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The dislocation-twin interaction and evolution of twin boundary in AZ31 Mg alloy

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ABSTRACT

The reaction of lattice dislocation with twin boundary plays a crucial role in the plastic deformation of magnesium alloys. In this study, we visit the basal dislocation-twin interaction in a hot-rolled AZ31 sheet through pre-compression along rolling direction (RD) and subsequent compression along 45° of RD and normal direction (ND), with focus on the twin boundary (TB) structure evolution and nucleation structure characterization. It is found that basal dislocation slip dominates the compression deformation when the strain along 45° of RD and ND is less than 14%; when the strain reaches 14%, new deformation modes are initiated. When the strain is in the range of 5%–14%, basal-prismatic (BP/PB) boundaries are created by dislocation-twin interaction. Meantime, the number of the BP/PB boundaries increase linearly with strain, leading to an extremely incoherent TB. When the strain reaches 14%, $\{10\bar{1}2\}$ twin nucleates from parent of previous $\{10\bar{1}2\}$ twin and $\{30\bar{3}4\}$ twin, a twinning mode not reported before, nucleates from previous $\{10\bar{1}2\}$ TB. Based on the direct experimental observations, the nucleation mechanisms of the new nucleuses are proposed. Moreover, TBs of these new nucleuses present faceted structures and previous $\{10\bar{1}2\}$ twin-new $\{30\bar{3}4\}$ twin interaction results in a low-angle asymmetrical tilt boundary. These correlations will significantly benefit the development of crystal plasticity modeling and enhance meso-scale understanding of structural evolution in hexagonal close-packed materials.

1. Introduction

Magnesium alloys are lightweight metal, with a density 23% that of steel and 66% that of aluminum, and their increased use could greatly save energy and reduce emission in many areas, especially aerospace and automotive industries [1,2]. Magnesium alloys have sufficient number of potential slip systems, but only a few of them are active or easily activated at room temperature because of their hexagonal close-packed (hcp) crystal structures [3–5]. In general, basal <a> slip ($\{0001\}\langle 11\bar{2}0\rangle$) and extension twinning ($\{10\bar{1}2\}\langle 10\bar{1}\bar{1}\rangle$) are the two maim deformation modes at room temperature [6]. Other deformation modes, such as prismatic <a> slip ($\{10\bar{1}0\}\langle 11\bar{2}0\rangle$) and pyramidal $\langle c+a\rangle$ slip ($\{11\bar{2}\bar{2}\}\langle 11\bar{2}3\rangle$), are hard to initiate because of their relatively large critical resolved stress at room temperature [7]. Consequently, basal dislocation-twin and twin-twin interactions are inevitable during plastic deformation, which has drawn considerable attention in both experiment and modeling at multiple length scales [8–12].

It is well known that $\{10\bar{1}2\}$ twinning mode can accommodate the tension strain along c-axes during plastic deformation and the activation of twinning is closely related to strain hardening behavior [13,14]. Furthermore, $\{10\bar{1}2\}$ twinning is also a main contributor to the development of texture because it results in an 86.3° reorientation of the basal pole [15]. Materials modeling tools at meso-scale have been developed to quantitatively simulate the contribution of twinning to plastic deformation and texture evolution [16–18]. Several twinning models have been developed to describe and elucidate the twinning process, such as Composite Grain (CG) model [19,20] and Probabilistic model [21]. However, these models only consider interaction between dislocation and twin based on a Hall-Petch mechanism assuming that twin boundary hinders the motion of lattice dislocation. In other word, these mechanisms only consider the barrier effect of twin boundary on the dislocation movement and fail to capture complex dislocation-twin interaction.

Extensive atomistic simulations have shown that twin boundary does not simply act as a barrier to dislocation slip [22–26]. Instead, lattice dislocation undergoes complex reaction at twin boundary.

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For example, Wang and Beyerlein concluded that when a basal dislocation interacts with a coherent twin boundary, twinning dislocations and residual defects are produced at the coherent twin boundary [27]. Accompanying the glide of twinning dislocations along twin boundary, the twin boundary migrates [28–30]. This can be a mechanism for enlarging or shrinking the twin domain. El Kadiri and Barrett pointed out that basal-prismatic (BP/PB) interface could be easily nucleated when a twin boundary is struck by two incoming Shockley partials [31]. Meantime, they elucidated the relationship between the gliding twinning dislocation and twin boundary which consists of coherent twin boundaries and BP/PB boundaries in the frame of topological theory of crystallography defect [32,33].

It is to be noted that, despite the atomic-scale simulations made on dislocation-twin interaction in magnesium, formation mechanism of BP/PB boundary or atomic modeling of basal dislocation-twin interaction, a critical component of enhancing crystal plasticity models and meso-scale understanding of hcp material evolution, is not confirmed by any experimental studying. A more recent study based on electron backscatter diffraction (EBSD) analysis indicated that the interaction between two $\{10\bar{1}2\}$ twin variant triggers new $\{10\bar{1}2\}$ twins near intersection region [12]. However, it is unclear whether $\{10\bar{1}2\}$ twins or other type of twins nucleate in the case of dislocation-twin interaction. It is still unclear how the interaction between basal dislocation and twin, in comparison with the twin-twin interaction, would influence subsequent twin nucleation.

It is therefore the purpose of this study to design experiments to investigate dislocation-twin interaction and twin evolution. As we know, schmid factor is determined by the angle between loading axis and slip systems and so basal dislocation slip is the most favored under uniaxial compression along 45° of c-axis. Thus, we visit dislocation-twin interaction through pre-compression along rolling direction (RD) to trigger tension twinning and subsequent compression along 45° of rolling direction (RD) and normal direction (ND) to introduce basal dislocation. After compression, the morphologies of twin band were characterized by EBSD and the configuration characteristics of twin boundary were characterized by high-resolution transmission electron microscopy (HRTEM). Based on comprehensive analysis of crystallographic orientations, morphologies, variation of work hardening rate during mechanical testing, together with electron diffraction patterns and HRTEM images, the formation mechanism of BP/PB boundary, the evolution of twin boundary and structure of new twin nucleus are elucidated. The twin nucleuses include the most frequently observed $\{10\bar{1}2\}$ twin and previously never reported $\{30\bar{3}4\}$ twin. $\{30\bar{3}4\}$ twinning is revealed and reported as a new twining system. Based on the direct observations, the nucleation mechanisms of the twin nucleuses are proposed. Meantime, the interaction between previous $\{10\bar{1}2\}$ twin and new $\{30\bar{3}4\}$ twin is also discussed. The results are believed to help deep understanding and modeling of twinning and offer insight into how to capture twin-dislocation interactions in crystal plasticity modeling.

2. Experimental procedure

2.1. Mechanical tests

A hot-rolled AZ31 thick plate was used. As seen in Fig. 1, the initial plate has a mean grain size of about 28 μm and a typical basal texture with (0002) pole largely parallel to the ND. In such a plate, if further compression is loaded along RD, $\{10\bar{1}2\}$ twinning will be triggered in most of the grains, as the c-axes of the grains are

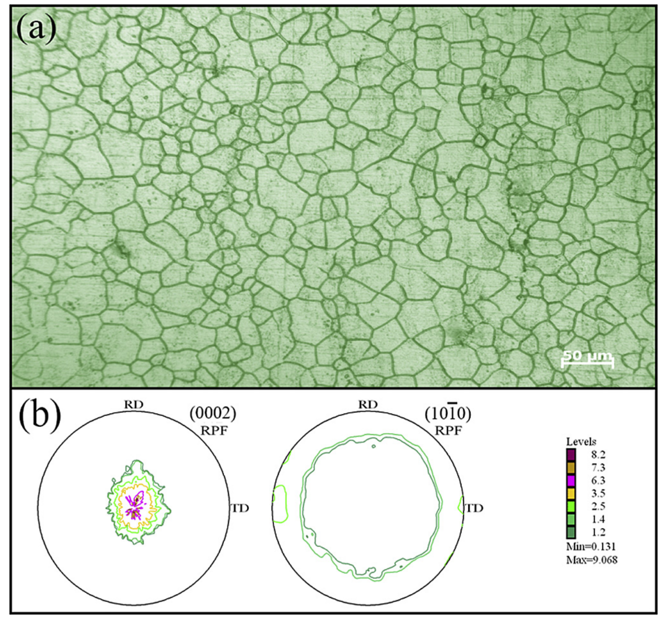

Fig. 1. (a) Optical microstructure and (b) pole figure (acquired by XRD) of the hot-rolled AZ31 Mg sheet used in the present study. RD and TD refer to rolling direction and transverse direction, respectively.

subjected to extension. Therefore, to generate $\{10\bar{1}2\}$ twin boundaries, four blocks of 30(ND) × 30(TD) × 31(RD) were compressed along the RD to a strain of 5.5%. The samples were designated as PS-1. Here, RD, TD and ND represent rolling direction, transverse direction and normal direction of the initial plate, respectively. To introduce different amount of basal dislocation, three PS-1 samples were further compressed along 45° of RD and ND to a strain of 8.5%, 12.5% and 14.5%; the resultant sample were designated as PS-2, PS-3 and PS-4 respectively. Mechanical tests were conducted on CMT6305-300 KN universal testing machine under a strain rate of 0.001 s^{-1} at room temperature.

2.2. Examination of microstructure and texture

For optical examination, the specimens were mechanically ground, and chemical etched in an acetic picral solution (2 ml acetic acid + 1 g picric acid + 2 ml H_20 + 16 ml ethanol). Pole figures were measured using an X-ray diffraction (XRD, Rigaku D/max-2500 PC) meter. To reveal the microstructure and their crystallographic orientations, electron back-scattered diffraction (EBSD) measurements were carried out by using a JOEL-JEM7800F field emission scanning electron microscope equipped with a HKL-EBSD system; the scanning step is 0.5 μm and the magnification is 400. The observed surface was ground mechanically followed by electrochemical polishing in commercial AC2 solution at 20 V. The EBSD data was analyzed using the channel 5 software. Cross-sectional TEM specimens were cut from the samples and gently polished to a thickness of ~50 μm. Perforation by ion milling was carried out on a cold stage (−70 °C) with low angle (3°) and low energy ion beam (3Kev). High-resolution transmission electron microscopy (HRTEM) was carried out on an FEI tecnai F20-G^2 electron microscope with a voltage of 300 KV.

3. Experimental results

3.1. Deformation mechanism

To analyze the deformation mechanism during the compression