Magnesium Technology 2016
Edited by: Alok Singh, Kiran Solanki, Michele V. Manuel, and Neale R. Neelameggham
TMS (The Minerals, Metals & Materials Society), 2016

NON-DISLOCATION BASED ROOM TEMPERATURE PLASTIC DEFORMATION MECHANISM IN MAGNESIUM

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Keywords: Magnesium, TEM, Twin, Basal-Prismatic interface, Unit-cell-reconstruction

Abstract

Dislocation and deformation twinning are traditionally known to be plasticity carriers of crystalline materials at room temperature. By using in-situ TEM mechanical testing technique, here we report that the plasticity of a specially orientated single crystal magnesium can be mediated neither by dislocation nor by twinning, but through a non-dislocation based process, termed as unit-cell-reconstruction. After the reconstruction, a ~7% strain is produced. The newly formed grain and its parent grain are separated by a boundary that mainly consisted of basal-prismatic interfaces. Such boundary can migrate back and forth under a cyclic loading and therefore produce a reversible plastic deformation. The reported novel mechanism may have important implications for the alloy design of magnesium.

Introduction

When external stress that is applied on the crystalline materials exceeds the so-called yield stress, plastic deformation will occur. Such process is traditionally known to be carried out through the slip of lattice dislocations or through the deformation twinning that accomplished by successively slip of twinning dislocations [1]. The dislocation slip and deformation twining produce shear strain that makes the material elongated or shorten. Both the dislocation activity and deformation twinning are restricted on a specific crystallographic plane. For dislocation slip, such plane is named as slip plane, which is usually a low index close-packed plane. For deformation twinning, such plane is named as twinning plane, which serves as the slip plane for the twinning dislocations. The twin boundary that separates the matrix volume and the twinned volume must be parallel to the twinning plane [2].

For magnesium and its alloys, the number of dislocation slip systems is limited. Only basal slip can be easily activated. Therefore, several deformation twinning modes play important role to accommodate the plastic strain. Among those twinning modes, the twinning on $\{10\bar{1}2\}$ plane is the most common one [3]. However, some unusual phenomena are difficult to understand by the above classical twinning theory based on the twinning dislocations. Examples include the deviation of twin boundaries from the twinning plane [4, 5], the easy de-twinning process and the reversibility of this twinning mode [6-8].

Recently, twinning mechanism based on non-dislocation process attracts strong research interesting [9-11]. By performing the in-situ TEM mechanical testing on micro/nano-scaled magnesium pillars or dog-bone shaped tensile samples, we reported a new plastic deformation mechanism, which is different from the traditional dislocation-based process [12, 13]. This new mechanism can be used to interpret the above unusual experimental phenomena.

Methods

A FEI Focus Ion Beam (FIB, Helios 600 Dual Beam system) was used to fabricate the tested pillar samples and dog-bone samples. The preparation of dog-bone shape sample consisted of two steps. First, a thin lamella was fabricated by a top-down ion beam. In order to minimize the taper, each side of the lamella was over-tilted by 2 more degree. Second, the lamella was shaped by ion beam from a front view to form a 'dog-bone' shape. In situ compression and tension testing was performed with a Hysitron PI-95 TEM PicoIndentor inside JEOL 2100F transmission electron microscope operating at 200 keV. All tension and compression tests were run under the displacement control mode. Figure 1 shows the experimental setup.

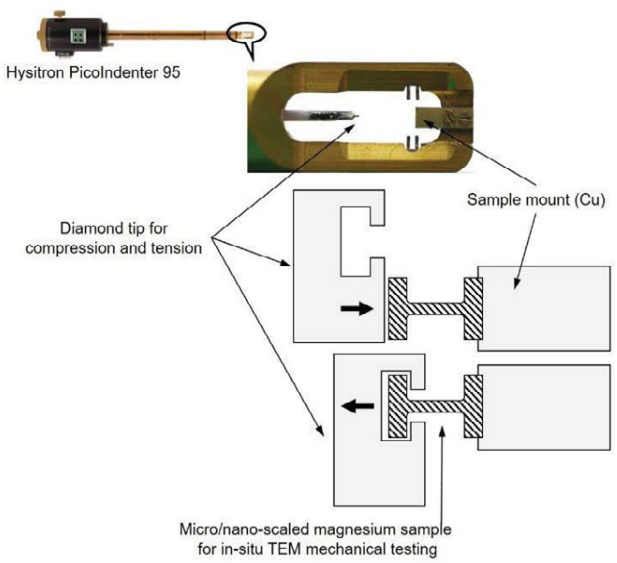

Figure 1. Experimental setup of the in-situ testing.

Results and discussions

Sixteen samples were tested, including 8 compression tests and 8 tension tests. The compression loading was along the axial direction of the pillar and the dog-bone sample, which were set to be the $[1\bar{1}00]$ orientation. The tension loading was along the axial direction of the dog-bone sample, which was set to be the $[0001]$ orientation. The electron beam was set to be along the $[11\bar{2}0]$

orientation. The geometric configurations are shown in Figure 2a and 2b.

Under the above loading condition, a new grain would be generated after the stress reached a critical value. The orientation relation between the new grain and the matrix grain was akin to that of the $\{10\bar{1}2\}$ deformation twining. The c-axis and the basal plane in the new grain are perpendicular to those in the matrix grain, respectively. However, the boundary between the new grain and the matrix grain significantly deviated from the $\{10\bar{1}2\}$ twinning plane. We defined the angle between the boundary and the loading direction as α. If the boundary is parallel to the twinning plane, it would appear to be edge-on when observed along the $[11\bar{2}0]$ orientation and α would be 43.15 degree under compression or 46.85 degree under tension. However, the measured values were in the range of 4 degree to 89 degree [12].

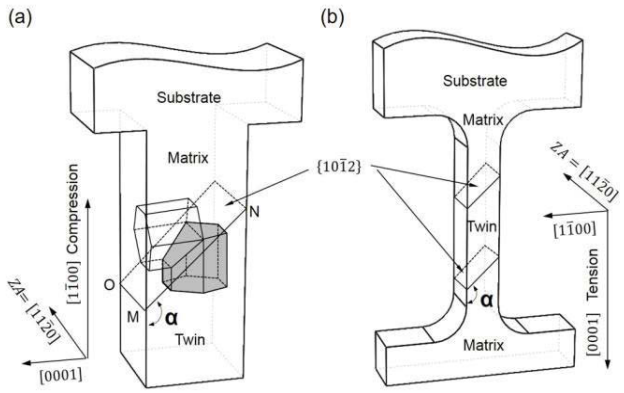

Figure 2. Loading condition and geometry configuration in pillar sample (a) and dog-bone shape sample (b).

One pillar sample was thinned down to about 100 nm by using FIB. After that, the boundary morphology between the new grain and its matrix was characterized by high resolution TEM (FEI Titan), as shown in Figure 3. The viewing direction was set to be$[11\bar{2}0]$. The basal plane in the matrix, and in the new grain, is outlined by white solid lines, as well as the orientation of the $\{10\bar{1}2\}$ plane. In Figure 3a, the boundary is almost parallel to the $\{10\bar{1}2\}$ plane. However, the boundary is fuzzy rather than a sharp line, which means the boundary is not edge-on along the observation direction. In Figure 3b, the boundary is almost perpendicular to the basal plane in matrix. Figure 3c-3e show boundaries with zigzag morphology [12]. Figure 3f shows a boundary with significant width. Fast Fourier Transformation finds that the broad boundary area is actually the overlap of the matrix and the new grain, which is the reason for the blurred boundary morphology in Figure 3a-3e. The above results point out that the boundary is not a crystallographic plane, and the boundary can possess an irregular morphology in 3D space, which is consistent with the observation in bulk experiments about the $\{10\bar{1}2\}$ twin boundaries deviating from the $\{10\bar{1}2\}$ plane in magnesium and its alloys.

In order to reveal the basic component of such boundary, Cs-corrected imaging was performed (ARM200F) under STEM mode. Figure 4a shows one typical example. The viewing direction was set to be$[11\bar{2}0]$. The new grain and its matrix are bonded by several steps. Part of the interface is parallel to the basal plane in new grain and the prismatic plane in matrix, while the other part is parallel to the basal plane in matrix and the prismatic plane in new grain. Therefore, such interfaces are termed basal-prismatic (BP) interfaces.

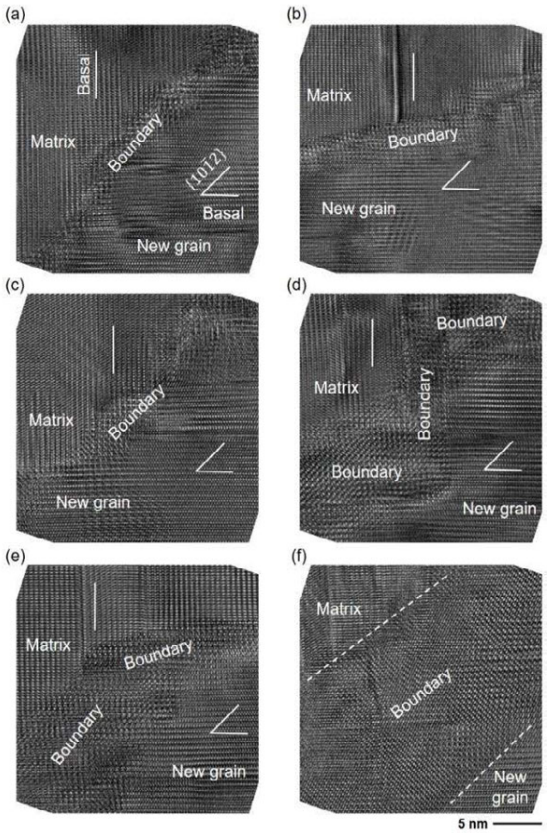

Figure 3. High resolution TEM images of the boundary. The basal plane in matrix and new grain, and the $\{10\bar{1}2\}$ plane are outlined by white solid lines.

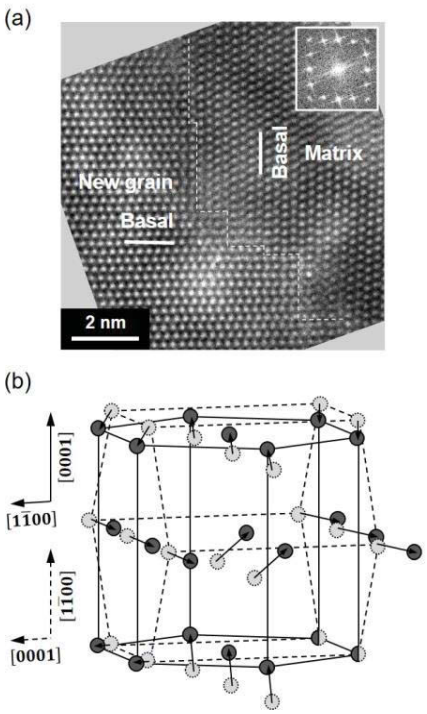

Figure 4. (a) Atomic scale image showing the basal-prismatic interface. (b) One possible route for the unit-cell-reconstruction. The matrix HCP cell is outlined by dashed lines, while the new HCP cell is outlined by solid lines [12, 13].

The BP interfaces can migrate through the conversion of basal plane and prismatic plane. One possible route is shown in Figure 4b [13]. Light gray spheres with dashed circles represent atoms in matrix. Dashed lines connecting those atoms form the original HCP structure. Dark gray spheres with solid circles represent atoms in new grain. Solid lines connecting those atoms form the new HCP structure. The original HCP cell can become the new HCP cell merely by the local movement of atoms, without involving dislocation activities. Therefore, such local atomic rearrangement is termed unit-cell-reconstruction. After such lattice reconstruction, the new basal plane is parallel to the original prismatic plane, and the new prismatic plane is parallel to the original basal plane. As a result, BP interfaces are created.

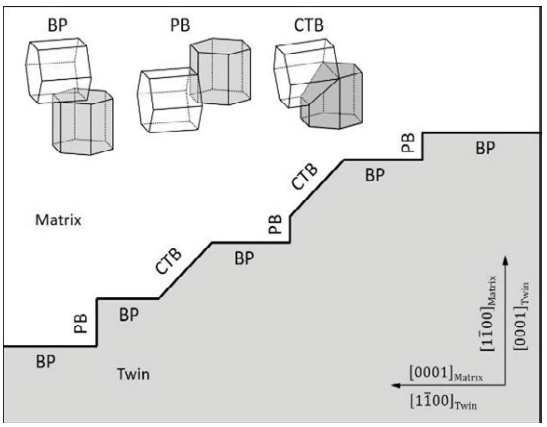

Figure 5. Schematic illustration showing a boundary consisting of segments of BP interfaces and coherent twin boundaries.

Note that the BP and PB interfaces are perpendicular to each other, Therefore, they can compose a boundary with arbitrary morphology in 3D space, as schematically shown in Figure 5.

During cyclic loading, such a BP boundary can migrate back and forth. The migration speed of the boundary is found to be closely related to the loading stress and the crystal structure, which will be discussed in detail elsewhere.

Summary

The newly found plastic deformation mechanism, unit-cell-reconstruction, is different from the dislocation slip and deformation twinning. First of all, it is the local atom rearrangement that dominates the plastic deformation instead of the gliding of lattice dislocations or twinning dislocations. Second, the boundary that separates the new grain and its matrix grain is not a crystallographic mirror plane. Third, both dislocation slip and deformation twinning produce shear strain, while the unit-cell-reconstruction doesn't have to involve shear strain. Details regarding the mechanical response of unit-cell-reconstruction will be discussed in future.

Acknowledgements

The authors acknowledge the support provided by grants from NSFC (50925104, 11132006, 51231005, 51201127 and 51321003), 973 Program of China (2010CB631003), and the support from the 111 Project of China (B06025). We also thank Dr. Jian Wang, Dr. Bin Li, and Dr. Ju Li for discussion. The authors declare no competing financial interests.

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