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ANOMALOUS TWIN BANDS IN AZ31 MAGNESIUM SHEET BENDING

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Abstract

Three-point bending was performed on an AZ31 magnesium sheet with a grain size ~8.0 μm at room temperature. In-situ electron backscatter diffraction and metallography examinations revealed an anomalous twinning pattern during bending. In the compression zone, the $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ twins appear in an extremely localized fashion, consisting of alternating twin bands. Each band comprises a high density of twins. In between the twin bands, twins are absent. As the bending angle increases, the twin bands grow into the tension zone although the stress disfavors the extension twinning.

Introduction

In recent years, lightweight Mg and Mg alloys have attracted significant attention for their potentials of improving fuel efficiency of automotive vehicles. A major barrier that bottlenecks extensive engineering applications of Mg alloys is the relatively poor ductility and low formability at room temperature, which inherently stem from the low symmetry hexagonal close-packed (HCP) crystal structure. In sharp contrast to high symmetry structures, e.g., face centered cubic (FCC), plastic deformation in Mg is dominated by mechanical twinning. This twinning dominated deformation gives rise to unique mechanical properties of Mg alloys, such as tension-compression asymmetry and anisotropy in plastic deformation [1].

In practice, forming of Mg alloys, e.g., sheet rolling, bending and drawing, has to be performed at elevated temperatures to prevent fracture. It is desirable to reduce the processing temperature of sheet forming. Hence, understanding microstructural and texture evolution *during* forming instead of post-forming is necessary. The mechanical properties of AZ31 Mg sheet metals have been studied extensively [2,3]. But, little attention was paid to microstructural evolution during forming. The purpose of this work is to examine microstructural evolution during three-point bending at room temperature, using in-situ electron backscatter diffraction (EBSD) and optical microscopy.

Experimental Methods

The material chosen for the current study was a magnesium alloy AZ31 rolled sheet with a thickness 1.0 mm. The as-received sheet was annealed at 300°C for 2 hours in an Argon atmosphere. Strips with a dimension 60×7×1 mm were cut for subsequent three-point bending tests. One of the through-thickness cross section of the strip was metallographically polished and then electropolished using a Struers electopolisher and the standard C1 Struers electrolyte (160 mg sodium thiocyanate, 800 ml Ethanol, 80 ml Ethylene glycol monobutyl ether, and 20 ml distilled water).

Three-point bending was performed with a specially designed fixture which allows us to conduct in-situ EBSD and metallography. By in-situ we mean that the sample was scanned with EBSD without unloading the sample, in contrast to conventional EBSD scans in which samples are unloaded after deformation. Details of our design will be described elsewhere. With the fixture we designed and fabricated, samples can be deformed continuously and EBSD scans can be carried out to examine the microstructure and texture evolution while the external load remains on the sample. This capability circumvents the problem of detwinning [4-6] after a deformed sample is unloaded, which is common in deformation of Mg and Mg alloys. Detwinning leads to the loss of microstructure and texture information.

The EBSD scans were performed through the thickness of the sheet using a Zeiss Supra 40 Field Emission Gun (FEG) Scanning Electron Microscope (SEM) equipped with an EDAX Hikari Electron Backscatter Diffraction (EBSD) detection system. After data collection, all data sets were rotated 90 degrees about the transverse direction (TD) so that all data analysis could be performed looking at the normal direction (ND). In the present study, all EBSD scans were performed with the load still on the sample. Samples during bending were also examined by metallography with differential interference contrast (DIC) illumination.

Results and Discussion

Figure 1 displays the inverse pole figure (IPF) which corresponds to the initial texture and microstructure of the rolled sheet. The pole figure is shown as well. The initial texture is typical of rolled materials exhibiting a strong basal (0001) pole, i.e., fiber texture. The grain size of the rolled sheet is about 8 μm.

The three-piont bending of the sheet introduces two specific stress states to the sheet, i.e., a compression zone right under the indenter, and a tension zone right next to the compression zone. In between, a neutral axis separates these two zones and experiences zero strain. These two different stress states provides an ideal scenario for in-situ study twinning-detwinning and other important issues related to materials mechanical responses by EBSD. The compression zone of the sample provides a preferred loading condition for the $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ extension twins which generate an elongation along the <*c*> axis that is nearly parallel to the normal direction of the sheet (Figure 1). But in the tension zone, the stress state disfavors the $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ twinning.

Figure 2 shows the IPF of a region in the compression zone. As expected, twinning occurred in this zone during bending. But surprisingly, the twins are localized in a band with a band width much larger than the grain size. The band runs roughly 45° from top to bottom. Away from the twin band, no twins are observed at all. Misorientation analysis shows that these twins are indeed $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ extension twins. The compressive stress creates an elongation along the <*c*> axis of the highly textured microstructure. Notably, the twin variants are aligned in two nearly perpendicular directions. Most of the twin variants run through whole grain, with the twins in the neighboring grains being

connected at the grain boundary. The pole figure confirms that the $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ twinning indeed took place, as two new intensity spots appear nearly 90° away from the rod intensity, a definitive signature of the extension twins.

Figure 2 shows only one twin band. Actually multiple twin bands were formed in the compression zone of the sheet, as shown in Figure 3. The EBSD scan was taken near the center line which is in the middle of the image. Similar penetrating pattern can be observed. Multiple twins connect at the grain boundaries of neighboring grains. More interestingly, as the bending angle increases, the twin bands continue to grow across the geometrical center line. Similar pole figure was captured, typical of the $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ twinning. It was found that the farther scans were taken from maximum compression and closer to maximum tension the intensity spot from twinning was reduced.

In addition to the in-situ EBSD scans in local regions of compression and tension, metallography observations were also made while the sample was still loaded. To better reveal the twin bands, differential interference contrast (DIC) illumination technique was used. Figure 4(a) shows one of the observations that macroscopically display the alternating twin bands. The width of the bands narrows toward the neutral axis, and the length of the individual bands decreases as the distance to the indenter increases. The bands roughly point to the same direction, about 45° with the top surface. Interestingly, the tip of the longest (indicated by an arrow) extended across the center line (also shown in Figure 3). As the bending angle increases, the twin bands widen laterally. Meanwhile, more twin bands appear in the direction nearly perpendicular to the original twin bands (indicated by an arrow).

More three-point bending tests were conducted on non-annealed sheet samples and we found that the results of the localized twin bands are repeatable.

Discussions

To our knowledge, such anomalous, highly localized twin bands in Mg sheet bending were not reported previously. Shear bands formed during sheet forming such as cold/warm rolling of AZ31 Mg sheets were reported by a number of researchers [2,3], but these bands are different from what we observed in the AZ31 sheet bending. Here we only briefly discuss the possible mechanism of the anomalous twin bands.

Despite the relatively fine grain structure of the AZ31 sheet, twinning did occur in a highly localized fashion during three-point bending. Close examinations on the twins in the individual grains show that for grains in the twin bands, one twin variant runs through whole grain, from one side of the grain boundary to the opposite side. At the location where this twin variant stops, another twin variant nucleates and propagates into the neighboring grain, approximately in the same direction. Such nucleation and growth of the twin variants in the neighboring grains cascades until the stress state of the sheet disfavors the $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ twinning. The twin variants conjoin at the grain boundaries and form a continuous band. Such an unusual twinning pattern indicates that the twin variants in the neighboring grains cannot be completely independent of each other, vastly different from dislocation controlled twinning modes where a twin variant must stop at a grain boundary because a twinning dislocation cannot penetrate a grain boundary.

In fact, penetrating twin variants were observed in previous reports where a twin variant can penetrate a grain boundary or another twin variant [7,8]. Hence, the $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ twinning mode must have a growth mechanism that is unique to other twinning modes in HCP metals. In the classical twinning theory [9], a homogeneous shear and atomic shuffling must be involved for low symmetry hcp structures. Atomic shuffling was nicely described by Christian and Mahajan [10], and confirmed by Li and Ma [11] in their molecular dynamics simulations. For the most commonly observed $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ twinning, the magnitude of shuffling is much greater than the magnitude of the theoretical twinning dislocation [11] which equals 0.024 nm for Mg [12]. Such an extremely small Burgers vector indicates that the $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ twinning is dominated by atomic shuffling, not by shear. In other words, a twinning dislocation is not needed for this particular twinning mode. This conclusion is supported by extensive experimental observations in which abnormal properties such as reversible twinning [4-6], non-Schmid effect [13], and large deviation between the actual twin boundaries and the $\{10\bar{1}2\}$ twinning plane [14]. In other twinning modes, a twinning dislocation is required, plus minor atomic shuffling or no shuffling at all [15-16]. The anomalous twin bands observed in this work again support the conclusion that the $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ twinning mode in HCP metals can only be controlled by atomic shuffling, not by twinning dislocations.

Conclusions

Three-point bending tests were performed on an AZ31 Mg sheet. In-situ EBSD scans and optical microscopy when samples were still loaded were performed. Extremely localized, alternating twin bands were observed. Each twin bands comprise high density $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ twins, whereas in between the twin bands, no twins were present. The results we obtained support the conclusion that the $\{10\bar{1}2\}$ twinning cannot be controlled by twinning dislocations, instead, by atomic shuffling.

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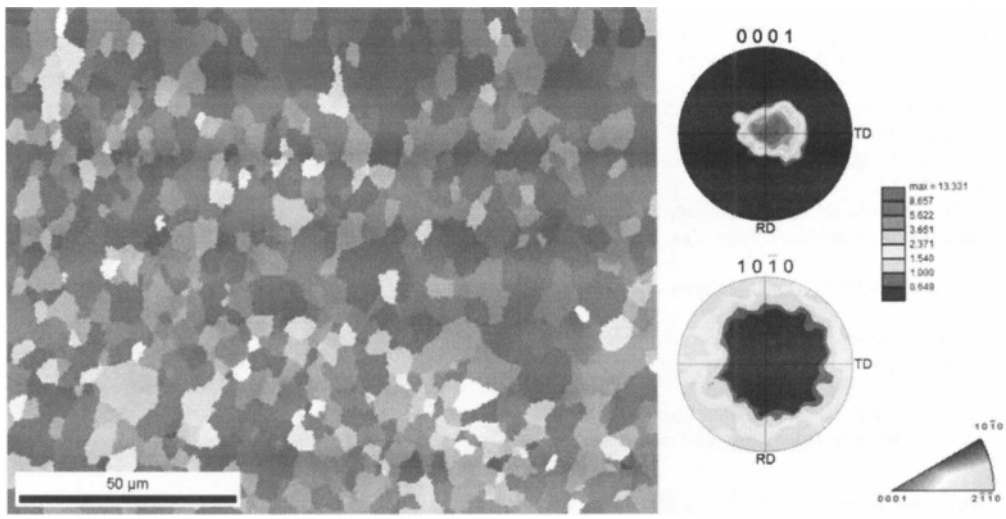

Figure 1. The initial microstructure and texture of the AZ31 rolled sheet. The texture is typical of the (0001) rod texture. The average grain size is about 8 µm.

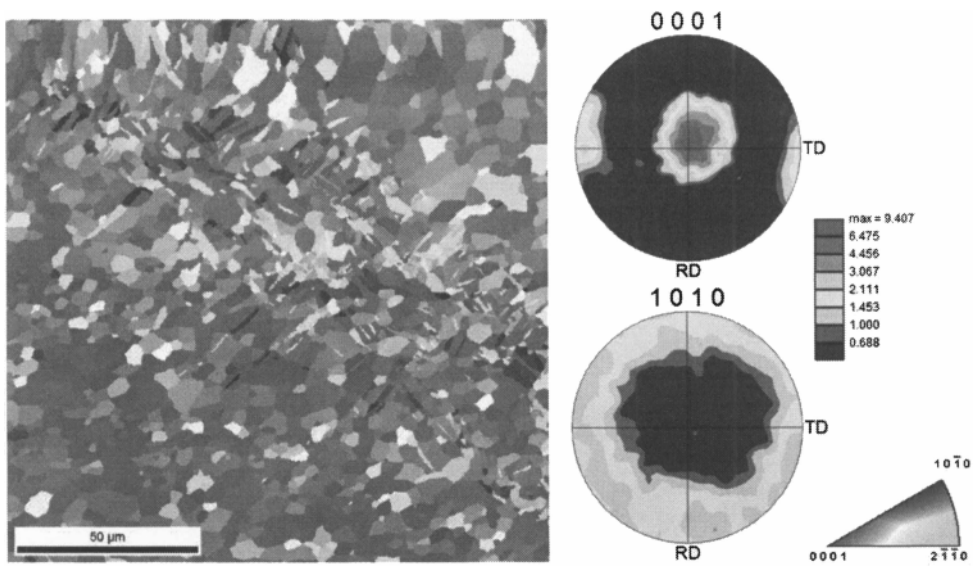

Figure 2. Electron backscatter diffraction (EBSD) shows a high density of twins in the sheet deformed in three-point bending. The twinning is highly localized. Away from the twin band, almost no twins can be observed. It can be seen from the pole figure that the twins are $\{10\bar{1}2\}<10\bar{1}\bar{1}>$ extension twins. The scan was taken near the top of the cross-section in the compression zone of the specimen.

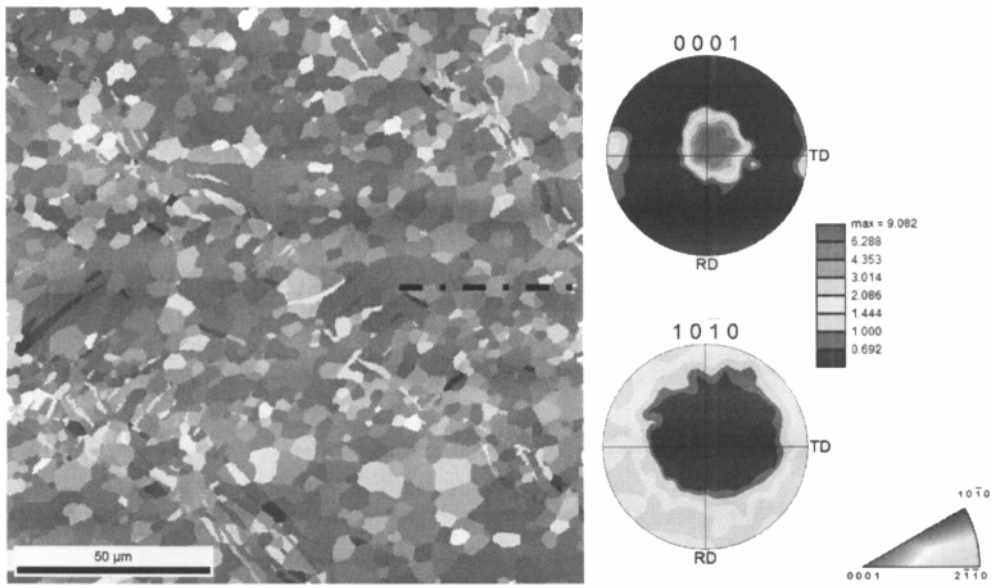

Figure 3. Multiple twin bands were observed near the geometrical center line of the specimen (indicated by a dash-dotted line in the middle). The twin bands cross the geometrical center line.

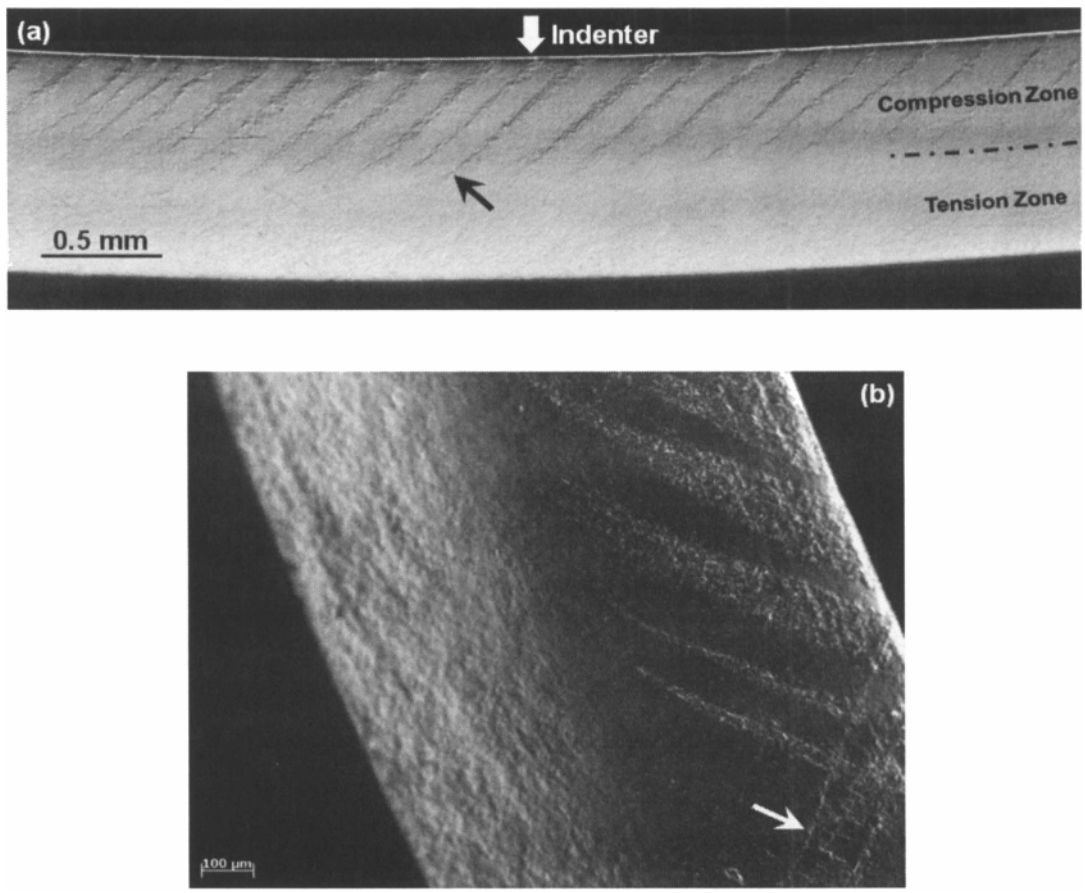

Figure 4. Through-thickness (1.0 mm) optical metallography with the differential interference contrast (DIC) illumination during three-point bending. The load remained on the specimen when the images were taken. (a) Alternating twin bands can be clearly observed. From the indenter toward both ends of the strip, the length and width of the twin bands decreases because the plastic strain decreases. The longest twin band (indicated by an arrow) passes the center line. (b) As the bending angle increases, the twin bands widen by lateral growth. Meanwhile, new bands (indicated by an arrow) that are nearly perpendicular to the original bands are formed.