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Improved strength and ductility of magnesium alloy below micro-twin lamellar structure

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ABSTRACT

The effect of {10 – 12} micro-twin lamellar structure on the mechanical properties of magnesium alloy has been examined. It has been found that the detwinning behavior effectively increases the flow stress of Mg alloy, and this strengthening effect becomes more significant with the volume fraction of twin lamellae increasing for the annealed materials. Meanwhile, the refined microstructure caused by the micro-twin lamellae plays an important role in improving the ductility of materials. But a latent Hall–Petch hardening correlated to grain refinement by twin lamellae was not substantiated by experiments, indicating strengthening from twin boundaries is relatively less pronounced below twin lamellae of micrometer scale. Here, the high density of twin boundaries and the high volume fraction of twins are considered as the structural characteristics of the critical {10 – 12} twin lamellae, which can effectively optimize strength and ductility of magnesium alloy.

1. Introduction

Due to the characteristic of the hexagonal close packed (HCP) structure, magnesium alloys have a limited number of slip systems, which results in their poor formability at room temperature. Consequently, deformation twinning plays an important role in plastic deformation of polycrystalline magnesium alloys. Among the several types of twins that have been found in magnesium alloys, {10 – 12} twinning has a more significant influence on the mechanical properties of magnesium alloys due to its own nature. For example, due to the polar nature of {10 – 12} twinning, the crystallographic texture always forms during mechanical processing and leads to a pronounced anisotropy of the mechanical properties of magnesium alloys [1,2]. Meanwhile, {10 – 12} twinning also plays a positive role in improving the mechanical properties of materials [3–5]. For example, the hardening contributions which result from dislocation pile-up within twin and on twin boundary (TB) and texture change caused by twinning, respectively; the abrupt change of orientation due to twinning may give rise to the activation of other slip systems, thereby elevating the ductility of metals. However, twinning contribution is relatively limited to the total plasticity due to the small twinning shear of only 0.1298 [6] and the confined volume of grain which would lead to twinning saturation with plastic strain increasing.

Despite the limited contribution of twinning itself to the deformation, the refined microstructure of the material caused by twins is considered to play an important role in strengthening and softening, such as the latent Hall–Petch hardening correlated to grain segmentation by {10 – 12} twins and strength softening caused by the defects within twins [7]. A typical study shows that ultrafine-grained copper containing nanotwins has an unusual combination of ultrahigh yield strength and high ductility [8,9]. And below a critical twin thickness, this metal even appears strength softening [10]. The above results not only confirm the effect of twin structure, but also break out of the common view that strength and plasticity cannot be improved simultaneously by twinning behavior. For the easier-to-twin magnesium alloys, there has been great expectation on the role of a critical twin-lamellar structure in improving the mechanical properties of HCP metals. However, this detailed information is relatively limited. In this study, we investigated the tensile deformation behavior of Mg alloy containing {10 – 12} micro-twin lamellar structure with the aim of analyzing scale effects of the microstructural refinement caused by twins on the mechanical properties of magnesium alloy.

2. Material and experimental methods

The hot-rolled AZ31 Mg alloy sheet (Mg–3% Al–1% Zn) has twin-free equiaxed grain structure and an average grain size of 34 μm (Fig. 1a). As generally observed in as-rolled AZ31 sheet, the

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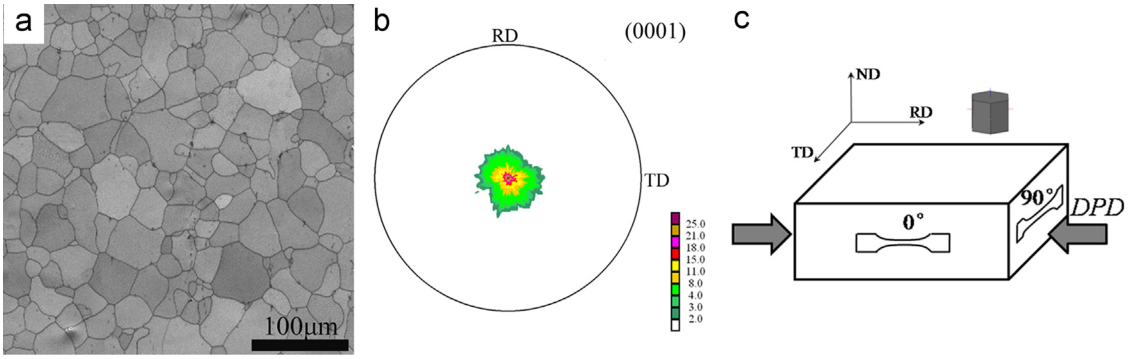

Fig. 1. (a) Microstructure characteristics and (b) (0001) pole figures of the as-rolled material; (c) schematic illustration of the sample orientations used for DPD and subsequent tensile testing. RD, TD and ND represent the rolling direction, the transverse direction and the normal direction, respectively.

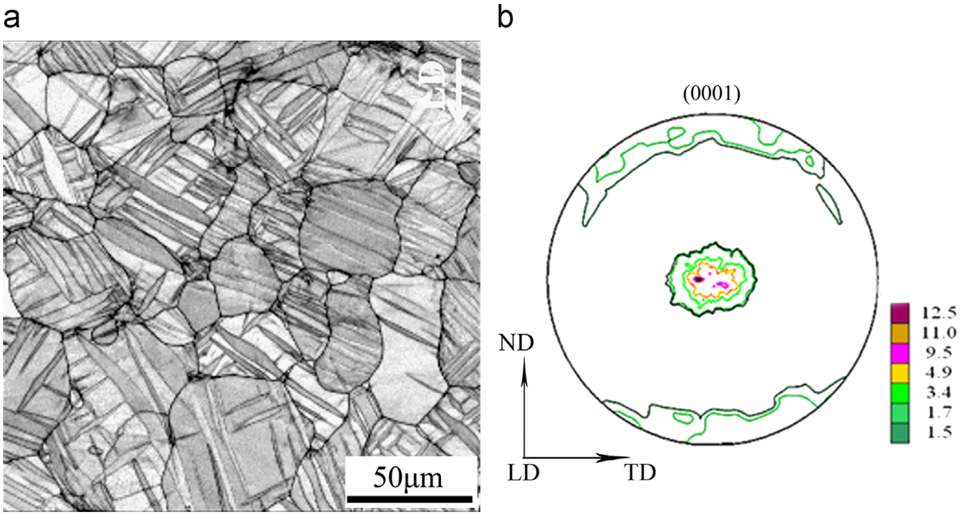

Fig. 2. (a) The {10 – 12} twin-lamellar structure and (b) (0001) pole figure of the DPD sample with 5% strain. LD represents the loading direction.

basal {0001} planes of this sheet were aligned almost parallel to the rolling plane, as shown in Fig. 1b.

Parallelepiped (30×30×22 mm in rolling–transverse–normal directions, as shown in Fig. 1c) was cut from this sheet. {10–12} twin nucleation and propagation can be dramatically enhanced at dynamic rates [11]. So to facilitate twinning, dynamic plastic deformation (DPD) as the pre-deformation mode was employed to impact samples to several true strains in this study. Samples were subjected to DPD along the rolling direction (RD) just once with an Instron Dynatup 8120 testing machine at room temperature and tests were interrupted at strains of 1%, 3%, 5% and 7%. The strain rate applied in each impact was estimated to be about 10^3/s. The twin-lamellar microstructure of 5% pre-deformed sample is shown in Fig. 2.

One set of pre-deformed AZ31 samples was annealed at 200 °C for 3 h to eliminate the dislocations and maintain the twin structure. At room temperature, quasi-static tensile tests were performed in two sets of the pre-deformed samples with and without annealing up to failure, respectively, using a SHIMADZU AG-X10KN machine at an initial strain rate of 10^{-2}/s. Meanwhile, the other two sets of tensile samples used for the microstructural analysis were interrupted at a strain of 6%. For convenience, the nomenclature adopted in the remainder of the paper for both the “initial” samples which would be used for the tensile tests is as follows: P_ε (only subjected to DPD pre-deformation) and PA_ε (first pre-deformed and then annealed), and ε indicates pre-strain value.

Tensile specimens with a dog-bone shape of 5 mm in gage length and 1.26 mm in width were machined parallel and perpendicular to the DPD direction, as illustrated in Fig. 1c, referred to as 0° and 90°, respectively. Scanning electron microscopy–electron back-scattered diffraction (SEM–EBSD) was utilized to analyze the microstructure and texture evolution of samples during deformation.

3. Experimental results and discussion

3.1. Detwinning strengthening

The flow curves of 0° tension of the 5% pre-deformed sample are presented in Fig. 3a. The concave-up curve reveals characteristics of twinning deformation, but the twin volume fraction decreases significantly, as listed in Table 1. Obviously, 0° tension leads to detwinning behavior of the pre-deformed AZ31 alloy, and {10 – 12} twins caused by pre-deformation are recovered by detwinning (Fig. 4a). This can also be seen from the (0001) pole figure in Fig. 4b, where the initial basal texture is recovered by detwinning. As shown in Fig. 3a, detwinning dominates the early plastic deformation of AZ31 samples containing the twin-lamellar structure and plays an important role in strengthening Mg alloy. Generally, the high-density dislocations caused by pre-deformation would become an obstacle to the mobility of TB, resulting in an increase in the activation stresses of detwinning behavior [12]. Meanwhile, dislocation slip also becomes more difficult. So in