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Three-dimensional effects of twinning in magnesium alloys

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This article provides experimental evidence on the pronounced three-dimensional surface effects caused by tension twinning at early stages of plasticity of a magnesium alloy. To achieve this goal, multiscale mechanical testing was combined with strain field, texture and surface morphology quantification. The current investigation correlates crystallography-driven, grain-scale surface roughening to the spatially heterogeneous micro- and macrostrain. It was found that tension twinning causes considerable surface extrusions and intrusions across multiple grains that are directly related to severe strain inhomogeneities.

Keywords: Twinning; Surface step; Strain localization; Digital image correlation (DIC); Local plasticity

Understanding twinning, including nucleation of different variants, their growth and interactions with other deformation modes, is a topic of increasing interest for hexagonal close-packed (hcp) alloys due to its role in plasticity [1]. Because of its relatively easy activation, much attention has been paid to $\{10\bar{1}2\}$ tension twinning [2–5]. Thompson and Millard [6] and Yang et al. [7] performed experimental analyses on cadmium and titanium respectively, based on which they suggested that lenticular twins resulted in step formations between two $\{10\bar{1}2\}$ lattice planes at the twin boundary. Furthermore, recent studies based on molecular dynamics simulations and electron backscattered diffraction (EBSD) data provided further evidence on twin nucleation [1,8–10]. The statistical analysis of twin nucleation presented by Beyerlein et al. [1] indicated that grain boundary misorientations influence twin nucleation and growth. It has also been proposed that the stress states in the vicinity of grain boundaries dictate the prevalence of specific twin variants [11].

In addition to the considerable effect of twinning on ductility [12,13], a study by Kocks and Westlake [14] and another by Hutchinson [15] suggested that the ductility of polycrystalline hcp metals is affected by local strain variations in neighboring grains. While boundaries clearly cause heterogeneous strain in adjoining crystals, it is not clear how this strain affects the cohesive properties of the grain boundary, because a strongly cohesive boundary may force heterogeneous strain in an adjacent grain to maintain compatibility. The local high strain concentration may therefore cause microcracks [16]. It has also been suggested that twinning is associated with crack formation at later stages of deformation [17–19]. Therefore, besides some of the known sources of crack initiation, such as surface roughness, inclusions, intermetallic and ductile/brittle phases [20], twinning, slip and strain inhomogeneities at the grain scale can be also envisioned as other sources of crack incubation and initiation [21]. In agreement with Muránsky et al. [22] and Barnett et al. [23], the authors recently demonstrated [24] that the onset of the distinct plateau region in the stress–strain curve during compressive loading perpendicular to the c-axis is associated with profuse and spatially inhomogeneous twinning. We recently showed that, although tension twinning could further give rise to crack initiation towards the end of the fatigue life in Mg alloys [25].

Similar to the earlier study by Vaidya and Mahajan [26], in which evidence of slip on $\{11\bar{2}1\}$ planes prior to twinning was reported, Koike et al. [3] demonstrated that twinning occurs in grains with high basal dislocation activity. Therefore, as Hull [18] and more recently Ando et al. [17] suggested that localized strain inhomogeneities resulting from the activation of slip can presumably be relieved by twinning. It is also plausible that stress concentrations due to incompatibilities between twins and their surrounding matrix regions can be relaxed by slip [17,26] or crack formation [12].

In order to explain the relationship between grain-scale microstructural changes and deformation in alloys, a number of recent investigations relied on the use of the digital image correlation (DIC) method [27–33]. Carroll et al. [32] combined ex situ texture measurements with

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high-resolution strain field mapping obtained by DIC to explain strain localizations near grain boundaries. Furthermore, Dave et al. coupled incremental straining of nickel foils with optical microscopy and showed the effect of grain boundaries and orientation mismatches on localized strain distributions [30].

In this letter, full-field deformation measurements in Mg alloys were first performed at the grain scale. A cube-shaped specimen consisting of grains with most of their *c*-axis perpendicular to the loading direction was prepared from a commercial AZ31 plate. A region of interest (ROI) of 1 mm^2 size was defined by using fiducial markers created by micro-hardness indentations. The sample was loaded utilizing an MTI/Fullam (SEMaster 1000 EBSD) stage at a compressive displacement rate of 0.5 $\mathrm{mm\ min^{-1}}$ up to about 2% overall strain. An optical microscope (Olympus BH-2) was fixed at 10 × magnification to record image sequences during loading. The images were recorded by a 10 megapixel camera with a 25 Hz acquisition rate. The gray intensity (contrast) field captured by the camera was created by the alloy microstructure without any additional surface patterning. Two-dimensional deformation measurements were performed in a field of view of $900 \times 675\ \mu\mathrm{m}^2$, which resulted in a maximum spatial resolution for deformation measurements of 11.25 $\mu\mathrm{m\ pixel^{-1}}$. The recorded digital images were post-processed using the commercially available ARAMIS GOM software (v6.30-4). A smaller ROI of $196 \times 239\ \mu\mathrm{m}^2$ at a specific location was analyzed to compute more accurate full-field and point strains. The surface morphology was inspected post-mortem by non-contact white light interferometry using a Zygo surface profilometer (model 6300) at 20× magnification. A lateral resolution of 750 nm and a vertical resolution of 0.1 nm were achieved. Note that, the orientation and topography for the deformed samples were performed without any further polishing or etching.

To validate the surface morphology observations at the grain scale, compression tests on cylindrical specimens of (ASTM) standard dimensions were also performed. The samples were flattened on one side to allow post-mortem microstructure analyses and then mechanically compressed with a strain rate of $4.5 \times 10^{-4}\ \mathrm{s}^{-1}$. Prior testing, the specimens were subjected to the polishing procedure described previously [34]. Fiducial markers on the polished surface were produced by microhardness indentation. The surface morphology in the ROI ($250 \times 250\ \mu\mathrm{m}^2$) was quantified using the interferometry method used for the grain-scale tests. Full-field strain fields were measured using DIC. The full-field strain measurement setup was capable of resolving strains with an accuracy of $\pm$ 150 $\mu\mathrm{m\ m^{-1}}$ and a resolution of 20 $\mu\mathrm{m\ pixel^{-1}}$.

Figure 1(a) shows twin nucleation and growth observed in situ by the optical microscope on the grain-scale specimen subjected to compression. Figure 1(b) displays the corresponding full-field strain evolution parallel to the loading direction, marked as global strain. Figure 1(c) plots the average global strain as a function of time. It also presents point-to-point measured strain values across the twin region highlighted in Figure 1a and b. This measurement shows how the local strain field within a grain develops as a result of twinning. The measured local and global strains demonstrate that, while the sample undergoes compression (see the black line in Fig. (1)c), favorable grains (G1 and G2) for twinning, according at least to the reported high Schmid factor (SF) criterion [35], display large tensile strains exactly at twin locations. It has been proposed by the authors [34] that strain localizations associated with twinning first initiate at grains with larger SF values [36,37].

Although the theoretical maximum tensile strain caused by twinning in Mg single crystal has been reported to be 6.5% [38], the current results provide locally considerably larger values which are suspected to be related to 3-D surface effects of twinning. It is known that out-of-plane motion directly affects any 2-D (in-plane) strain measurements. This was verified in Figure 1(e), which shows examples of pronounced surface morphology changes (differences in height are represented by a color bar in micrometers)

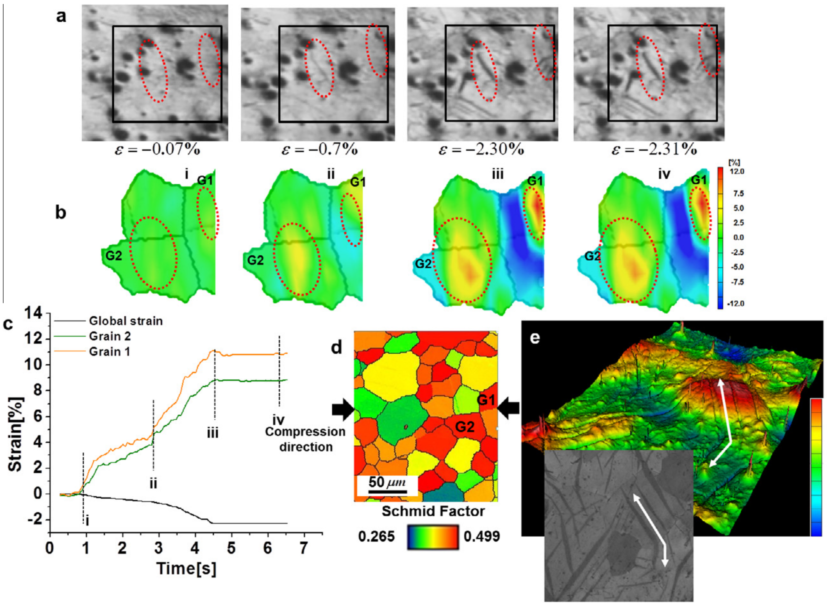

Figure 1. (a) Optical microscope images of twin nucleation and growth obtained in situ. (b) Full-field strain maps obtained by DIC with overlaid grain structure. (c) Local (for two different grains) and global (average) strain evolution in time. (d) Measured SF values in the ROI. (e) 3-D views of the surface contour displaying grain-scale extrusions and intrusions, and their close relationship to twinning.