ND toward ED in {10-10} pole figure at a tensile strain of 0% (Fig. 3(a)) clearly indicate the existence of some grains having the c-axis inclined at approximately 90° from ND toward TD. In the case of TD sample, these two orientations are favorable for the activation of [10-12] twinning, because the c-axis is parallel to the tensile direction. To prove whether the twinning occurs or not during the tensile deformation, the optical micrographs of TD sample before and after tensile deformation should be carried out by non-basal slips, which will further increase the anisotropy in the yield strength. According to the above discussion, the marked difference of yield strength between ED and TD samples can be successfully explained.

However, the difference of deformation modes between TD and ED samples cannot be solely explained by the initial texture. The developed texture during the tensile tests should be taken into consideration. To explain the influence of the developed texture on the deformation modes, two schematic illustrations of tensile modes for single crystal have been proposed, i.e. the grip holder with and without constraint, as shown in Fig. 5. When applying a tensile stress to a specimen, the critical resolved shear stress (CRSS) \( \tau_K \) on the slip plane can be expressed as:

\[
\tau_K = \sigma_s \cos \gamma \sin \chi = \sigma_s \mu \tag{1}
\]

Where \( \sigma_s \) is the yield strength and \( \mu \) is the orientation factor defined as “\( \cos \gamma \sin \chi \)” and \( \gamma \) and \( \chi \) are the angles between the stress axis and the slip direction and the slip plane, respectively. The initial (0002) pole figure (Fig. 3(a)) shows that the initial angle \( \chi_0 \) for all grains for ED sample is lower than 10°, whereas for TD sample, the initial angle \( \chi_0 \) for some grains can reach to 20°. Therefore, the orientation factor of the basal slip for TD sample is approximately two times as large as that for ED sample. Based on the eq. (1), the yield strength of ED sample should be 2 times as high as that of TD sample. Recently, Agnew and Duygulu\(^{11}\) performed a detailed TEM analysis of deformed samples of rolled AZ31 alloy providing the evidence of extensive non-basal slip and estimated the ratio of CRSSs as \( \tau_{\text{prim}}/\tau_{\text{basal}} \approx 2 \sim 2.5 \). Although the reported value is much lower than the previously reported values (near to 100), the activation energy for non-basal slips is still higher than that for basal slip. Compared with TD sample, due to the unfavorable initial orientation of basal slip for ED sample, more shear deformation should be carried out by non-basal slips, which will further increase the anisotropy in the yield strength.

When the grip holder is constrained (Fig. 5(b)), slip planes must rotate to remove the deviation of the axial direction of the tensile sample, which will lead to the reorientation of the slip planes. Due to the marked basal texture (Fig. 3(a)), the as-extruded ZK60 polycrystalline alloy can be looked on as the combination of many crystals with the uniform orientation of basal plane. Therefore, the proposed models should be applicable to the TD and ED samples. In addition, it has been reported that during hot rolling processing, [10-12] twinning was the dominant deformation mechanism and could make the basal plane in the twinned region reorient nearly parallel to the rolling direction.\(^{12}\) However, the c/a ratio of Mg is 1.624. Thus, there is a 43° angle between the basal plane and the [10-12] planes. Because of this hexagonal close-packed crystal structure, the activation of [10-12] twinning will lengthen the crystal inside the twinned region along the c-axis of the parent matrix. The [10-12] twinning is thus most easily activated when the c-axis is perpendicular to the
Fig. 3 The texture evolution of the TD sample with the tensile strains of (a) 0%, (b) 5%, (c) 10% and (d) 15%.

Fig. 4 Optical micrographs of TD sample: (a) before and (b) after tensile deformation. The observation surface of the optical sample is perpendicular to the tensile direction or transverse direction (TD).
compression stress or parallel to the tensile direction. Although the [10-10] pole figure indicates the existence of some grains having the c-axis inclined at approximately 90° from ND toward TD, basically no twins can be observed for the tensile deformed TD sample (Fig. 4). Therefore, the effect of [10-12] twinning on the mechanical properties and reorientation of basal plane for TD and ED samples can be omitted. The influence of texture evolution during tensile tests on the deformation modes for ED and TD samples will be discussed as follows.

For ED sample, due to the low yield strain (near to 1.3%), the corresponding lattice reorientation should be very slight. When the tensile stress reaches to yield strength, the resolved shear stress for the basal slips is still very low. Koike et al. indicated (13) that if the two deformed grains are to be bonded at a grain boundary, additional shear stresses (compatibility stresses) are needed and activate the non-basal slip systems. Since the non-basal (a) dislocations are not sufficient to ensure homogeneous deformation, the activation of (a+c) dislocations is necessary to satisfy the Von-Mises condition. (13) It also suggested that for the 2%-elongated sample, the (a+c) dislocations were observed only in the limited grains having their basal plans parallel to the tensile axis. It has also been predicated that (a+c) dislocations could be activated by further deformation of more than 2% and (a+c) dislocations would bring about a rapid work hardening together with the cross-slipping of (a) dislocations. (15) However, in the present study, the strong work hardening only proceeds until to the 2.5% strain. When the strain exceeds 2.5%, the orientation of basal plane for most grains gradually inclines to the tensile direction and the increased tensile stress can activate the basal slip of most grains. Therefore, the work hardening will be greatly weakened during the subsequent tensile processing (Fig. 2). Thus, for ED sample, its deformation mode mainly includes two steps, i.e. quick work hardening firstly and subsequent increase of plasticity. On the other hand, for TD sample, the initial angle $\chi_0$ for a small amount of grains can reach to 20°. When the yield strength is reached, the shear deformation can be mainly carried out by the basal slips. However, due to the lower yield strength (about 90 MPa) for TD sample, the subsequent plastic deformation will need the further increase of the tensile stress. In addition, with the increase of the strain, the lattice reorientation gradually increases the resolved shear stress for the basal slips, which results in the gradual weakening of the work hardening. Therefore, for TD sample, the deformation mode includes only one step, i.e. the plasticity gradually increases with the increase of the tensile stress.

4. Summary

Through determining the texture evolution of the tensile sample with different strains, it is indicated that the mechanical anisotropy and the difference of deformation modes for wrought Mg alloys not only depend on the initial texture, but also on the texture evolution during the tensile tests. Based on the results of tensile tests, it is suggested that ED sample has the higher yield strength and its deformation mode mainly includes two steps, i.e. quick work hardening firstly and subsequent increase of plasticity. On the other hand, for TD sample, due to the initial favorable orientation of basal plane for some grains, its yield strength has been greatly reduced. Due to the more remarkable reorientation of basal plane during the tensile test, the plasticity gradually increases with the increase of the tensile stress.

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