Postprint: Twinning Behavior of AZ31 Magnesium Alloy During Plane Strain Compression

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Date: 2023-03-19T00:00:00+00:00

Abstract

The twinning behavior of AZ31 magnesium alloy during plane strain compression was investigated using the EBSD technique. The results indicate that when the compression direction is TD and the constraint direction is RD, the twinning type is predominantly {1012} extension twins, and the selection of twin variants is primarily determined by the twinning Schmid factor (m) along TD, while also being influenced by RD. The twinning strain tensor can be employed to explain the differences among different types of twinned grains. For grains where only a single {1012} twin variant is activated, the average twinning strain tensor of the twin variant in the constraint direction leads to specimen elongation; for grains containing two or more variants, the average twinning strain tensor in the constraint direction of the variant with a larger twinning m leads to specimen elongation, whereas the variant with a smaller m causes specimen shortening in the constraint direction. During plane strain compression deformation, different types of twin variants accommodate deformation cooperatively.

Full Text

Study of Twinning Behavior of AZ31 Mg Alloy During Plane Strain Compression

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Supported by National Natural Science Foundation of China (No.51301040)

Abstract

Magnesium alloys with hexagonal close-packed (hcp) structure exhibit poor workability at room temperature due to the difficulty in activating a sufficient number of independent slip systems to accommodate deformation. Twinning plays a crucial role in plastic deformation of Mg alloys at low to medium temperatures to accommodate imposed strain, particularly strain along the c-axis. This work investigates the twinning behavior of AZ31 magnesium alloy during plane strain compression at room temperature using electron backscatter diffraction (EBSD). Rectangular specimens with dimensions of 10 mm × 9 mm × 7 mm were sectioned from a hot-rolled plate. The results demonstrate that {1012} twinning is dominant when the compression direction is parallel to the transverse direction (TD) and the constraint direction is parallel to the rolling direction (RD) of the plate. Twin variant selection is primarily governed by the Schmid factor (m) along the compression direction, while also being influenced by the constraint direction. Differences in twinning behavior can be interpreted through the twinning strain tensor. For grains containing only a single {1012} twin variant, the average twinning strain tensor of the variant in the constraint direction causes specimen elongation. For grains containing two or more variants, the variant with higher m produces an average twinning strain tensor that elongates the specimen in the constraint direction, whereas the variant with lower m causes shortening in the constraint direction. During plane strain compression, different twin variants coordinate their deformation to accommodate the imposed strain.

Keywords: AZ31 Mg alloy, plane strain, EBSD, twin variant

Introduction

Magnesium and its alloys offer numerous advantages including low density, good thermal and electrical conductivity, damping capacity, and electromagnetic shielding, making them promising for widespread applications. However, due to their hcp structure, magnesium alloys have limited independent slip systems at room temperature, resulting in poor plastic deformability. The plastic deformation of magnesium alloys primarily occurs through slip and twinning. Common slip systems include basal, prismatic, and pyramidal slip, while typical twinning modes include {1011} compression twinning, {1012} tension twinning, and {1011}-{1012} double twinning. The critical resolved shear stresses (CRSS) for these deformation mechanisms at room temperature are: basal slip 0.45–0.81 MPa, prismatic slip 39.2 MPa, pyramidal <c+a> slip 45–81 MPa, {1011} twinning 76–153 MPa, and {1012} twinning 2–3 MPa. Evidently, basal slip and

{1012} tension twinning are the easiest deformation modes to activate at room temperature. However, basal slip only provides two independent slip systems and cannot accommodate strain along the c-axis, necessitating twinning to coordinate deformation. With its low CRSS and easy propagation, {1012} tension twinning represents the most important twinning type in magnesium alloys. Previous studies have demonstrated that deformation twinning plays a significant role in plastic deformation of Mg alloys.

As an hcp material, each primary twinning type in magnesium alloys has six variants, each with specific twinning plane and direction. A grain may activate only one variant or multiple variants. During actual deformation, polycrystalline materials deform heterogeneously, leading to stress concentration and high local strains in certain regions. These regions must not only activate plastic deformation mechanisms to accommodate external strain but also undergo elastic or plastic deformation to coordinate local strain. Numerous studies have investigated various twinning types—including tension twinning, compression twinning, and double twinning—under different loading conditions such as compression, tension, and rolling. For {1012} tension twinning, which has low CRSS and is primarily driven by external strain, most twin variant selection follows the Schmid factor law, meaning the variant with the highest twinning Schmid factor preferentially activates. However, the Schmid factor law cannot explain all tension twinning behaviors, particularly cases where multiple twin variants appear within a single grain, which require analysis of internal stress and strain states. While several studies have examined twinning behavior during plane strain compression, most have focused on microstructure and texture evolution, with limited investigation of twin variant selection rules and their relationship with Schmid factor behavior. Therefore, this work selects a loading direction favorable for tension twinning to investigate twinning behavior and reveal twin variant selection rules in magnesium alloys under plane strain compression.

Experimental

The material used in this study was a commercial AZ31 (Mg-3%Al-1%Zn, mass fraction) magnesium alloy hot-rolled and annealed plate with a strong {0001} basal texture. The initial microstructure before deformation is shown in [Figure 1: see original paper], revealing mostly equiaxed grains with an average grain size of approximately 30 m.

Rectangular specimens measuring 10 mm × 9 mm × 7 mm were prepared, with the 10 mm dimension along the rolling direction (RD), 9 mm along the normal direction (ND), and 7 mm along the transverse direction (TD) of the plate. Plane strain compression was conducted at room temperature using a channel-die apparatus, with compression applied along TD and constraint along RD at a strain rate of 0.01 s^{-1} to a total strain of 8%. The deformed specimens were sectioned along the compression direction, mechanically polished, and then electropolished at room temperature using AC2 electrolyte at 20 V and 0.4 A for 60–70 s. Electron backscatter diffraction (EBSD) characterization was performed using a Supra 55 field-emission scanning electron microscope (SEM) with HKL Channel 5 system for microorientation analysis.

Results

2.1 Microstructure and Texture Analysis [Figure 2: see original paper] presents the microstructure and texture evolution after 8% plane strain compression at room temperature. The orientation information obtained from EBSD enables analysis of orientation-dependent phenomena and quantitative characterization of specific grain boundary types and texture components. In [Figure 2a: see original paper], gray lines represent low-angle grain boundaries (2°–15° misorientation), black lines represent high-angle grain boundaries (>15°), red lines indicate {1012} tension twin boundaries, and green and blue lines denote interfaces where two tension twin variants meet. The initially clean grain interiors exhibit numerous subgrain boundaries and twin interfaces after deformation. During room temperature compression of magnesium alloys, non-basal slip systems have high CRSS and are difficult to activate, whereas basal slip has low CRSS and can be extensively activated. Therefore, the numerous subgrain structures observed in [Figure 2: see original paper] are associated with extensive basal slip activity. The pole figures ([Figure 2b: see original paper]) show that the initial orientation had most grains with their c-axes parallel to ND. After plane strain compression, 84% of grains underwent twinning, causing their c-axes to rotate by 86.4° toward TD with some tilt toward RD. Non-twinned grains retained orientations near ND.

The deformed microstructure can be classified into five categories: (I) Partially twinned grains containing only one twin variant within a grain, identified by single-direction red traces with some matrix remaining—these account for 28% of twinned area fraction; (II) Partially twinned grains containing two or more twin variants, showing multiple red traces or green/blue interfaces with residual matrix—33% area fraction; (III) Completely twinned grains containing two or more variants with green or blue interfaces, showing full twinning without matrix—11% area fraction; (IV) Completely twinned grains without visible variant interfaces, appearing clean with full twinning and no matrix—12% area fraction; and (V) Non-twinned grains—6% area fraction.

[Figure 3: see original paper] shows the misorientation angle and rotation axis distributions. The rotation axis near 7° misorientation is primarily <1120>, representing interfaces where two twin variants from the same variant pair meet. The rotation axis near 60° misorientation is mainly <1010>, indicating interfaces between variants from different variant pairs. The rotation axis near 86° misorientation is primarily <1120>, representing {1012} twin boundaries.

2.2 Twinning Behavior Analysis To better understand the relationship between twinning behavior and orientation, statistics were collected for twinned grains where the matrix could be identified—corresponding to type I and type II grains in [Figure 2: see original paper]. These 165 grains contained 259 twin variants. Using the method proposed by Jiang et al., the twin variant types were identified and analyzed. The orientation changes before and after twinning for these two grain types are shown in [Figure 4: see original paper]. For type I grains, the parent grain orientations are relatively scattered near ND, some deviating more than 40° from ND, while the twinned orientations rotate to near TD. For type II grains, parent orientations are closer to ND, and when twinning occurs with two or more variants, the twinned orientations mostly distribute on both sides of TD tilted 20°–40° toward RD, similar to orientation changes during uniaxial compression.

Twinning activation in magnesium alloys can be predicted by calculating the twinning Schmid factor (m) for each possible variant in the initial orientation. During plane strain compression, the specimen experiences stresses along two directions: compressive stress along TD and constraint compressive stress along RD. When calculating twinning Schmid factors, contributions from both stress directions must be considered:

$$m_{TD} = \cos\phi_{TD}\cos\lambda_{TD}$$

$$m_{RD} = \cos\phi_{RD}\cos\lambda_{RD}$$

$$m_{TD+RD} = \frac{(\cos\phi_{TD}\cos\lambda_{TD} + \cos\phi_{RD}\cos\lambda_{RD})}{2}$$

where m_{TD}, m_{RD}, and m_{TD+RD} are Schmid factors along TD, RD, and their combined direction, respectively; ϕ_{TD} and λ_{TD} are the angles between the twin plane normal/twin shear direction and TD; ϕ_{RD} and λ_{RD} are the corresponding angles with RD.

To clarify the influence of both stress directions during plane strain compression, this work calculates the twinning m values relative to TD, RD, and their combined direction based on actual pre- and post-twinning orientations. [Figure 5: see original paper] shows the deviation of parent grain c-axes from TD and RD and the corresponding m distributions for type I and type II grains. Most twinned orientations deviate more than 40° from ND, with actual twin variants showing significantly larger m_{TD} than m_{RD}, and many m_{RD} values being negative, indicating that twinning primarily accommodates deformation along TD. For type II grains, more stringent orientation requirements exist, with most parent orientations deviating more than 60° from ND.

[Figure 6: see original paper] presents the m_{TD}, m_{RD}, and m_{TD+RD} distributions for type I grains. For partially twinned grains with only one variant, the variant's m_{TD} is significantly higher than m_{RD}, with m_{TD} mostly distributed between 0.1–0.5 and ranking primarily first among the six variants. In contrast, m_{RD} is small, with many values below zero, and ranks mainly in the 5th and

6th positions. The m_{TD+RD} values fall between m_{TD} and m_{RD}, with rankings distributed relatively uniformly between 1st and 5th without obvious preferential distribution, because small m_{RD} values reduce the overall m_{TD+RD}. During uniaxial compression and tension, twin variant activation generally follows Schmid's law, where the variant with maximum m activates preferentially. The analysis shows that for grains containing only one twin variant during plane strain compression, variant selection is controlled primarily by TD, following Schmid's law along TD and exhibiting uniaxial compression-like characteristics. Twinning in these grains mainly accommodates strain along TD, and can occur even when unable to coordinate constraint direction strain (m < 0), provided it can accommodate TD strain.

[Figure 7: see original paper] shows the m distributions for the two twin variants in type II grains. With multiple variants activated, the m distribution becomes more complex. During uniaxial compression, the most common variant combinations in a grain are 1-3 and 1-2 rankings, with 1-2 being less frequent. In this work, considering only TD stress, the first variant's m_{TD} distributes between 0.3–0.4, while the second variant's m_{TD} distributes between 0.1–0.5. The most common combinations are 1-3 and 1-4 rankings, with 1-2 being rare. Most m values are positive, indicating these variants can accommodate deformation along both TD and RD. When considering combined TD and RD effects, both variants' m_{TD+RD} values distribute mainly between 0.1–0.3 without clear patterns. This analysis indicates that for type II grains, variant selection is still primarily determined by TD but simultaneously influenced by RD.

Generally, twinning Schmid factor depends on the spatial relationship between stress direction and grain orientation. Uniaxial compression involves only unidirectional stress, whereas plane strain compression involves both TD and RD stresses, creating a more complex stress state. The m analysis above can only judge whether twinning can be activated from a stress perspective. However, in actual deformation, the specimen's dimension along RD is constrained by the die, so the macroscopic strain along RD theoretically equals zero. Therefore, twinning behavior analysis must consider whether the twinning strain tensor of activated variants can accommodate overall deformation. The contribution of twinning to plastic deformation can be quantitatively characterized by calculating the strain expressed in the sample coordinate system. Deformation twinning produces homogeneous shear with shear strain γ related to the c/a ratio. For {1012} tension twinning in magnesium alloys, the shear strain γ is:

$$\gamma = \frac{c/a - \sqrt{3}}{2\sqrt{3}c/a}$$

In the crystal coordinate system, defining the twin plane normal as **n** and twin direction as **b**, the tension twinning strain tensor ε_{ij} can be expressed as:

$$\varepsilon_{ij} = \frac{1}{2}(b_i n_j + b_j n_i) \times \gamma$$

Substituting the twin plane normals and twin directions for the six variants yields six twinning strain tensors in the crystal coordinate system. These can be transformed to the sample coordinate system using the grain orientation matrix g. When twinning occurs, the six twinning strain tensors are fixed regardless of loading direction. In plane strain compression, the twinning strain tensor along TD should theoretically be negative (shortening), positive along ND (elongation), and the macroscopic strain along RD should be zero. The total strain caused by twin variants in the constraint direction cannot exceed zero; otherwise, deformation cannot be accommodated and twinning would be suppressed.

[Figure 8: see original paper] and [Figure 9: see original paper] show the twinning strain tensor distributions (e_{ND}, e_{TD}, e_{RD}) for type I and type II grains. For type I grains, most variants show $e_{ND} > 0$ and $e_{TD} < 0$, consistent with plane strain compression characteristics. However, e_{RD} shows both positive and negative values, with a total strain tensor of 0.409 for 90 variants and an average of 0.0046 per variant, indicating elongation along RD. This contradicts the zero macroscopic strain requirement in the constraint direction during plane strain compression, necessitating coordination from type II grain twinning.

For type II grains, twin variants primarily accommodate strain along ND and TD. Both variants show similar e_{ND} values, larger than those of type I grains, indicating that type II grain variants can provide greater elongation along ND. This occurs because type II grains activate two or more variants whose orientations mostly rotate to both sides of TD rather than directly to TD, providing larger twinning strain tensors along ND. The e_{TD} values differ between the two variants, with the higher-m variant 1 showing greater twinning strain tensor than the lower-m variant 2. The e_{RD} values are relatively small and show both positive and negative distributions, predominantly negative, indicating that twinning in these grains produces overall shortening in the constraint direction that can coordinate deformation in type I grains. Notably, the e_{RD} values differ significantly: variant 1 has an average e_{RD} of 0.0006 per variant (causing RD elongation similar to type I grains), while variant 2 has an average e_{RD} of -0.0104 per variant (causing RD shortening). During plane strain compression, variant 2 in type II grains can coordinate deformation with variant 1 and type I grain variants until the macroscopic strain in the constraint direction reaches zero, at which point twinning becomes suppressed.

Conclusions

1. When compression is applied along TD with constraint along RD, {1012} tension twinning dominates. Some grains contain only one {1012} twin variant, while others contain two or more variants.

2. Twin variant selection is primarily determined by the Schmid factor along the compression direction TD. The m_{TD} values mostly distribute between 0.1–0.5, while m_{RD} is smaller, distributing between -0.5–0.3. Twinning mainly accommodates strain along TD, but when $m_{RD} > 0$, variant selection is also influenced by RD to coordinate strain along that direction.

3. The specific constraint conditions in plane strain compression allow interpretation of different twinning behaviors through twinning strain tensors. For type I grains containing only one twin variant, the twinning strain tensor in the constraint direction causes specimen elongation. For type II grains containing multiple variants, the higher-m variant 1 causes elongation in the constraint direction, while the lower-m variant 2 causes shortening. During plane strain compression, variant 2 in type II grains can coordinate deformation with variant 1 and type I grain variants.

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Note: Figure translations are in progress. See original paper for figures.