Numerical study on the plastic deformation behavior of AZ31 magnesium alloy under different loading conditions

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Abstract
Based on the stress characteristics of the instantaneous cross-section deformation of the wall reducing section during the cold rolling of two-roll Pilger pipes, the rectangular samples with 0° and 90° to the extrusion direction (ED) were cut from the extruded AZ31 magnesium alloy bar for 3% pre-deformation test to simulate its stress state equivalently. The sample was then cut from the pre-deformed sample by wire cutting for secondary compression, and the sample that is not pre-deformed is selected. The mechanical behavior and texture evolution of AZ31 magnesium alloy under different loading conditions were respectively studied by EBSD experiment and VPSC simulation. Results show that the true stress–strain curve and texture evolution characteristics of AZ31 magnesium alloy during the secondary compression process are in good agreement with the prediction of the VPSC model. The secondary compression behavior can be effectively explained by the relative activity of the deformation modes. The pre-deformation in the ||ED (⊥ED) direction is conducive to the shift of the pole density of the {0001} basal surface texture to the positive and negative directions of the ED (TD). The pre-deformed sample exhibits a higher yield strength than the non-pre-deformed sample in the same loading direction. The high ductility of magnesium alloys can be achieved by activating pyramidal (c+a) slippage.

1. Introduction

Among many structural materials, the extruded AZ31 magnesium alloy has recently received considerable attention due to its low density, high strength-to-weight ratio, environmental protection, and recyclability and has been increasingly used in the automotive and aerospace fields [1–3]. However, starting a sufficient number of independent slip systems during plastic deformation of magnesium alloys at room temperature is difficult due to their hexagonal close-packed crystal structure, thus mainly contributing to their limited plasticity and low formability [4–6].

Studies have found that pre-deformation [7–9] can change the microstructure, thereby improving the properties of magnesium alloys. He et al [10] reported that further compression along the RD direction after pre-compression of AZ31 magnesium alloy sheet along the TD direction can significantly improve the forming performance. Song et al [11] found that compared with direct aging, the yield strength of ZK60 hot-rolled magnesium alloy can be effectively improved by using pre-twinning and aging treatment. Zhang et al [12] introduced [10–12] tensile twins by pre-cold rolling AZ31 magnesium alloy followed by hot compression, which weakened the basal texture and improved the mechanical properties. Long et al [13] first pre-compressed the rolled AZ31 magnesium alloy along the TD direction and then performed secondary compression along the ND direction. The yield strength was substantially reduced due to the occurrence of the de-twinning mechanism.

The crystal plasticity method has been widely used in recent years to calculate the texture evolution of magnesium alloys during deformation [14–16]. A popular method based on crystal plasticity theory is the viscoplastic self-consistent (VPSC) model [17, 18]. Ma et al [19] analyzed the plastic deformation mechanism of
magnesium alloy bars compressed in different directions based on the results of VPSC simulation. Chapuis et al [20] studied the effects of different initial orientations on the microstructure, deformation mechanism, and macro-mechanical behavior of the AZ31 magnesium alloy rolled sheet through the room temperature tensile test combined with crystal plastic simulation. Kang et al [21] used the VPSC model to simulate the simple plane shear deformation behavior of rolled AZ31 magnesium alloy sheets. Hu et al [22] also utilized the VPSC model to study the uniaxial tension and compression deformation of AZ31 magnesium alloy. Steglich et al [23] used the VPSC model to simulate the tensile and compressive mechanical behaviors and texture evolution of magnesium alloys ZE10 and AZ31 along different directions in the strain rate range of 0.001–0.1 s⁻¹.

Overall, most scholars have used the VPSC model to conduct a considerable amount of research on the uniaxial tension and compression deformation mechanism of magnesium alloys. However, magnesium alloys are often plastically deformed in the actual processing process under complex stress conditions. The deformation mechanism remains unclear. Two-roll Pilger cold rolling is a complex process of multistroke and unsteady state under local loading. The material undergoes complex external loading paths and stress-strain conditions during the rolling process, especially for magnesium alloys. The hexagonal structure of the material has low symmetry and significant anisotropy, which intensifies the preferential orientation probability of the internal grains of the material and strengthens the pipe texture [24]. Therefore, studying the influence of the previous deformation on the subsequent rolling is important.

The mechanical behavior of extruded AZ31 magnesium alloy is studied in this paper based on room temperature pre-deformation and secondary compression tests. The plastic deformation process of secondary compression at room temperature is simulated through the VPSC model, and the activation and relative activity of basal, prismatic, pyramidal slip, and {10–12} tensile and {10–11} compression twins in the plastic deformation process are analyzed. Combining the results of electron backscatter technology (EBSD) experiments and simulations, the mechanical behavior of the AZ31 magnesium alloy with the initial extruded wire texture distribution at room temperature was studied from the perspective of the microscopic plastic deformation mechanism for the secondary compression mechanical behavior of the AZ31 magnesium alloy. High-performance magnesium alloy provides theoretical support.

2. Experimental and modeling procedures

2.1. Experiment

Figure 1 (a) is a two-roll Pilger cold rolling model. The model mainly comprises an upper roller, a lower roller, a pipe, and a mandrel. The process action follows the characteristics in figure 1 (a). The mandrel remains stationary under the restriction of the chuck, the upper and lower rollers reciprocate, and the pipe is finally formed after continuous quantitative feeding and rotation. Figure 1 (b) is a schematic of the stress characteristic position of the instantaneous deformation of the pipe cross-section of the reduced wall section. Area I is selected for stress analysis. The circumferential stress σθ and the radial stress σr are compressive stresses, and the axial stress σl is tensile stress.
The above stress state can be equivalently simulated by plane-strain compression (PSC), which comprises equivalent uniaxial compression (UC) combined with transverse constraints. PSC has been conducted on metal to simulate the plane rolling process [25, 26], as shown in figure 2(a). German GKSS Materials Research Institute Graff S et al [27] found that twinning is the main reason for the serious anisotropy of magnesium in plane compression and flow stress based on the calculation and simulation of the mechanical behavior in four orientations. Xin et al [28] found that the activation of stretch twins in PSC is largely suppressed compared with UC. Figure 2(a) is a schematic of conventional plane compression. Therefore, the die is improved. Figure 2(b) shows two wedge blocks on both sides of the sample to facilitate the removal of the sample for re-compression, and the gasket between the upper and lower dies is used to control the amount of pressure down.

The initial material selected in this paper is extruded AZ31 magnesium alloy bar with a diameter of 40mm. The pre-deformed samples are intercepted in different directions of the bar to obtain the compression mechanical properties of extruded AZ31 magnesium alloy bar in various directions. The initial compression directions are 0° and 90° to the extrusion direction (ED), which are respectively called ||ED and ⊥ED. A 3% pre-deformation test was conducted on pre-deformed specimens (I and II), with a size of 20 mm × 27 mm × 30 mm, as shown...
in figure 3(a). Before the experiment, apply a small amount of molybdenum disulfide lithium base grease on the contact end face between the sample and the die, so as to reduce the friction interference at the contact end face and improve the experimental accuracy. Next, the secondary compression samples (III and IV) were cut from the center of the sample. The secondary compression samples are serially numbered $\parallel$ED3 and $\perp$ED3. Samples that were not pre-deformed were also selected for comparison, and the numbers are $\parallel$ED0 and $\perp$ED0. The size of the secondary compression sample is 6 mm $\times$ 8 mm $\times$ 12 mm. The 12 mm direction is the loading direction, and the secondary compression test is shown in figure 3(b). The room temperature pre-deformation and secondary compression experiments were respectively conducted on the computer-controlled electrical industry servo motor testing machine (WAW-1000) and the WDW-E100D electronic universal testing machine, and the selected strain rates were both $10^{-3}$ s$^{-1}$. The surfaces characterized by electron backscatter diffraction (EBSD) before and after the two deformations are all ED $\times$ TD surfaces.

Figure 4 shows the initial texture of magnesium alloy extruded bar in the test obtained by EBSD. EBSD was conducted on the JEOL JSM-7800F field emission scanning electron microscope to analyze the microscopic structure, crystal orientation, and structural characteristics of the sample. Mechanical grinding and electrochemical polishing were finished when preparing EBSD. In mechanical grinding, the sample was grounded to 2000 mm with sandpaper until there was no scratch on the surface. Then, electrolytic polishing was carried out. The polishing parameters are as follows: voltage 20 V, temperature $-30$°C, polishing time 120s,
polishing current 0.03-0.08a. The sample was cleaned with alcohol after polishing. The voltage of the EBSD data collection is 20 kV, the inclination angle is 70°, the current is 15 mA, and the working distance is 15 mm. Channel 5 software is used to process the data collected. The figure reveals that the c-axis of most grains is perpendicular to the extrusion direction, that is, the base plane is parallel to the ED direction. This condition leads to a strong basal texture in the initial pole figure distribution of magnesium alloy.

2.2. Basic principles of the viscoplastic self-consistent model (VPSC)
Polycrystals are represented by weighted orientation scores in the VPSC model. Among them, the orientation represents crystal grains, and the weighted fraction represents the volume fraction occupied by a certain orientation. Each grain is regarded as an ellipsoidal ‘impurity’ embedded in an equivalent medium (HEM) [29], and the “impurity” and the equivalent medium are anisotropic. Slip and twinning obey Schmid’s law during deformation; that is, the dislocation or twin starts when their shear stress reaches critical stress. The basic equation of the VPSC model was first proposed by Molinari et al and later extended to anisotropy by Tome and Lebensohn. The following describes the basic equations of the VPSC model developed by Lebensohn.

The local viscoplastic (inside a grain) constitutive relationship can be described as a rate-dependent expression:

\[ \dot{\varepsilon}_{ij} = \sum_{S=1}^{N} m_S^g \gamma_S = \gamma_0 \sum_{S=1}^{N} m_S^g \left( \frac{\tau_S}{\tau_{crit}} \right)^n = \gamma_0 \sum_{S=1}^{N} m_S^g \left( \frac{m_S^g \sigma}{\tau_{crit}} \right)^n \]  

where \( \tau_S \) and \( m_S^g \) are the critical slitting stress and Schmid factor of the slip system (twin), respectively, and \( n_i \) and \( b_i \) are the normal direction and Burgers vector of slip plane of slip system (twin); \( s \) represents each slip and twinning mechanism; \( \dot{\varepsilon}_0 \) and \( \sigma \) are the deviatoric strain rate and deviator stress, respectively; \( \dot{\gamma}^S \) is the local shear strain rate of the slip system. \( \gamma^0 \) represents the normalized coefficient, and \( n \) is the rate sensitivity index.

The behavior of grain after linear treatment can be described as follows:

\[ \varepsilon^g = M^g : \sigma + \varepsilon_0^g \]  

where \( M^g \) and \( \varepsilon^g \) are the viscoplastic compatibility and response terms of grain g, respectively.

Similar to the crystal grain, the behavior of the equivalent medium can be expressed as

\[ E = \bar{M} : \varepsilon + E_0 \]  

where \( \bar{M} \), \( E \), \( \varepsilon \), and \( E_0 \) are the viscoplastic compatibility terms, strain rate, stress, and response terms of HEM, respectively.

The relationship between the grain-scale stress and strain rate to the grain aggregate stress and strain rate can be expressed as an adoptive relationship.

\[ (\varepsilon^g - \varepsilon) = -\bar{M} : (\varepsilon^g - \varepsilon) \]  

where the interactive influence tensor \( \bar{M} \) is given by

\[ \bar{M} = (I - S)^{-1} : S \cdot \bar{M} \]  

\( S \) is the grain Eshelby tensor, and \( I \) is the unit tensor.

When \( E = \varepsilon^g \) and \( \varepsilon = \varepsilon_0 \), where \( \langle \rangle \) represents the volume average method, the macroscopic adaptive viscoplastic compatibility term can be derived as follows:

![Figure 4. Initial texture of AZ31 magnesium alloy bar.](image)
The displacement rate gradient tensor is \( L^c \) (aggregate/average poly crystal), which can be decomposed:

\[
L^c = \frac{1}{2} (L^c + L^{cT}) + \frac{1}{2} (L^c - L^{cT}) = D^c + W^c
\]

The symmetric part of \( L^c \) is \( D^c \), which is called the macroscopic strain rate tensor, while the antisymmetric part of \( L^c \) is \( W^c \), which is called the rigid rotation rate tensor, that is:

\[
\frac{\partial u_i}{\partial x_j} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} - \frac{\partial u_j}{\partial x_i} \right) = D^c_{ij} + W^c_{ij}
\]

The displacement rate gradient tensor contributed by slip is \( L^s \):

\[
L^s = \gamma^s h^s_{ij} b^s_{ij}
\]

Decompose \( L^s \), the symmetric part of \( L^s \) is \( D^s \), which is called strain rate tensor, and the antisymmetric part of \( L^s \) is \( W^s \), which is called spin rate tensor:

\[
L^s = \frac{1}{2} (L^s + L^{sT}) + \frac{1}{2} (L^s - L^{sT}) = D^s + W^s
\]

Opening any slip system (twin) for the hardening behavior of single crystals is assumed to require increased critical slitting stress to overcome the resistance (the current strength of the material). The strength of the material will generally continue to increase as the deformation progresses (strain hardening). The Voce hardening model is adopted in VPSC and expressed as follows:

\[
\tau^s_{\text{crit}} = \tau_0 + (\tau_1 + \theta_1 \Gamma) \left\{ 1 - \exp \left( -\frac{\Gamma |\theta_0|}{\tau_1} \right) \right\}
\]

where \( \Gamma = \sum_{j=0}^{N} \Delta \gamma^s_{ij} \) is the accumulated strain in the crystal grain, \( \tau_0 \) denotes the initial critical stress, \( \theta_0 \) stands for the initial hardening rate, \( \theta_1 \) refers to the saturation hardening rate, and \( \tau_0 \) and \( \tau_1 \) are the initial and extrapolated critical shear stresses of mechanisms, respectively. The physical meaning is shown in figure 5.
VPSC uses the predominant twin reorientation (PTR) model to describe the twin deformation. The PTR model is only one of many twin models, and its largest feature is that the total number of grain orientations remains unchanged. At each incremental step, the cumulative fraction of each twin system in each grain is compared with the critical fraction $V^{th, mode}$ [31]. If this fraction is satisfied, then twinning occurs.

$$V^{th, mode} = A^{th1} + A^{th2} \frac{V^{eff, mode}}{V^{acc, mode}}$$

(14)

where $V^{acc, mode}$ and $V^{eff, mode}$ are respectively the accumulated and equivalent twin fractions in the crystal grain. $A^{th1}$ and $A^{th2}$ are material parameters: the former is the minimum volume fraction of activated twins, and the sum of the two is the saturated volume fraction of twins. $V^{th, mode}$, $A^{th1}$, and $A^{th2}$ jointly determine the evolution of twins during plastic deformation.

3. Results and discussion

3.1. Mechanical behavior

Table 1 shows the hardening parameters of each slip and twin systems in the secondary compression simulation of AZ31 magnesium alloy $\parallel$ ED and $\perp$ ED directions. The hardening parameters are changed and the calculated stress–strain curve by VPSC corresponding to each group of parameters is compared with the measured compressive stress–strain curve until the two curves are consistent to determine the hardening parameters [15, 32]. Figure 6 shows the measured and fitted stress–strain curves. The stress–strain curve fitted in accordance with the VPSC model fits well with the corresponding experimental data. Its relative compression performance is shown in Table 2. Notably, these results are obtained using a viscoplastic modeling framework, which does not capture elastic behavior and elastoplastic transitions. The elastic part of the experimental curve is removed from the results to compare the experimental and predicted stress–strain curves. The figure shows that the yield strength of the pre-deformed specimens at room temperature has been improved to a certain extent; particularly, the yield strength of $\parallel$ED3 secondary compression increased by 67%. Simultaneously, the plasticity of the pre-deformed specimens at room temperature is lower than those of non-pre-deformed samples.

![Figure 6. Comparison of fitting results and test results of stress-strain curves.](image)

**Table 1. Hardening parameters of AZ31 magnesium alloy material used in VPSC simulation at room temperature.**

| Deformation mode | $\tau_0$/MPa | $\tau_1$/MPa | $\delta_0$/MPa | $\delta_1$/MPa |
|------------------|--------------|--------------|---------------|---------------|
| Basal $<a>$      | 32           | 60           | 350           | 35            |
| Prismatic $<a>$  | 130          | 34           | 500           | 50            |
| Pyramidal $<c+a>$| 270          | 10           | 50            | 400           |
| Extension twin   | 83           | 0            | 10            | 400           |
| Compression twin | 295          | 0            | 0             | 600           |
Figure 7 shows the prediction results of the relative activity of the deformation mechanism during the secondary compression along the $\parallel$ED and $\perp$ED directions. The figure reveals that the basal slip is always the main deformation mode throughout the entire deformation because the basal $<a>$ slip CRSS value of AZ31 magnesium alloy at room temperature is lower than other actuation mechanisms and is easy to actuate. Thus, basal slip is dominant. The critical shear stress of the prismatic slip system is two to three times that of the basal slip system [33]. Therefore, the amount of prismatic slip is remarkably small. The deformation mechanism of $\parallel$ED0 specimens in the initial stage of deformation is mainly tensile twin, supplemented by basal slip. The activating rate of tensile twinning decreases while that of basal, prismatic, and pyramidal slip systems increases with the continuous rise in compression due to the twin growth and fusion behavior of the sample after deformation [34]. The phenomenon includes the disappearance of the twin boundary and the reduction in volume fraction of tensile twins. The dominant deformation mode of $\perp$ED0 and $\perp$ED3 specimens is basal slip supplemented by tensile twinning. The difference is that the activating amount of basal slip of $\perp$ED3 is larger than that of $\perp$ED0; the activities of basal slip and tensile twin are equivalent for $\parallel$ED3 at the initial stage of deformation. The following conditions are observed when the deformation reaches approximately 0.06: the shear stress of compression twin reaches the corresponding shear stress value, the compression twin begins to activate, the contribution of basal slip to the overall deformation reaches the maximum, and then the

| Loading mode | Yield strength (MPa) | Ultimate strength (MPa) |
|--------------|---------------------|------------------------|
| $\parallel$ED0 | 87                  | 300                    |
| $\parallel$ED3 | 145                 | 400                    |
| $\perp$ED0   | 121                 | 378                    |
| $\perp$ED3   | 129                 | 350                    |

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contribution to the overall deformation gradually decreases. Compression twins replace tensile twins when the deformation is larger than 0.07. Moreover, the figure shows that the activating amount of basal slip of the pre-deformed sample is larger than that of the non-pre-deformed sample, which may be related to the high work hardening rate during compression. In addition, figure 7 shows that the pyramidal \(<c+a>\) slip of the pre-deformed specimen is hardly activated during the secondary compression process due to the restrained activation of the pyramidal \(<c+a>\) slip system by pre-deformation. This phenomenon corresponds to another deformation characteristic obtained in figure 6, in which the plasticity of the pre-deformed specimen is lower than that of the non-pre-deformed specimen, which is consistent with the results of previous studies [35, 36]. Therefore, a magnesium alloy material with high strength and good plasticity can be obtained by activating additional pyramidal \(<c+a>\) slip in the magnesium alloy to adapt to the plasticity.

3.2. Micro-texture evolution

VPSC not only simulates the relative activity of slip twins but also simulates the evolution of macro-texture. In order to verify the correctness of VPSC simulation, another set of secondary compression tests was conducted to compress the pre-deformed specimen to 8%. Figure 8 shows the predicted pole figure of \(\parallel ED\), \(\parallel ED\), \(\perp ED\), and \(\perp ED\) samples compressed to 8% using the VPSC model. Compared with the initial texture shown in figure 4, the \{0001\} strong basal surface texture with the c-axis perpendicular to the ED direction of the samples of \(\parallel ED\) and \(\parallel ED\) disappeared, forming a twin texture with the c-axis approximately parallel to the ED direction. Similarly, \(\perp ED\) and \(\perp ED\) form a texture with the c-axis approximately parallel to TD. Comparison results reveal that the simulation results are consistent with the texture characteristics shown in the measured pole figure. This finding verifies the accuracy of the VPSC model in simulating the texture evolution of the magnesium alloy.

Figure 9 compares the evolution of the \{0001\} pole figure when the secondary compression amount is 0%, 4%, 8%, 12%, and 16% along the \(\parallel ED\) and \(\perp ED\) directions. The figure shows that the \{0001\} pole figure of \(\parallel ED\) and \(\parallel ED\) specimens mainly shifted to ED during the compression process with the increase in strain.

![Figure 8. Comparison of simulation and experiment with secondary compression to 8%: (a) \(\parallel ED\); (b) \(\parallel ED\); (c) \(\perp ED\); (d) \(\perp ED\).](image-url)
This shift is a typical change in the texture orientation of magnesium alloy bars with strong basal texture under axial compression. Comparing figures 9(a) and (b), the \{0001\} strong base texture of the previous c-axis perpendicular to the ED direction was pre-weakened due to the pre-deformation of the \|ED3 sample. The extreme density of the \{0001\} base texture is conducive to the ED offset in the positive and negative directions. Simultaneously, figures 9(a) and (b) show that the c-axis of the grains tilted during compression tends to be distributed within a typical ± 30° range from the initial texture orientation [37]. Figures 7(c) and (d) respectively reveal that the dominant deformation mechanisms of \perp ED0 and \perp ED3 samples at the initial stage of deformation are basal slip. Most grains continuously and gradually rotate, and the \{0001\} base surface normal rotates in a direction parallel to the compression axis. The strength peak is always near the TD direction with the increase in strain, and the polar density at the center of the polar diagram disappears due to the sudden change in grain orientation caused by tensile twinning.

4. Conclusion

This paper uses room temperature pre-deformation and secondary compression experiments to analyze the texture distribution and compression performance of AZ31 magnesium alloy under different loading conditions. The experimental process of secondary compression is simulated on the basis of VPSC theory, and the anisotropic behavior of AZ31 magnesium alloy is explained from the start of the slip system. The following conclusions are presented.

(1) The true stress–strain curve and texture evolution characteristics of AZ31 magnesium alloy during the secondary compression process are in good agreement with the prediction of the VPSC model. The secondary compression behavior can be effectively explained by the relative activity of the deformation modes.

(2) The simulation results show that the pre-deformation in the direction of \|ED (\perp ED) is conducive to the shift of the pole density of the \{0001\} basal surface texture to the positive and negative directions of ED.
(TD). This finding is mainly due to the change in grain orientation in the pre-deformed sample after a certain amount of twinning. Thus, the orientation of the base plane is conducive to slip, resulting in the enhancement of \( \langle a \rangle \) slip activity of the base plane.

(3) The pre-deformed and the non-pre-deformed samples have similar texture after secondary compression to 8%, and both samples form twin textures with the c-axis approximately parallel to the ED (TD) direction. However, the pre-deformed sample shows a higher yield strength than the non-pre-deformed sample due to additional hardening caused by twinning.

(4) The high ductility of magnesium alloys can be achieved by activating additional pyramidal \( \langle c+a \rangle \) slipage. The plasticity is lower than that of the non-pre-deformed specimen during the secondary compression of the pre-deformed specimen. This finding is due to the pre-deformation, which inhibits the opening of the pyramidal \( \langle c+a \rangle \) slip system.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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