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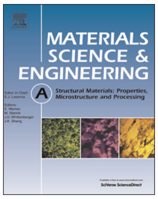

Geometrically necessary twins in bending of a magnesium alloy

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ABSTRACT

Evidence for the formation of geometrically necessary twins (GNTs), or twins that accommodate a strain gradient in a multi-axial stress state, in quasi-static, room temperature three-point bending of a rolled magnesium alloy is presented. Electron backscatter diffraction analysis showed that $\{10\bar{1}2\} < 10\bar{1}\bar{1}>$ extension twins (rather than $\{10\bar{1}1\} < 10\bar{1}\bar{2}>$ contraction twins) form in arcs in the tension zone, and that twinned grains have very low Schmid factors. The main tensile stress component in the tension zone was nearly perpendicular to the *c*-axis of the parent grains. The mechanism for such unusual twinning behavior was analyzed from the perspective of strain components that are generated by $\{10\bar{1}2\} < 10\bar{1}\bar{1}>$ twinning. After twinning, an extension strain component along the *c*-axis and a contraction strain component perpendicular to the *c*-axis of the parent lattice are generated simultaneously due to the misfit between the parent and the twin lattice. The contraction strain component by twinning provided an extra strain accommodation for the compressive strain in the tension zone produced by the bending, despite the fact that the local stress state strongly disfavored the $\{10\bar{1}2\} < 10\bar{1}\bar{1}>$ twinning. Thus, the $\{10\bar{1}2\} < 10\bar{1}\bar{1}>$ twins in the arcs in the tension zone of the bent specimen present the characteristic of being geometrically necessary, similar to geometrically necessary dislocations and boundaries.

1. Introduction

Magnesium (Mg) alloys have drawn substantial attention in recent years owing to their broad technological significance and intriguing materials science. Their high strength-to-weight ratio along with low density (~35% lighter than Al alloys and ~78% lighter than steel) make them attractive replacement materials for more mass-intensive ferrous and non-ferrous alloys currently used in transportation industries [1,2]. Magnesium alloys also offer significant potential for fuel efficiency improvements and reduced hydrocarbon emissions. However, room temperature (RT) applications of wrought Mg alloys have been limited, in part, by poor ductility. This results from the large difference in critical resolved shear stresses between basal and prismatic slip in the hexagonal close packed (HCP) lattice (two independent $\frac{1}{3} < 11\bar{2}0>$ basal slip systems are active at RT). The stress required to plastically deform Mg along its (easy) basal slip plane is two-orders of-magnitude lower than the (hard) prismatic plane at RT, requiring elevated temperatures to enhance ductility in component forming processes [3,4]. Magnesium sheet formability at elevated temperatures is sensitive to the chosen material manufacturing process (e.g. direct chill, twin roll casting) [5]. The materials science of Mg alloys is quite complex. In addition to the multitude of slip systems, both active and inactive, the nearly ideal *c*/*a* ratio (γ) of Mg, promotes twinning, for which there are two systems, namely: $\{10\bar{1}2\} < 10\bar{1}\bar{1}>$ and $\{10\bar{1}1\} < 10\bar{1}\bar{2}>$. The $\{10\bar{1}2\} < 10\bar{1}\bar{1}>$ system is the most commonly observed twinning mode in all HCP metals [6–8]. Yoo [9] plotted the twinning shear with respect to the *c*/*a* ratio of the major twinning modes in HCP metals. For $\gamma < \sqrt{3}$, the slope of the twinning modes was shown to be negative but turns positive when $\gamma > \sqrt{3}$. Thus, the negative slope was as an indication that the twinning mode is *c*-axis extension. Hence, $\{10\bar{1}2\} < 10\bar{1}\bar{1}>$ twinning is most favorable when a tensile stress is applied along the *c*-axis of a Mg crystal. However, it is suppressed when a compressive stress is applied along the *c*-axis or a tensile stress is applied perpendicular to the *c*-axis.

In dislocation-mediated plastic deformation, an important class of dislocations, i.e. geometrically necessary dislocations (GNDs), was first proposed by Nye [10]. The GNDs are generated when a strain gradient is present within a deformed material. For instance, in bending tests of crystalline metals, the slip planes for dislocations are curved by the deformation [10]. Thus, the curvature of the slip planes gives rise to a slip gradient on successive slip planes

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that can be compensated by GNDs [11]. Additionally, GNDs are distinguished from statistically stored dislocations (SSDs) that are created in the absence of a large strain gradient. Here, GNDs are associated with the organization of dislocations into low energy configurations, such as dislocation cells or walls that result in the development of a locally non-uniform strain field [12]. Closely related to GNDs are geometrically necessary boundaries (GNBs), including dense dislocation walls (DDWs) and microbands (MBs) that are necessitated by the accommodation of the lattice misorientation between the dislocation cells [13–17]. GNBs were proposed as a means to account for the flow stress anisotropy in deformed metals with medium to high stacking fault energies [18].

Using the GND concept in dislocation-dominated plastic deformation, Sevillano [19] first proposed the concept of “geometrically necessary twins” (GNTs). A GNT was treated as a “pseudo-dislocation line” at the twin edge with an effective Burgers vector in the direction of the twinning shear. The resultant hardening effect and strain accommodation by GNTs was also discussed [14]. Unfortunately, there has been a dearth of experimental evidence of GNTs since Sevillano's [19] initial proposition. Some preliminary experimental observations were reported by Li et al. [20]. In slip-controlled deformation, dislocations interact as they intersect with each other. Dislocations also interact with secondary phases and interfaces such as grain boundaries and cell boundaries, resulting in changes in the original slip pattern via cross-slip, transmission, reflection or absorption at interfaces [21–23]. In contrast, twinning results from successive glide of twinning dislocations restricted at the twin/parent interfaces, i.e. twin boundaries (TBs) that should satisfy the invariant plane strain condition [24]. Thus, strain accommodation by shear-dominated twinning is different from dislocation slip. Alternatively, twinning is unidirectional [24] since the twinning shear is uniquely defined by the second invariant plane, i.e. the K_2 plane, and the twinning direction η_1. Because of these differences, GNTs that behave similarly to GNDs have received little attention in experiments.

In this study, we present experimental evidence for GNTs in Mg AZ31-O, the most common of all wrought Mg alloys, deformed in quasi-static three point bending at RT. Bending was chosen, in part, because it is a significant deformation component in many practical applications in transportation industries [25]. The GNTs result from the macroscopic strain gradient produced by the bending load. We specifically characterized twins in the tension zone using electron backscatter diffraction (EBSD) and showed that they present the characteristic of being geometrically necessary.

2. Experiments

A twin-roll cast sheet of AZ31 Mg alloy [26] with thickness of 1.0 mm was cut into strips with dimensions $76 \times 7 \times 1\ \text{mm}^3$. Quasi-static, three point bending was performed using an Instron 5882 testing system and an in-house three point bend fixture. The distance between the bending anvil pivots was 28 mm. The specimens were deformed at a rate of 10 mm/min and through a maximum bending angle of ~132° and ~30 mm displacement. The bend was parallel to the rolling direction (RD). One of the specimens was immediately cold mounted and the microstructure of the cross-section through the thickness was studied in detail using optical microscopy. This specimen was mechanically polished and then etched using an Acetic Picral solution containing 3 g picric acid, 100 ml ethanol, 10 ml distilled water, and 5 ml acetic acid. The specimen was then examined using a Zeiss Axiovert optical microscope (OM). To better reveal the deformation twins, differential interference contrast (DIC) illumination was used in imaging: this improves the contrast of the twins [27]. After optical microscopy, the specimen was then mechanically re-polished followed by electrochemical polishing with an electrolyte composed of 160 mg sodium thiocyanate, 800 ml of ethanol, 80 ml of ethylene glycol monobutyl ether, and 20 ml of distilled water. Electron backscatter diffraction (EBSD) was then performed on the through-thickness cross-section using a Zeiss Supra 40 field emission gun scanning electron microscope (SEM) equipped with an EDAX Hikari EBSD detection system. The EBSD step size was 0.1 μm. When the scans were completed the data was rotated at 90° about the transverse direction (TD) using the EDAX analysis software (TSL OIM 6) so as to align it with the normal direction (ND) of the sheet specimen, which is the direction perpendicular to the tension and the compression surfaces of the bend specimen.

3. Results

Fig. 1 shows optical microscopy of the Mg AZ31 specimen microstructure after three point bending. The image was taken on the through-thickness cross-sectional area. With the DIC illumination, two zones can be clearly distinguished, namely, a compression zone and a tension zone. In the compression zone, a very high density of deformation twins is observed. Away from the surface of the compression zone, twins are localized in bands. The tips of the bands extend near the center line, i.e. midway along the thickness of the specimen. Such localized twin bands in three point bending were first reported by Baird et al. [27]. The twin bands are aligned in two directions that are nearly perpendicular to each other. EBSD analysis showed that the twins are $\{10\bar{1}2\} < 10\bar{1}\bar{1}>$ extension twins [27]. Alternatively, no twins are observed in the tension zone of Fig. 1 at the selected magnification.

After removing the DIC illumination, the twin bands present a different contrast than that in Fig. 1. As indicated by the long black arrows midway along the thickness of the specimen, the tips of the twin bands can still be seen but in weak contrast. However, another pattern of twins in the region at the vicinity of the tips of the twin bands is observed. Near the center of the field of view in Fig. 2a, where the deformation transitions from compression to tension, an arc of twins, which has a different contrast than the twin bands (indicated by the long black arrows), is observed

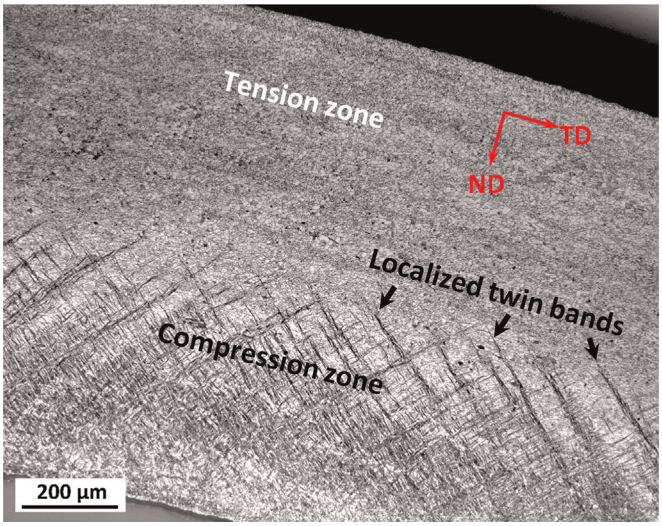

Fig. 1. Optical microscopy of localized twin bands in the compression zone of the sample after three point bending (the bending angle after springback is ~132°) [20]. Differential interference contrast (DIC) illumination was used in imaging. Each band comprises a high density of extension twins. In the tension zone, where the stress disfavors extension twinning, no twins are observed at this magnification (100X). The black arrows point to the twin band tips.