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Mechanical Anisotropy Induced by Strain Path Change for AZ31 Mg Alloy Sheet

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Abstract: The variation of strain paths induces anisotropy during practical sheet forming processes, which is very important for the subsequent processing technology of anisotropic Mg alloys. In this study, two-step loading tests (tension-tension) were performed to clarify the effect of strain path changes on the evolution of anisotropy on rolled AZ31 sheet. Specimens were preloaded with tension along the rolling direction (RD) with 9% of prestrain. Then, second tension was conducted along 0°, 30°, 45°, 60° and 90° from the RD. It was found that yield strength during the second loading increased along the same direction compared to uniaxial tension without prestraining. For the second loading, the yield strength and flow stress decreased with the increase of the angle from the RD. It was found that the strain path change resulted in stronger anisotropy than that induced by texture. Moreover, it was found that the main deformation modes were basal and prismatic slips during the second loading based on visco-plastic self-consistent (VPSC) modeling. The relative activities of basal and prismatic slips were affected by the second loading direction due to texture evolution. The mechanical anisotropy induced by strain path changes was ascribed to the coupling of the heterogeneous distribution of dislocations and texture evolution induced by prestraining.

Keywords: anisotropy; strain path changes; heterogeneous; texture; Mg alloy

1. Introduction

Due to low density, high specific strength and good damping ratio, magnesium alloys are promising lightweight materials in automotive industries, aerospace and 3C products [1–3]. Wrought magnesium alloy sheets usually exhibit strong initial basal texture resulting in strong in-plane anisotropy [4]. Namely, the mechanical properties depend on direction due to texture or preferred orientations. The yield and plastic strain anisotropy are stronger in the rolling direction (RD) than in the transverse direction (TD) for AZ31 alloy sheets, due to the spreading of basal pole along the rolling direction [5]. The mechanical anisotropy of an extruded AZ31 bar with initial fiber texture is affected significantly by the activity of basal slip and tensile twinning [6]. For the ZK10 alloy, the yield strength and flow stress of tension along the RD are higher than that of the tension along the TD due to the initial basal poles spreading to the TD [7]. The mechanical behavior of AZ31 alloy was studied systematically with

different strain rates, temperatures and loading paths [8]. The strength and r -value are high in the TD at lower strain rate. The texture strengthens during tension and the texture appears to be unchanged from its initial texture. These studies focused on the mechanical behavior of monotonic loading for Mg alloys. It is believed that the initial in-plane anisotropy results from the distribution of initial texture. However, the strain paths during the forming process vary, e.g., from pure shear to biaxial tension during deep drawing, which further induce mechanical anisotropy during practical sheet processing. This mechanical anisotropy impedes the forming ability and restricts wider applications of wrought Mg alloys. Due to the hexagonal close-packed (HCP) structure, the deformation mechanisms of wrought Mg alloys depend on the relationship between the strain path and the c -axis, which exhibits pronounced strain path dependency.

Two-step loading tests can be employed to investigate the effect of strain path changes on the evolution of mechanical responses. Rapid transient strain hardening (yielding at low stresses and rapid change of work hardening rate) and long-term (or “permanent”) softening were observed for DP steels [9,10] and pure aluminum [11] during strain path changes. Tension two-step loading was subjected to the investigated mechanical behavior of AZ31 alloy under strain path changes by Wen et al. [12]. The yield stress during reloading decreased with the reloading changing from the RD to the TD. The back-stress effect was considered to lead to a decrease in basal slip activity and an increase in prismatic slip activity during reloading from visco-plastic self-consistent (VPSC) modeling. Tension two-step tests with pre-tension in the transverse direction were performed on AZ31 alloy sheet by He et al. [13]. It was found that the degree of softening (early yielding) increased with the increasing loading angle from the transverse direction to the rolling direction. An extended homogeneous anisotropic hardening (HAH) model was proposed to capture the softening behavior. For compression two-step loading of AZ31 alloy, the sigmoidal shape of the stress-strain curve weakened as the angle of reloading increasing from the rolling direction due to the decrease of detwinning activity [14]. The effect of strain path on the anisotropic fracture and yielding of ZK100 alloy was studied by Abedini et al. [15]. The prestraining could reduce fracture strain under the plane strain tension but, in contrast, not significantly affect fracture strain under shear state. The biaxial prestraining resulted in remarkable reduction. Cruciform biaxial tension tests with in situ neutron diffraction were employed to study the effect of strain path changes in AZ31 alloy [16]. It was found that the increased yield strength during reloading resulted from dislocation accumulation in the initial loading impeding dislocation motion in the reload process. From evolution of the subsequent yield surfaces, it was observed that the subsequent yield strength increased during the orthogonal loading [17]. However, the variation in subsequent yield strength and plastic strain for in-plane tension after prestrain was neglected compared with initial monotonic loading. The anisotropic behavior and underlying physical mechanism of subsequent deformation with prestrain were unclear. Thus, the effect of strain path change on the evolution of mechanical anisotropy was studied for wrought Mg alloy.

In the current work, the mechanical (yield and plastic flow stress) anisotropy of a rolled AZ31 Mg alloy sheet under two-step loading was investigated experimentally and numerically. Crystal plasticity models were a straightforward approach for studying the underlying mechanism of mechanical anisotropy [18]. The deformation mechanisms for HCP metals were predicted by the visco-plastic self-consistent (VPSC) modeling successfully [19–22]. In addition, the VPSC modeling had a higher computational efficiency than crystal plasticity finite element methods. Therefore, the VPSC model was employed to explore the underlying deformation mechanisms under strain path changes.

2. Experimental Setup

The received material was a commercial AZ31 cold rolled magnesium alloy sheet with a thickness of 1 mm. An average grain size of 12 μm was detected as shown in Figure 1. The schematic geometry of samples for two-step loading is shown in Figure 2a. Firstly, large samples were cut along the RD with a gauge length of 80mm and width of 20 mm as shown in Figure 2b. The samples were loaded to plastic strain $\epsilon = 9\%$. Subsequently, small samples were cut from the center part of the

prestrained sample along different directions by using wire electric discharge machining as shown in Figure 2c. The angle between the first loading direction and the second loading direction was defined as θ , which was 0° , 30° , 45° , 60° and 90° . The small samples were subjected to uniaxial tension tests with the Gleeble 3800 machine (Dynamic Systems Inc., Poestenkill, NY, USA). The strain rate was 0.001/s in both the first and second loading at room temperature. Three specimens were tested under each reloading to validate the reproducibility of the results. The good repeatability of stress-strain response during second tension suggests that the deformation is homogeneous in the gage length of the prestrained sample.

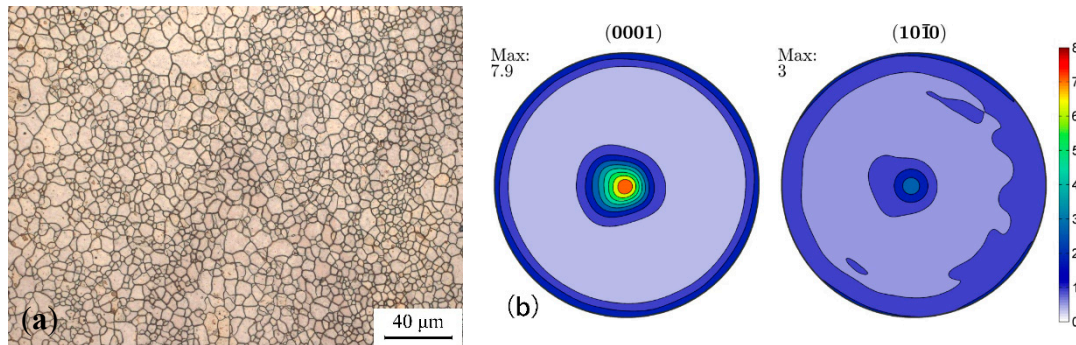


Figure 1. (a) Optical micrograph and (b) initial pole figures of the rolled AZ31 sheet. The rolling direction (RD) is horizontal and the transverse direction (TD) is vertical.

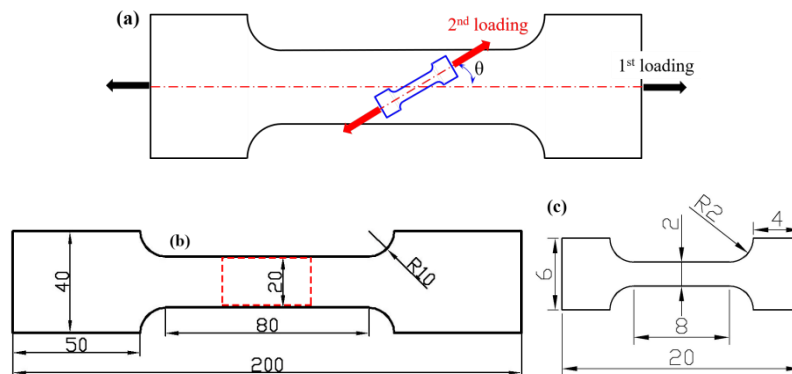


Figure 2. (a) The schematic diagram of the two-step loading test and the geometries of two-loading samples; (b) the large samples for first loading and (c) the small samples for second loading. (Unit: mm).

The texture was detected on the rolling plane of deformed samples by optical microscopy and X-ray diffraction with Cu K α radiation (Rigaku D/Max-2500PC, Rigaku Inc., Tokyo, Japan). The (0001) and (10–10) pole figures were calculated using the MTEX algorithm developed by Hielscher and Schaeben [23].

3. Simulation Framework

The VPSC model [24] with predominant twin reorientation (PTR) [25] was employed to clarify the deformation mechanism of magnesium alloys under strain path change. The deformation in the grain is characterized by the displacement gradient tensor L^c and the deformation gradient tensor F^c , defined as shown in Equation (1):

$$L_{ij}^c = \frac{\partial u_i^c}{\partial x_j}, \quad F_{ij}^c = \frac{\partial x_i}{\partial X_j} \quad (1)$$

where X and x are a point in the reference configuration and current configuration, respectively. The displacement of the point $u = x - X$.

A rate-dependent constitutive model was applied in the VPSC framework in Equation (2) [26,27]:

$$\varepsilon_{ij}(\bar{x}) = \sum_s m_{ij}^s \gamma^s(\bar{x}) = \gamma_0 \sum_s m_{ij}^s \left\{ \frac{m_{kl}^s \sigma_{kl}(\bar{x})}{\tau^s} \right\}^n = M_{ijkl} \sigma_{kl}(\bar{x}) \quad (2)$$

where $\varepsilon_{ij}(\bar{x})$ is the deviator of strain rate, $\sigma_{kl}(\bar{x})$ is the deviatoric tensor of stress and s represents each slip and twinning. M_{ijkl} is the visco-plastic compliance. τ^s is the threshold stress; $m_{ij}^s = \frac{1}{2}(n_i^s b_j^s + n_j^s b_i^s)$ is the symmetric Schmid tensor associated with slip (or twinning) system (s), $\bar{n}^s$ and $\bar{b}^s$ are the normal and Burgers vector of slip (or twinning) system (s), $\gamma^s(\bar{x})$ is the local shear-rate on slip system (s), which can be obtained by Equation (3):

$$\gamma^s(\bar{x}) = \gamma_0 \left\{ \frac{m_{kl}^s \sigma_{kl}(\bar{x})}{\tau^s} \right\}^n \quad (3)$$

The critical resolved shear stresses (CRSS) of the slip and twinning system are described by extended Voce hardening model as shown in Equation (4) [27,28]:

$$\tau_c^s = \tau_0^s + (\tau_1^s + \theta_1^s \Gamma) \left[1 - \exp\left(-\Gamma \left| \frac{\theta_0^s}{\tau_1^s} \right| \right) \right] \quad (4)$$

where τ_0^s is the initial CRSS; τ_1^s is the back-extrapolated CRSS; θ_0^s is the initial hardening rates; θ_1^s is the asymptotic hardening rates. $\Gamma = \sum_s \Delta\gamma^s$ is the accumulated shear strain in the grain. The hardening effect of each mode is defined in Equation (5):

$$\Delta\tau^s = \frac{d\tau^s}{d\Gamma} \sum_s h^{ss'} \Delta\gamma^{s'} \quad (5)$$

where $h^{ss'}$ is the latent hardening coupling coefficients.

The PTR scheme was proposed by Tomé et al. [25] within each grain g . Consequently, an “accumulated twin fraction” $V^{acc, mode}$ in the aggregate for the particular twin mode is defined in Equation (6):

$$V^{acc, mode} = \sum_g \sum_t \gamma^{t,g} / S^t \quad (6)$$

where $\gamma^{t,g}$ is the shear strain contributed by each twin system t , and $V^{t,g} = \gamma^{t,g} / S^t$ is the associated volume fraction (S^t is the characteristic twin shear). The PTR scheme adopts a statistical approach. A threshold volume fraction is defined in Equation (7):

$$V^{th, mode} = A^{th1} + A^{th2} \frac{V_{eff, mode}}{V_{acc, mode}} \quad (7)$$

where $V_{eff, mode}$ is the “effective twinned fraction” which associates with the fully reoriented grains, A^{th1} and A^{th2} are two material constants.

For Mg alloys, compressive twinning is neglected due to high CRSS at room temperature. Thus, basal $\langle a \rangle$, prismatic $\langle a \rangle$, pyramidal $\langle c + a \rangle$ slips and tensile twinning are considered in the VPSC modeling [12,14]. The two-step loading process was simulated with sequential simulation work. Firstly, the pre-tension test was simulated up to 9% along the RD. Then, the simulated results of prestrain were set as the initial states of the reloading stage, and pre-tension along different directions

was carried out to predict the strain path change. The model parameters were defined by fitting the uniaxial tension and compression stress–strain curves as shown in Table 1.

Table 1. Voce hardening parameters for visco-plastic self-consistent (VPSC) simulations of AZ31 at 298 K.

Mode	τ_0/MPa	τ_1/MPa	θ_0/MPa	θ_1/MPa	$h^{ss'}$	A^{th1}	A^{th2}
Basal<a>	18	2	10	0	1		
Prismatic<a>	100	40	600	30	1		
Pyramidal<c+a>	125	110	1500	40	1		
Tensile Twin	20	10	100	10	1	0.8	0.6

4. Results and Discussion

The true stress-strain curves of uniaxial tension with 0° , 45° and 90° from the RD were probed as shown in Figure 3a. It was found that the yield strength and flow stress increased with the increase of loading angles from the RD. Strong initial mechanical anisotropy was observed. In order to investigate the strain path effect, the true stress-strain responses under different reloading directions along the RD with 9% prestrain were observed as shown in Figure 3b. It was found that the strain-hardening behavior was independent of the loading direction with typical slip dislocation dominating deformation [29], whereas the yield and flow stresses along the RD were the largest and decreased with the increasing angle. Compared to the initial yield stress of uniaxial tension, it was found that the one during reloading along the same directions increased as shown in Table 2. Much stronger anisotropy was observed during reloading than under initial loading.

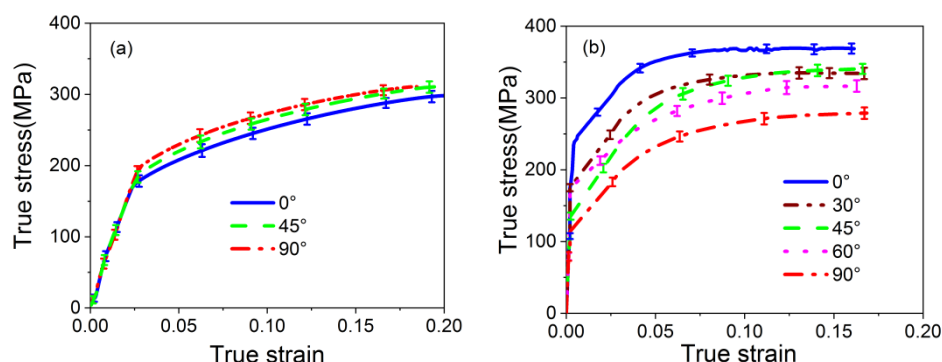


Figure 3. True stress-strain curves of AZ31 sheet under (a) uniaxial tension along 0° , 45° and 90° from the RD; (b) reloading along 0° , 30° , 45° , 60° and 90° with 9% prestrain from the RD.

Table 2. The comparison of yield strength $\sigma_{0.2}$ for initial and after prestrain.

Samples	0°	45°	90°
Initial	175 MPa	180 MPa	188 MPa
After Prestrain	240 MPa	200 MPa	195 MPa

For uniaxial tension without prestrain, the anisotropy mainly depended on the distribution of initial texture. The initial basal poles in the center of (0001) pole figure spread toward the RD exhibiting an ellipsoidal intensity distribution as shown in Figure 1b. The c-axes in the grains were tilted to the RD. The angle between the c-axes of the grains and the RD favored the activation of basal slip. Further, the basal slip could be activated during the onset of uniaxial tension along the RD due to low CRSS [4,30]. With the angle increasing from the RD, the activated stress of basal slip was increased due to a low angle between c-axes of the grains and tension direction. In contrast, the c-axes of the grains were tilted away from the TD. It was difficult to activate basal slip with a low angle between c-axes

and the TD. Therefore, the prismatic slip was activated during tension along the TD in most grains. Therefore, the difference in the stress-strain behavior along different tensile loading directions was present for the rolled AZ31 alloy sheet. The rotation of basal poles of grains with activation of basal slip to the TD could be observed from the (0001) pole figure as shown in Figure 4a. The shape of basal poles in the center of (0001) pole figures was changed by prestrain. Twinning may occur during prestrain due to stress state inhomogeneities, which do not affect mechanical behavior of tension [5,30]. It has been confirmed that the activation of basal slip leads to rotation of basal poles toward compressive direction [8,31]. Therefore, the basal poles rotated toward the TD after uniaxial pre-tension along the RD as shown in Figure 4a. The texture evolution for reloading along 0, 30, 45, 60 and 90° after 9% pre-tension along the RD were determined as shown in Figure 4b–f. The shape of basal poles along 0° is unchanged compared with that after prestrain in the center of (0001) pole figure as shown in Figure 4b. For reloading along 30°, 45°, 60° and 90°, the shape of basal poles is “elongated”. The rotation of basal poles was pronounced during reloading along the TD.

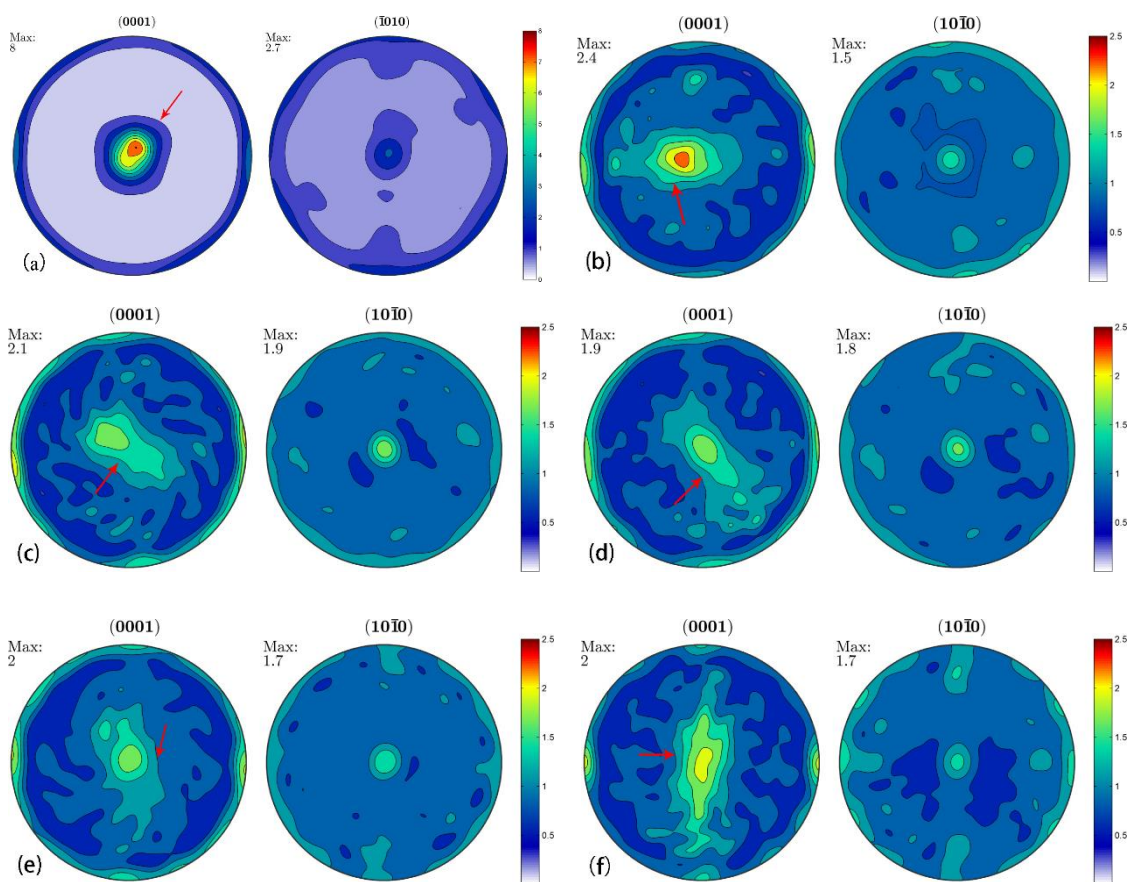


Figure 4. The (0001) and (10–10) pole figures evolution (a) 9% prestrain and along (b) 0°, (c) 30°, (d) 45°, (e) 60° and (f) 90° for reloading from the RD. The RD is horizontal and the TD is vertical.

The relative activities of deformation mechanisms were calculated to investigate the activation of deformation mechanisms during reloading as shown in Figure 5. The stress-strain curves of reloading can be predicted by VPSC modeling as shown in Figure 5a. Based on the VPSC results, it was found that the relative activities of basal and prismatic slips were high during reloading. The contributions of twinning and pyramidal slips to plastic deformation were relatively small and thus neglected. Therefore, the basal and prismatic slips were the main deformation mechanisms during reloading along all directions as shown in Figure 5b–f. The initial dominant deformation mechanism was basal slip. Then, the prismatic slip took over deformation with plastic strain increasing. Therefore, the slip-dominant deformation was the main mechanism during reloading along all directions.

The relative activity of basal slip increased with the loading angle changing from the RD to the TD. Therefore, it implied that the basal slip was more easily activated with the reloading direction increasing due to the spreading of basal poles after prestraining. The rotation of texture induced by basal slip during prestrain contributed to the evolution of mechanical anisotropy during strain path changes. More precisely, the increase of the tensile yield strength during reloading along the RD resulted from the activation of prismatic slip with high CRSS. In contrast, the decreasing of tensile yield strength during reloading along the TD resulted from the activation of basal slip with low CRSS.

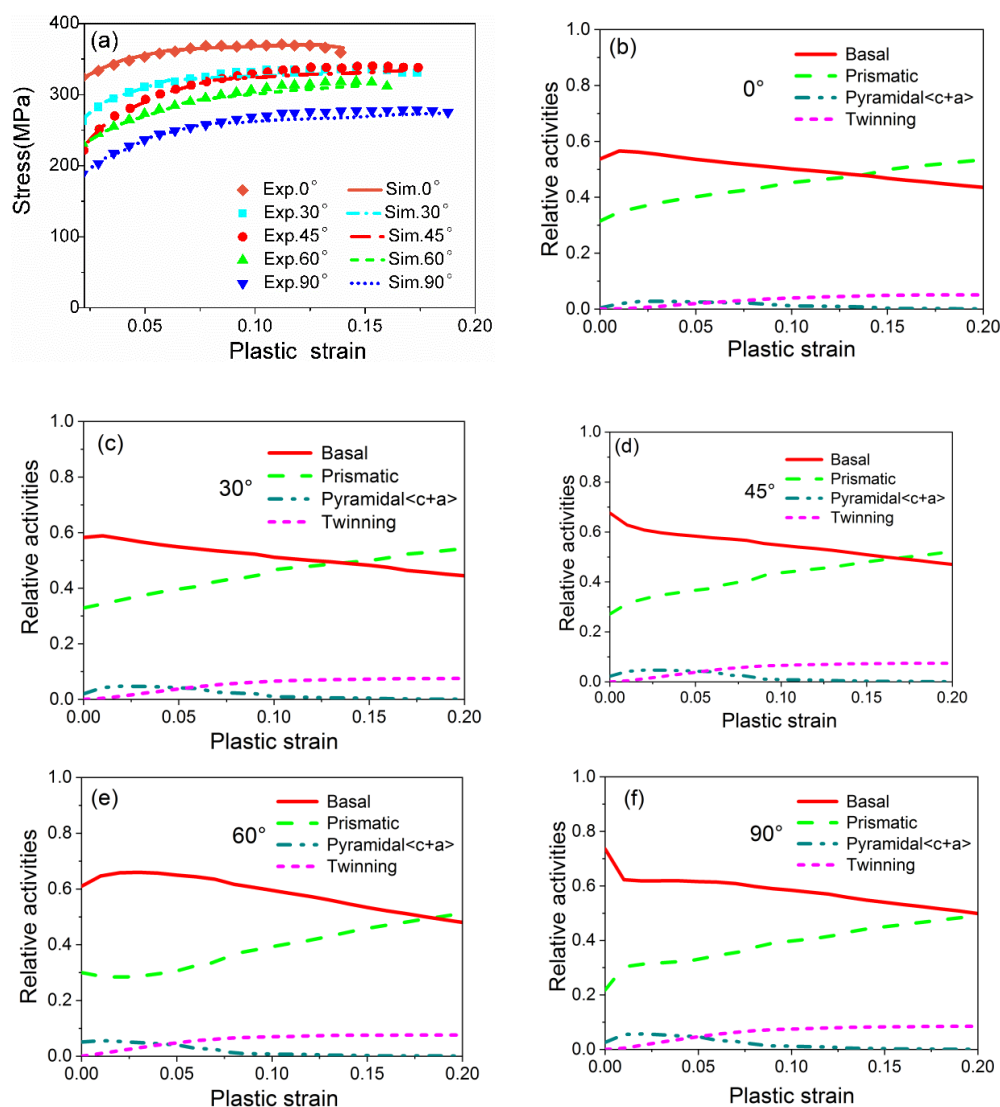


Figure 5. Mechanical responses and VPSC simulation results on the deformation mechanisms (a) stress-strain curves; (b–f): relative activities of each deformation mechanism during reloading along different directions from the RD with 9% prestrain, (b) 0°, (c) 30°, (d) 45°, (e) 60° and (f) 90°.

From VPSC results, the plastic deformation during tension was dominated by the slip dislocation. The distribution of dislocation was heterogeneous at grain level which related to the prestrain direction [10,32,33]. Dislocation hardening during reloading is induced by dislocation pile-up produced by prestrain. The strong dislocation hardening was detected in the prestrain direction [12]. Therefore, the heterogeneous distribution of dislocations led to a strong hardening effect along the RD during reloading. The contribution of dislocation hardening to yield strength decreased with the increase of the angle from the prestrain direction, the RD to the TD. The coupling of texture and dislocation hardening led to the pronounced difference in yield strength during reloading.

5. Conclusions

The mechanical anisotropy of a rolled AZ31 Mg alloy sheet under two-step loading was investigated experimentally and numerically. Conclusions are drawn as follows:

(1) The initial yield strength and flow stress increase during tension from the RD to the TD. In contrast, the yield strength in the second loading decreases as the reloading direction changes from the RD to the TD, exhibiting pronounced anisotropy. Moreover, the subsequent yield strength after prestrain increases compared with initial loading in the same direction.

(2) The deformation mechanisms are basal and prismatic slips during reloading, based on the VPSC modeling. The rotation of basal poles to the TD results in the increasing of the relative activity of basal slip with the reloading direction changing from the RD to the TD.

(3) The texture evolution is determined along a different direction after prestraining. The orientation hardening changes from strong to weak, due to the texture evolution induced by prestrain. In addition to dislocation hardening, the texture evolution induced by the activation of basal slip also contributes to the pronounced anisotropy during strain path changes compared to conditions under uniaxial tension without prestrain.

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Data Availability: The raw data required to reproduce these findings are available to download from <https://zenodo.org/record/3722662#.XnWCifmsd-U>.

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