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The relationship between macro-fracture modes and roles of different deformation mechanisms for the as-extruded Mg–Zn–Zr alloy

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The mechanical anisotropy of as-extruded Mg–Zn–Zr plate has been investigated. It indicated that the critical resolve shear stress (CRSS) for basal slip was 60 MPa. Based on macro-shear fracture angles and deformed microstructure, it suggested that for samples with tilt angle β between 30° and 60°, the plastic deformation should rely on basal slip, whereas for samples with tilt angle β greater than 60°, the plastic deformation should be dominated by $\{10\bar{1}2\}$ twinning.

Keywords: CRSS; Macro-shear fracture angle; Basal texture; Mechanical anisotropy

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 [1]. However, these procedures generally give rise to a strong basal texture, which results in strong mechanical anisotropy and asymmetry, particular in the case of the plastic behavior of non-cubic materials, such as hexagonal close packed (hcp) magnesium and its alloys [2]. Since the critical resolved shear stress (CRSS) for prismatic slip was about 100 times higher than that for basal slip during the deformation at room temperature [3,4], the mechanical anisotropy of wrought Mg alloys should be closely related to the basal texture [5–9]. In research on an as-extruded AZ61 Mg alloy bar, Kleiner and Uggowitzer [9] gave a comprehensive report about the mechanical anisotropy, the role of basal slip and the strain caused by $\{10\bar{1}2\}$ twinning. However, when it comes to which one of the deformation mechanisms (basal slip and $\{10\bar{1}2\}$ twinning) plays the key role during the plastic deformation for Mg alloys under different orientation conditions, there is basically no literature that can be referred to. In this work, an as-extruded ZK60 Mg alloy plate with a strong basal texture was chosen as the experimental material. By analyzing the macro-shear fracture angles and investigating the deformed microstructures of differently oriented samples, the dominant roles of basal slip and $\{10\bar{1}2\}$ twinning have been studied in depth.

The material used in the present study was an as-extruded ZK60 magnesium alloy (Zn 5.68, Zr 0.78 and balance Mg, by wt%), prepared in the Magnesium Alloy Research Department of IMR, China. The extrusion ratio was 10:1.

Previous studies have indicated that the average grain size of this as-extruded ZK60 alloy was about 15 μm [10]. The crystallographic texture distribution of the alloy was examined with a D/Max 2400 X-ray diffractometer (XRD) using monochromatic Cu Kα radiation from a cross-sectional plane (20 mm × 20 mm) in the transverse and extrusion directions (TD and ED, respectively). To investigate the mechanical anisotropy and roles of different deformation mechanisms systematically, tensile samples with the tensile axis forming angles β of 30°, 45°, 60°, 70°, 75°, 80°, 85° and 90° to the basal plane of most grains were machined from the extruded plate, as shown in Figure 1. Generally, when tilt angle β is less than 30°, the macro-shear fracture angle (θ_T) of samples is more sensitive to contours in the (0002) pole figure, and the macro-shear fracture angle

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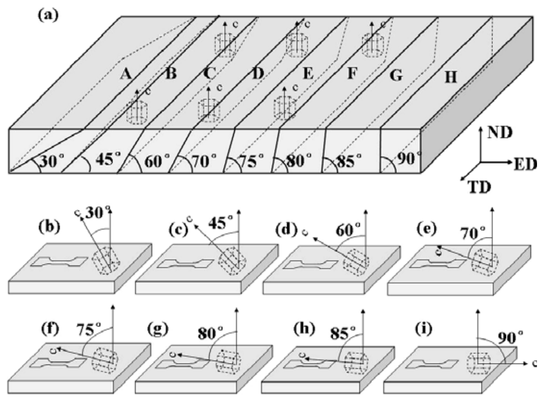

Figure 1. (a) Thin sheets with the normal forming angles of 30°, 45°, 60°, 70°, 75°, 80°, 85° and 90° to the *c*-axis of most grains were selected and designated as *A*, *B*, *C*, *D*, *E*, *F*, *G* and *H*, respectively. Illustrations of the cut tensile samples with the tensile axis (loading direction) forming angles β with the basal plane of most grains: (b) 30°, (c) 45°, (d) 60°, (e) 70°, (f) 75°, (g) 80°, (h) 85° and (i) 90°.

for ED samples can vary from 30° to 60°. Therefore, to avoid the influence of weak contours of (0002) pole figure, only samples with tilt angles greater than 30° were investigated. The final tensile sample geometry has a gauge length of 6 mm, a cross-sectional area of 4 mm × 1 mm and a radius between the gauge length and the grip ends of 1.7 mm. To ensure the small scatter of the tensile data, three repeated tensile tests were performed on differently oriented samples. Tensile tests were performed on a Instron 5848 Micro-force Testing System (produced by Instron Corporation, with the maximum load of 2000N) at a strain rate of $1 \times 10^{-3}\ s^{-1}$ at room temperature. Scanning electron microscopic (XL30-FEG-ESEM) observations using backscatter electron imaging were made to determine the macro-fracture angles (θ_T) of differently oriented samples. The activated twin mode in the plastic deformation was determined by the electron backscattered diffraction (EBSD) technique.

Figure 2 shows pole figures of the as-extruded ZK60 alloy plate. It reveals that the *c*-axis of most grains is basically parallel to the normal direction of the extruded plate (ND). Meanwhile, weak intensity contours in the prismatic and pyramidal pole figures indicate that no strong preferential orientation can be formed for the $\{10\bar{1}0\}$ and $\{10\bar{1}1\}$ planes. Therefore, the as-extruded ZK60 polycrystalline alloy can be roughly viewed as a combination of many single crystals with a uniform orientation of their basal planes or *c*-axis, as shown in Figure 1a.

Table 1. Mechanical properties of the as-extruded ZK60 Mg alloy with different orientations

Tilt angle β (°)	$\sigma_{0.2}$ (MPa)	UTS (MPa)	δ (%)
30	134	267	14.2
45	128	258	20.5
60	139	276	14.9
70	147	315	10.1
80	177	308	8.9
90	195	314	6.1

To reflect the pronounced mechanical anisotropy of differently oriented samples, the mechanical properties of samples with tilt angles β of 75 and 85° were investigated. The tensile results for differently oriented samples are shown in Table 1, which shows that the mechanical anisotropy is very remarkable. With increasing tilt angle β, the yield strength increases gradually but the plasticity decreases greatly. However, the yield strength is at its lowest for the sample with tilt angle of 45°. Table 1 also indicates that the mechanical properties of samples with tilt angles β of 30° and 60° are basically the same.

Figure 3 shows the macro-tensile shear fracture angles (θ_T) of differently oriented samples. Compared with Figure 1, it reveals that for differently oriented tensile samples shear angles (θ_T) are firmly consistent with tilt angle β between the tensile axis and the basal plane of most grains. Microstructural observations of the failed tensile samples reveal that with increasing tilt angle β, the density of activated twins increases remarkably, is shown in Figure 4. EBSD analysis of the 60° sample indicates that the misorientation angle between most twinned area and the parent matrix is about 86.25°, as shown in Figure 5. Since only $\{10\bar{1}2\}$ twinning can lead to a reorientation of 86.3° of the crystal lattice [11–13], this firmly indicates that the primary activated twin is $\{10\bar{1}2\}$ twinning.

Based on the Tresca criterion [14], fracture always occurs along the maximum shear stress plane at a critical shear stress. It has been pointed out that the Tresca criterion is more suitable for the slip deformation of polycrystalline materials that obey Schmid's law [15]. Since the CRSS of basal slip for Mg alloys is much lower than that of non-basal slips [3,4], basal slip should be more easily activated. Galiyev et al. [16] also indicated that, although twinning and short and thin $\langle \mathbf{a}+\mathbf{c} \rangle$ dislocations can be observed, the plastic deformation of ZK60 alloy at a temperature lower than 473 K was dominated by basal slip. In this work, the experimental material has a strong basal texture. Therefore, based

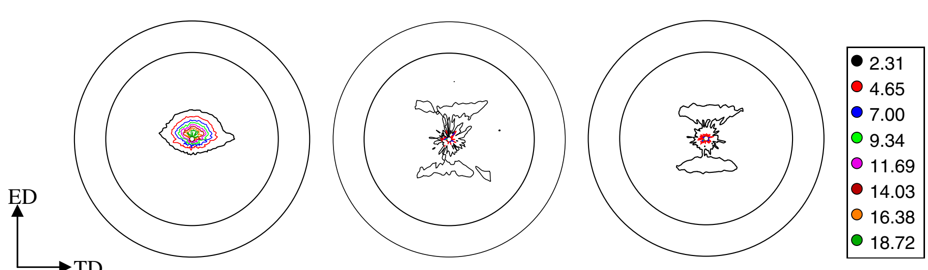

Figure 2. Basal, prismatic and pyramidal pole figures for the as-extruded ZK60 alloy plate.