Texture-dependent character of strain heterogeneity in a Magnesium AZ31 under reversed loading

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Abstract

Depending on operational micromechanisms and crystallographic texture, the innate strain localization at microstructural length scales of a polycrystal can spatially coordinate to induce macroscopic strain localization. A challenge for material performance and modeling, this behavior is observed in wrought Magnesium alloys when they deform with heavy tensile twinning. With in-situ, multi-surface image correlation, a compression-tension experiment is implemented on samples with extrusion and rolling texture that have a consistent 11 $\mu$m grain size. While samples of both textures exhibit a clear twin plateau with close stress levels (90/99 MPa for rolled/extruded samples), the strain localization patterns are vastly different, both in terms of geometric structure and intensity. Rolled sample exhibits sharp shear banding structures with a fixed plane of shear. Extruded sample exhibits strain localization that is not in macroscopic $\pm 45^\circ$ shear form and much weaker in intensity (by about a factor of 2). Once the load is reversed and the tensile twin is deactivated, strain accommodation largely homogenizes for both textures during detwinning and subsequent high hardening stages.

\textit{Keywords:} strain measurement, magnesium alloys, twinning, strain heterogeneity, shear banding

1. Introduction

The mechanical behavior of textured Magnesium alloys exhibit a very high level of dependence on the loading path \([1] [2] [3]\). Consequently, highly-distorted stress strain loops result when extruded or rolled components are put under cyclic loading\([4] [5] [6]\). The primary factor underlying this behavior is the profuse activation of deformation twinning in these hexagonal-close-packed (HCP)
materials. Unlike dislocation slip, twinning mechanisms exhibit unipolar activation: If one load path activates a twinning mechanism, loading in the reversed path will not.

Fueled by a drive to employ the low density Magnesium alloys in structural applications, their compound micromechanical behavior that employs multiple slip and twin mechanisms has been studied heavily [7]. With a focus on understanding the abrupt twinning phenomenon, monotonic loading experiments typically employ a texture and load path combination that favors twin activation. In these, twin inception and growth is the dominant mode of deformation typified with a twin plateau on the stress-strain curve. The wide array of accompanying observation techniques include neutron diffraction (ND) [8, 9, 10], high-energy x-ray diffraction (HEXRD) [11, 12], electron microscopy [13, 14, 15], acoustic emission (AE) [2] and digital image correlation (DIC) [16, 17]. When the load is reversed after threading on the twin plateau, strain in the opposite direction is accommodated near immediately by detwinning. Only after exhausting this mode, the material exhibits significant hardening. Micromechanism transitions across the segments of the reversed loading path is investigated in the extensive cyclic/reversed loading literature of textured Magnesium alloys (ND [18, 19, 20, 21], AE [2], ND-AE [22], SEM [23, 24], TEM [25], optical microscopy [26, 27]).

Guided particularly by neutron diffraction, polycrystalline models that consider plasticity [8, 9, 10, 21] as a combination of slip and twinning activity have been posed. These models factor in crystallographic texture but, presuming various forms of strain regularity, are not built to predict the spatial progression of deformation. On the other hand, the degree of strain heterogeneity in the actual deformation patterns is a key issue regarding formability and failure. While strain localization is innate at microstructural length scales of a deformed polycrystalline aggregate [28], the physical issue associated with strain heterogeneity deepens if the microscopic deformation structures spatially coordinate and lead to strain localization at the macroscopic length scale. At this point, the models are also severely challenged, as fundamental assumptions like the existence of a representative volume element come into question. As for Magnesium alloys, the tensile twin becomes the focal point of attention in this regard as well, since it has been shown by, e.g, Beyerlein et al. [14], Barnett et al. [29] and Wang et al. [13], that it operates with pronounced local coordination.

Using multi-scale, in-situ DIC, Aydiner and Telemez [16] presented precisely that rolled Magnesium AZ31 deformed via sharp macroscopic shear-banding over the twin plateau and the bands
were manifested by coordinated twinning events. The macroscopic bands were were extruded \( \pm 45^\circ \) cross-patterns that go through the entire sample. The fixed orientation of these bands approximately conformed to the cross-pattern of the two highest resolved-shear-stress \( \{10\overline{1}2\}\{\overline{1}011\} \) tensile twin variants inside the abundant crystallite orientation. The nature of the rolling texture, characterized by the preferential alignment of c-axes, is clearly crucial for this single-crystal-like deformation pattern.

The present in-situ DIC study explores the relations between strain heterogeneity, active micro-mechanisms and texture by expanding the findings of Aydıner and Telemez [16] in two primary directions. First, the effect of texture is explored comparatively by considering both main wrought Magnesium textures: extrusion and rolling. The extrusion texture is deemed similar to the rolling texture since, again, twin-dominated deformation can be realized by applying compression normal to c-axis of the preferred orientations. It has a distinct character, however, with the axisymmetric distribution of c-axes. Secondly, with a developed setup, samples of both textures are reverse loaded after traversing over the twin plateau, thereby exploring the effect of deactivating the tensile twin. Deformation patterns in the detwinning zone as well as high-hardening region that follows are presented. For a contained treatise, attention is limited to large-scale coordination of deformation structures.

2. Materials and Methods

Rolled and extruded bulk materials of Magnesium AZ31 were received in the form of 100 × 50 × 9.5mm\(^3\) hot rolled plate and a hot extruded rod with 20 mm diameter and 500 mm length, respectively. Average grain sizes are intentionally consistent, determined to be \( \sim 11 \mu m \) for both. Textures were evaluated with x-ray data from a Panalytical X-Pert Pro MPD four-circle diffractometer analysed with MTEX [30] software. \((0001)\) pole figures shown in Fig. [1]a confirm the typical preferred orientations: c-axes are aligned with ND for the rolled plate (RD/TD/ND stand for rolling/transverse/normal directions); c-axes are axis-symmetrically distributed normal to extrusion direction (ED) for the rod. The extrusion texture naturally has fiber symmetry about the drawing axis and the rolling texture exhibits near fiber symmetry about ND.

Dog bone samples are designed with a hefty square cross-section (3x3 mm\(^2\) nominal) relative to their 8 mm gage length to impede buckling (Fig[1]b)). They are cut out from the bulk material.
with wire EDM. For the rolled sample, the load axis is set to be aligned with RD; top(side) DIC observation surfaces are perpendicular to TD (ND). The extruded sample has been cut with its loading axis aligned with ED. Rolled (extruded) sample is henceforth designated ‘RD sample’ (‘ED sample’) to stand for the exact description ‘rolled sample uniaxially loaded in RD’ (‘extruded sample uniaxially loaded ED’).

A small form-factor Kammrath&Weiss load frame, with grips and structure specialized for reversed loading, is utilized. Load is applied incrementally in displacement control. At each load point, images of top and side surfaces are recorded with an AVT Pike F505B camera with a 5 Megapixel CCD, fitted with an Edmund Optics 0.5x telecentric lens (working distance 110 mm, depth of field 2 mm, optical resolution 6.8 \(\mu m/pixel\)). The lens looks down on the horizontally placed load frame directly recording the top surface images. The images from the side surface are recorded with the help of a 45° mirror shown in Fig. 1(b). The top surface DIC field contains the entire 8 mm gage section whereas side surface images spot a \(~5\) mm range due to geometric constraints (Fig. 1(b)). A computer-controlled Z-stage under the load frame makes the working distance adjustment switching back and forth between top surface and mirror imaging. DIC strain error due to small variations in lens-object distance is eliminated since the utilized telecentric lens inherently maintains magnification.

In the DIC technique, deformed images of the sample surface are compared with the undeformed reference to yield deformation maps [31]. Here, displacements are determined over regularly-spaced grids with 15 pixel (0.1 mm) spacing using first-order subsets. Reported strain and infinitesimal
rotation components are obtained by numerical differentiation of the displacement results \( u, v, w \) (along \( x, y, z \) as defined over Fig. 1(b).) with the central difference formula over the DIC grid

\[
\varepsilon_{yy} = \frac{\partial v}{\partial y}, \quad \varepsilon_{xx} = \frac{\partial u}{\partial x}, \quad \omega_{xy} = \frac{1}{2} \left( \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} \right), \quad \varepsilon_{zz} = \frac{\partial w}{\partial z}.
\] (1)

Here, one notes that \( \varepsilon_{xx} \) and \( \varepsilon_{zz} \) are the lateral strains exclusively measured on top and side surfaces, respectively, and \( \omega_{xy} \) is the small rotation tensor component measured on the top surface.

Further details of DIC implementation are provided elsewhere [16].

3. Results

3.1. Average behavior

Figure 2(a) and (b) show the stress-strain graphs of RD and ED samples, respectively. Mean strain, \( \varepsilon_m \), is the average of the \( \varepsilon_{yy} \) field measured on the top surface; \( \sigma \) is the engineering stress.

![Figure 2](image-url)

**Figure 2**: Macroscopic stress-strain curves for (a) rolled sample, (b) extruded sample. TP, DR and HHR stand for ‘twin plateau’, ‘detwinning ramp’ and ‘high-hardening ramp’, respectively.

The implemented load cycle starts with compression, straining the samples to \( \varepsilon_m \approx -2\% \). This is followed by reverse loading in tension. The micro-mechanistic nature of the resulting highly distorted loops in Fig. 2 is well established in literature [2, 7]. Accordingly, the three distinct regions in the cycle are designated ‘twin plateau’, ‘detwinning ramp’ and ‘high-hardening ramp’. Samples exhibited abrupt advances in strain both in the twin plateau and the detwinning ramp. Mean and standard deviation, \( \delta \varepsilon_{yy} \), of the top-surface \( \varepsilon_{yy} \)-fields are provided in Table II for marked points a-i on the stress-strain curves. \( \delta \varepsilon_{yy} \) is intended as a raw measure of strain heterogeneity.
Table 1: Mean value, $\varepsilon_m$, and standard deviation, $\delta\varepsilon_{yy}$, of axial strains over all selected load points a-i.

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<th>Rolled (RD) sample</th>
<th>Extruded (ED) sample</th>
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<tr>
<td>load</td>
<td>$\varepsilon_m$</td>
<td>$\delta\varepsilon_{yy}$</td>
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<tr>
<td>a</td>
<td>-0.43</td>
<td>0.47</td>
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<tr>
<td>b</td>
<td>-0.72</td>
<td>0.70</td>
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<td>c</td>
<td>-0.85</td>
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<td>d</td>
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<tr>
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<tr>
<td>g</td>
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<td>0.42</td>
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<tr>
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<td>0.13</td>
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<tr>
<td>i</td>
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<td>0.09</td>
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3.2. Deformation fields

Deformation patterns and the corresponding strain heterogeneity levels are presented with contour plots in Fig. 3. Parts (a) and (b) present plots for RD and ED samples, respectively, for five variables: axial and lateral strains on the top surface ($\varepsilon_{yy}$, $\varepsilon_{xx}$), infinitesimal rotation component on the top surface ($\omega_{xy}$), and axial and lateral strains on the side surface ($\varepsilon_{yy}$, $\varepsilon_{zz}$). Rows a-i correspond to the load points of interest marked in Figure 2.

The utilization of red tones for positive and blue tones for negative values (colorbar, Fig. 3) is purposeful, adopted from [16]. As this reference discusses thoroughly with caveats, this scheme allows $\omega_{xy}$ contours to distinguish individual $+45^\circ$ and $-45^\circ$ simple shear bands by color ($+45^\circ$ red and $-45^\circ$ blue). Figure 3(c) outlines the principle that, while the associated strains are equivalent, material rotation senses are opposite for $+45^\circ$ and $-45^\circ$ simple shear processes. Further, in this ideal picture, $\omega_{xy}$ matches in-plane principal strains ($\varepsilon_{yy} = -\varepsilon_{xx}$; principals aligned with x-y axes here) in magnitude. Clearly, $\omega_{xy}$ is descriptive in this manner only if (i) individual simple shear processes are at the length scale of the measurement and (ii) the observation surface matches the plane of shear.

On the twin plateau of the RD sample [rows a-e, Fig. 3(a)], strain indeed gets accommodated with such (macroscopic) shear processes that exhibit abrupt formation and expansion. $\omega_{xy}$ column shows the first $+45^\circ$ (red) shear band formed at load point a. It is complemented with an opposite
Figure 3: Deformation maps on top (axial strain, lateral strain, infinitesimal rotation) and side (axial strain, lateral strain) surfaces for (a) the rolled sample, (b) the extruded sample at selected load points a-i in the compression-tension cycle; (c) description of ideal ±45° simple shear bands on the x-y plane.
sense $-45^\circ$ (blue) band as the sample is further compressed to point $b$. The side surface, on the other hand, shows horizontal streaks of strain localization whose span matches the shear bands on the top surface. ( "△, ▽" marks corner intersections the $+45^\circ$ band on Fig. 3(a). Due to its more limited span of observation, some (sections of) bands do not register on the side, e.g., the $-45^\circ$ band at point $b$.) The implication is that these $\pm 45^\circ$ bands are actually not surface phenomena limited to the top surface, but volumetric bands that run across the sample (supporting detail and evidence in [16]).

By load point $e$ at the end of the twin plateau, the three bands that exhibited distinct formation (the last one forming at $-45^\circ$ orientation at load point $c$) expanded to cover most of the gauge section [Fig. 3(a), row $e$]. These are still individual shear bands at the macroscopic length scale, as evidenced by the rotation-$\omega_{xy}$ largely reflecting strain magnitudes and distribution. The only exception to this is discerned in the area indicated with a dashed circle where rotation no longer depicts deformation in any sense. Here, as opposite sense shear bands intersect, characteristically, strains add up but rotations cancel.

The first points considered after reversing the load are $f, g$ on the detwinning ramp (Fig. 2(a)). Comparing consecutive deformation patterns $e-f$ and $f-g$, it is observed that positive strain increments are accommodated by relieving the strain content of the shear bands; i.e., the regions outside the shear bands at point $e$ remain plastically dormant in the detwinning region. Since the bands were manifested by twinning events, it stands to reason that detwinning operates on the same regions. A less obvious observation is that, while shear bands formed and expanded with cascaded activity over limited regions, the strain reversal has a rather homogenous nature and occurs simultaneously over all banded structures. By load point $h$ ($\varepsilon^h_m = 0.13\%; \delta \varepsilon^h_{yy} = 0.07\%$), all localization bands are recovered completely. This point approximately marks the end of the detwinning ramp and it is located just past the $\varepsilon_m = 0$ axis in Fig. 2(a).

Over the near null background of point $h$, a tensile strain increment in the high hardening region leads to point $i$ (Fig. 3(a)). This strain is accommodated by the entire gauge section and any strain localization is unpronounced, contrasting the strictly structured bands on the twin plateau. In statistical terms, $\delta \varepsilon_{yy}^i = 0.09\%$ hardly developed over the point-$h$ value and is significantly below the mean $\varepsilon^i_m = 0.6\%$. In comparison, at points $a, b$ of the twin plateau, $\delta \varepsilon_{yy}$ is as large as the mean values $|\varepsilon_m^a| = 0.43, |\varepsilon_m^b| = 0.72\%$. (Though $\delta \varepsilon_{yy}$ is intended for rough order comparisons; its
utilization requires to note: (i) $\delta \varepsilon_{yy}$ tending to scale with the mean around $a$, $b$ is related to the nature of the statistical strain distribution that is composed of distinct populations; (ii) $\delta \varepsilon_{yy}/|\varepsilon_{yy}|$ shows a decrease towards point $e$ as bands progressively cover the gauge section, comparatively homogenizing the deformation.)

For the ED sample (Fig. 3(b)), the deformation on the twin plateau also initiates with a banded strain localization at point $a$. $\varepsilon^a_m \simeq -0.4\%$, consistent with the point-$a$ value of the RD sample. The localization band of the ED sample, however, is noticeably more disperse and, consistently, lower strain-intensity. To quantify, $\varepsilon_{yy}$ is averaged exclusively over the bands (indicated with dashed lines in Fig. 3 row a). The resulting localization strain is -1.44% for the RD sample and only -0.65% for the ED sample. The disperse formation of the band in the ED sample also implies a more rapid strain homogenization. By point $d$, the band in the ED sample expands to cover the entire gauge section and, unlike the RD sample, no stand-alone macroscopic band structures are noted. Lower strain heterogeneity levels of the ED sample also reflect in the $\delta \varepsilon_{yy}$ values. For all points $a$-$e$, the $\delta \varepsilon_{yy}/|\varepsilon_{yy}|$ values are less than half the RD sample counterparts (Table 1).

In the following detwinning and high-hardening regions, the strain heterogeneity level of the ED sample becomes akin to the RD sample. Detwinning (points $f,g$) occurs simultaneously over the entire section and yields a near strain-free deformation landscape at point $h$. The standard deviation value is in fact equivalent to RD sample, $\delta \varepsilon^h_{yy} = 0.07\%$. Stepping into the high-hardening region, the tensile strain at point $i$ ($\varepsilon^i_m = 0.84\%$) is borne by the entire gauge section with a low $\delta \varepsilon^i_{yy} = 0.11\%$. The similarity in strain heterogeneity levels is despite a noticeable difference in hardening levels particularly during the detwinning stage. $\sigma^h =108$ MPa for the ED sample, 30% higher than the corresponding value (80 MPa) for the RD sample. So, while macroscopic strain localization structures are recovered to the same degree at point $h$ for both samples; this state requires a significantly higher stress level for the ED sample.

4. Discussion

Deduced from the disparity between the deformation of RD and ED samples, texture dependence of strain heterogeneity is clearly more pronounced when twinning is dominant (points $a$-$e$). To elaborate, Fig. 4 plots the effective Poisson’s ratios over top and side surfaces, defined as $\nu_{yx} = -\varepsilon_{xx}/\varepsilon_{yy}$ and $\nu_{yz} = -\varepsilon_{zz}/\varepsilon_{yy}$. For the RD sample, as the simple shear bands cover more
of the sample volume, $\nu_{yx}$ progressively tends to 1 while $\nu_{yz}$ tends to 0 [16], revealing extreme 
plastic anisotropy. (Incidentally, $\nu_{yx} + \nu_{yz} = 1$ implies zero volumetric strain.) These values of 
course conform to $\pm 45^\circ$ processes of Fig. 3(c), whose plane of shear is exclusively confined to the 
x-y plane ($\varepsilon_{yy} = -\varepsilon_{xx} \implies \nu_{yx} = 1$).

![Figure 4: Effective Poisson’s ratio on top ($\nu_{yx}$) and side ($\nu_{yz}$) surfaces of (a) the rolled (RD) sample, (b) the 
extruded (ED) sample.](image)

The ED sample, in contrast, is expected to exhibit transverse isotropy about its load axis just by 
its texture—a consideration that largely motivated this study. In particular, $\nu_{yx} = \nu_{yz}$ is implied. 
With plasticity, $\nu_{yx}, \nu_{yz}$ should exhibit the characteristic rise from an elastic region value ($\sim 0.3$) 
towards the volume-preserving 0.5 (again, $\nu_{yx} + \nu_{yz} = 1$). Experimental $\nu_{yx}, \nu_{yz}$ curves of the 
ED sample (Fig. 4) reveal only a limited difference from this ideal assessment. (Exact transverse 
isotropy would mean horizontal localization bands and zero rotation fields on both observation 
surfaces. Rows a-c of Fig. 3(b), however, show the band developing with an angle on the top rather 
than the side and a measure of rotation $\omega_{xy}$ accompanies the band. These imply an excess of shear 
activity in the xy-plane over yz. A higher slope of $\nu_{yx}$ in Fig. 4 up to point c seems to be due to 
this anisotropy effect; it subsides afterwards with opposite sense shear activity.) However, sample-
specific details of this difference—presumably due to texture and loading imperfections combined 
with the stochastic nature of strain localization—should not deter from the overall conclusion: ED 
data in Fig. 4 reveals near transverse isotropy in the twinning plateau, with an obvious contrast 
to the compared RD $\nu$-curves.

This vast difference is not evident in the stress-strain curves of RD and ED samples (Fig. 2): 
both exhibit twin plateaus whose stress levels are within 10% of each other. Its interpretation is
rather in the geometry of the intergranular coordination of twinning: While twinning in the RD-sample can coordinate in sharp two-dimensional deformation patterns, the ED sample has to adopt three-dimensional networks. Note the macroscopic strain localization is not evaded but reduced in the ED sample. Quantified over the initial (yet unmingled) bands, RD-sample bands are more intense than those of the ED sample by a factor about 2. The implication that the intergranular coordination of the twinning events is stronger for the tighter set of grain orientations in the rolling texture is consistent with studies of twin transmission (high strain compatibility factor [29, 13], low misorientation [14]).

Besides texture, the other major factor underlying strain localization is the existence of a localizing micro-mechanism. In generic terms for the tensile twin, the probability of further twinning is increased about the site of a twin occurrence. (Slip mechanisms typically cause self-hardening at their site which increases the probability of remote occurrence, favoring strain homogeneity.) Indeed, we show that once the load is reversed and \{10\bar{1}2\}⟨1011⟩ twin deactivates, macroscopic strain heterogeneity levels decline even for the sharper rolling texture. The interpretation of this observation would be more straightforward if slip-dominant deformation follows the load reversal immediately. However, reversal of the twin-transformation zones (detwinning) precedes the slip-dominant deformation at the high-hardening region. Interestingly, we find that detwinning operation is largely homogeneous as well, though temporally, the sample exhibits abrupt jumps of strain accommodation—a trait shared with the twin plateau deformation.

The one clear difference in the detwining stage of the ED sample compared to the RD sample, namely, 30% higher hardening, might be reasoned in the light of the aforementioned geometry of strain accommodation in the twin plateau: The three-dimensional twin networks and collaborating slip structures are likely harder to untangle. The ED sample, while requiring an higher stress to do so, still achieves the same level of recovery in the strain fields as the RD sample (recall equivalent $\delta e^h_{yy} = 0.07\%$). This corroborates that, till the onset of the high-hardening region, twinning-detwinning processes dominate the overall strain accommodation to a similar degree in both samples. Of course, to reiterate, the primary difference between them surfaced in the geometric arrangement of the formed-and-reversed deformation patterns.
5. Conclusion

A quantitative study on texture and micro-mechanism connections of macroscopic strain localization in wrought Magnesium alloys is performed. These materials possess the two characteristics that promote heterogeneous strain accommodation at the macroscopic length scale: (i) a micro-mechanism that favors locally-coordinated activation, in this case, the tensile twin, (ii) sharp crystallographic textures. Texture is parameterized over both major cases: rolling and extrusion, and the effect of micro-mechanisms are studied by reverse loading, thereby deactivating the tensile twin. In situ DIC is implemented on both orthogonal faces of the sample, allowing a volumetric identification of the texture-dependent structure of strain localization (summarized in Figure 4).

The article has two major results:

1) While samples of both textures exhibit a clear twin plateau with close stress levels, the type of strain localization is vastly different, both in terms of geometric structure and intensity. Rolled sample exhibits sharp shear banding structures with a fixed plane of shear. Extruded sample exhibits strain localization that is not in macroscopic shear form and much weaker in intensity (by about a factor of 2).

2) Once the load is reversed and the tensile twin is deactivated, strain accommodation proceeds relatively homogeneously for both textures. This might be expected if predominant strain accommodation directly switched to slip. But, we show the interesting result that detwinning also proceeds rather homogeneously.

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