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ARTICLE

Effect of Tensile Orientation on Twinning and Texture Evolution of AZ31 Magnesium Alloy

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Abstract: The relationship between the twin behavior, the evolution law of texture and the plastic anisotropy of AZ31 magnesium alloy during tensile deformation was studied by combining room temperature uniaxial tensile experiment with crystal plastic finite element through tensile orientation control. Based on the rate-dependent crystal plastic constitutive theory, a plastic constitutive model of crystals with different orientations coupled by slip and twin mechanisms was established, and the effect of twins on the structural evolution and mechanical properties of AZ31 magnesium alloy during plastic deformation was studied by introducing twin crystal integrals. Results show that the specimens with two different orientations show significantly different texture evolution laws during the plastic deformation process, and exhibit obvious anisotropy. When the specimen is axially stretched, the twin is suppressed, and the twin activation volume fraction is low. The twin crystal is easily generated when the specimen is radially stretched, and the twin activation volume fraction is high. The axial specimen has a small shift in the {0001} polar map throughout the plastic deformation process, and the radial specimen has a significant shift in the polar density of the {0001} prismatic surface texture gradually towards the positive and negative directions of RD due to the activation of a large number of tensile twins.

Key words: AZ31 magnesium alloy; twinning; crystal plasticity finite element; texture evolution; mechanical properties

Magnesium alloys have the advantages of low density, high specific strength and specific stiffness, and good machinability, and are considered ideal as key structural materials in the aerospace and automotive industries[1–4]. The plastic processing of magnesium alloy raw materials is mainly conducted by rolling, extruding sheets, and extruding bars [5–8]. Among them, the magnesium alloy bar is easy to form the basal filament texture structure parallel to the extrusion direction during the extrusion process, and the structural parts formed by the magnesium alloy bar are constantly plastically deformed during the service process, showing obvious anisotropy[9–12]. Therefore, it is of practical significance to study the texture evolution law of magnesium alloys with different orientations in the tensile process, which can guide the development of magnesium alloy plastic forming process, improve the mechanical properties of magnesium alloy structural parts during service, and expand the application of magnesium alloy in industry[13–16].

In recent years, scholars have done much research on the stretching of AZ31 magnesium alloy and achieved certain progress. Chen et al[17] performed uniaxial tensile experiments on AZ31 magnesium alloy plates with different initial textures and studied the bimodal textures produced by the process. Hu et al[18] studied the relationship between the activity of the deformation mechanism and the evolution of the structure and texture during the uniaxial stretching of the AZ31 magnesium alloy with non-substrate texture. Wang[19] used the viscoplastic self-consistent model to investigate the microscopic microstructure evolution asymmetry of the extruded AZ31 magnesium alloy. Li et al[20] studied the non-proportional multiaxial ratchet behavior of AZ31 magnesium alloy by establishing a single crystalline plastic constitutive model of magnesium alloy. Lan

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et al[21] studied the plastic deformation behavior along different loading paths by establishing the plastic constitutive relationship of the crystal.

In this study the relationship between twinning behavior, texture evolution law, and anisotropy during the tensile plastic deformation of AZ31 magnesium alloy was studied by controlling the tensile orientation. In order to explain the reasons in more detail, a crystal plasticity model with different orientations was established based on the rate-related crystal plasticity theory, coupled with slip and twinning mechanisms, in which the twin crystal integration number was introduced to quantitatively analyze the influence of plastic deformation process on macroscopic strain by secondary development on ABAQUA/UMAT platform. In order to verify the crystal plasticity model, cubic specimens stretched along the axial and radial directions were cut from the extruded AZ31 magnesium alloy bar, uniaxial tensile experiments were carried out, the microstructure and deformation texture were characterized by electron backscattering, and the simulation results were compared, revealing the influence of tensile orientation on twins, texture evolution and mechanical properties during the stretching process of AZ31 magnesium alloy.

1 Experiment

The material selected for this experiment was the extruded AZ31 magnesium alloy bar with a diameter of 40 mm, and the tensile specimens required for the experiment were cut along the radial and axial directions of the bar, whose size is shown in Fig. 1a. The gauge distance was 12.5 mm, the PLD-10 microscopic observation electro-hydraulic private service fatigue testing machine was selected at room temperature, and static tensile control was selected. Through EBSD experiments, the crystallographic orientation information required for finite element modeling of crystal plasticity was obtained, and the initial texture measured by the experiment was expressed in the form of polar diagram, as shown in Fig. 2a. Then, according to Eq. (1)[22], the experimentally obtained Euler angles were converted into cosines of the crystal coordinate system in the macroscopic coordinate system, and finally, the grain orientation information was assigned to the crystal plasticity model to achieve the prediction of the texture. Fig. 2b shows the polar diagram of the initial texture during the simulation. By comparing the experimental initial texture with the simulated initial texture, it was confirmed that the initial texture used in the prediction is representative, which ensures more accurate prediction results.

$$g=\begin{bmatrix}\cos\varphi_2 & \sin\varphi_2 & 0\\ -\sin\varphi_2 & \cos\varphi_2 & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\varphi & \sin\varphi\\ 0 & -\sin\varphi & \cos\varphi\end{bmatrix}\begin{bmatrix}\cos\varphi_1 & \sin\varphi_1 & 0\\ -\sin\varphi_1 & \cos\varphi_1 & 0\\ 0 & 0 & 1\end{bmatrix}=\begin{bmatrix}u & r & h\\ v & s & k\\ w & t & l\end{bmatrix} \quad (1)$$

2 Crystal Plasticity Finite Element Simulation

Fig. 1b shows the 3D crystal plastic finite element modeling (3D CPFEM) process. Based on the rate-dependent crystal plastic model, the initial microstructure is constructed by the Voronoi method. Firstly, the crystallographic orientation information required for the simulation is obtained from the experiment, from which representative 768 sets of Euler angles with the same volume fraction are extracted, and the initial orientation required for this model is generated using the method of Euler spatial partitioning. Then set the *x*-axis, *y*-axis, and *z*-axis, corresponding to the RD, TD, and AD in the experiment, respectively. The finite element model is established according to the number of grains required by the model and the average grain size measured in the experiment, and the model is meshed. Finally, material properties of each divided cube are given to form a crystalline plastic finite element model.

Fig. 3 shows the magnesium alloy model with different initial textures. Fig. 3a is the axial crystal plasticity finite element model, Fig. 3b is the radial crystal plasticity finite element model. The model contains 768 cells, each cell represents a grain; different colors reflect the orientation difference; finally, the numerical simulation model is

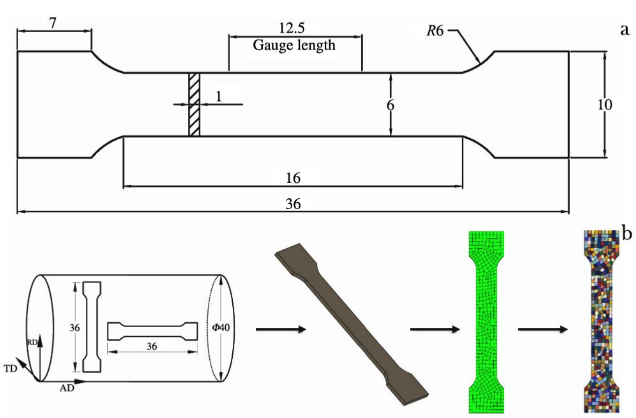

Fig.1 Tensile specimen size (a) and corresponding 3D CPFEM modeling (b)

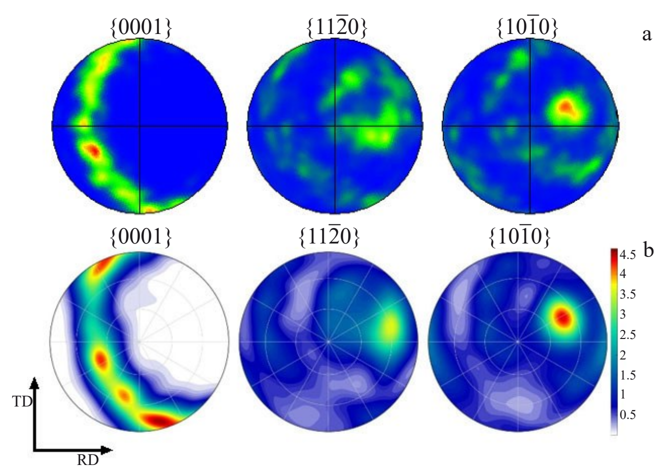

Fig.2 Initial texture of experimental (a) and simulated (b) specimens

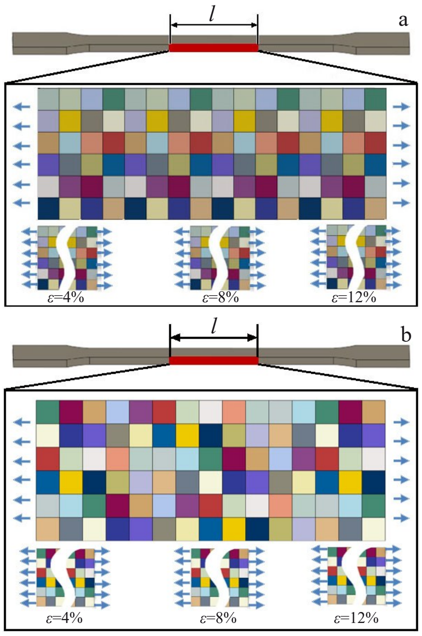

Fig.3 Crystal plasticity finite element model: (a) axial and (b) radial

established by the method of input file inp, and the accurate prediction of the deformation texture of magnesium alloy during stretching is realized by the finite element software ABAQUS using the custom material interface UMAT.

3 Results and Discussion

Fig. 4 shows the axial tensile true stress-strain curve and stress cloud diagram. It can be seen from the stress-strain curve that the strain hardening rate does not change much, and the stress-strain curve is gentle. It can be seen from the stress cloud diagram that the stress distribution within and between each grain is uneven, and with the increase in deformation, stress concentration occurs and the grain changes significantly.

Fig. 5 shows the radial tensile true stress-strain curves and stress clouds. Compared with the axial stress cloud, the stress concentration is relatively less; compared with the axial true stress-strain curve, the yield strength and tensile strength in RD are significantly lower than in AD, the difference in initial texture leads to obvious anisotropy of tensile behavior, so the selection of suitable initial texture can improve the forming and service performance of deformed magnesium alloy to a greater extent.

Fig.6 shows the predicted axial and radial texture evolution pattern in the tensile process. During axial stretching, with the increase in plastic strain, the {0001} basal plane texture is continuously shifted, indicating that most of the grains under uniaxial tensile stress are rotated at large angles. With the increase in strain, the polar density of the {0001} prismatic plane texture is first gradually shifted toward the TD-AD plane and then rotated perpendicular to the RD direction,

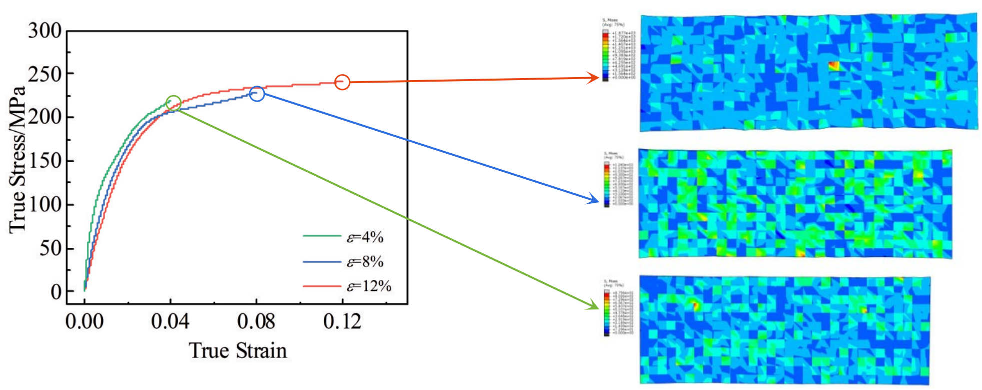

Fig.4 True stress-strain curves and stress cloud in axial tension under different strains

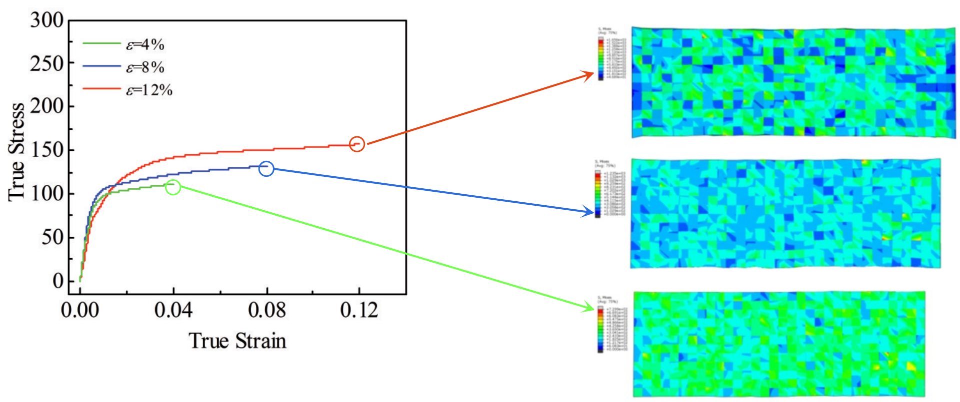

Fig.5 True stress-strain curves and stress cloud in radial tension under different strains

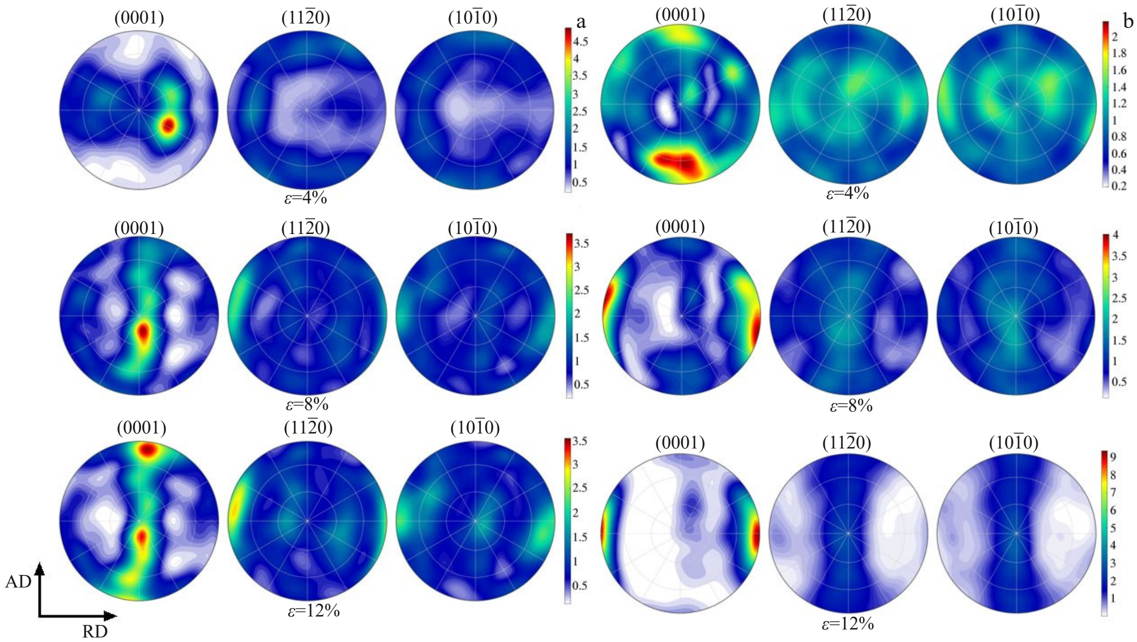

Fig.6 Predicted texture evolution pattern during axial (a) and radial (b) stretching process under different strains

$\{11\bar{2}0\}$ and $\{10\bar{1}0\}$ prismatic surface texture does not change significantly with the increase in strain, and only the texture strength increases. During the radial stretching process, due to the significant rotation of the grains caused by the massive activation of the twins, the polar density of the $\{0001\}$ prismatic surface texture gradually shifts toward the positive and negative directions of the RD, and the polar density of the $\{11\bar{2}0\}$ and $\{10\bar{1}0\}$ prismatic surface texture gradually tends to the TD-AD plane.

Fig. 7 shows the axial and radial polar diagram of $\{0001\}$, $\{11\bar{2}0\}$, $\{10\bar{1}0\}$ when the true strain is 0.12. Compared with the predicted results, the crystal plasticity finite element simulation results agree well with the experimental results for the same texture stretching process, which can reasonably reflect the microscopic texture evolution process of AZ31 magnesium alloy during compression and tension, and verify that the crystal plasticity finite element can accurately predict the texture evolution process of AZ31 magnesium alloy.

Fig. 8 shows the twinning change law in axial stretching process. Fig. 8a shows the activation volume of twinning under different strains, and Fig. 8b shows the integral number curve of twinning crystals under different strains. It can be seen that with the increase in strain, twinning crystals are formed continuously within the grain, and twinning crystals change the orientation of the grain so that the crystal orientation unfavorable to slip or twinning becomes favorable to stimulate further slip and achieve continuous plastic deformation.

Fig. 9 shows the variation law of radial tensile twins under different strains. Compared with Fig. 8, the radial twin activation volume fraction is significantly higher than the axial plastic deformation, because during the axial plastic deformation process, the deformation direction is parallel to the *c*-axis, the twin is suppressed, and the twin crystal nucleus only occurs in part of the grain, and the twin activation volume fraction is relatively low. In the radial plastic deformation process, the twin crystal behavior conforms to the Schmid factor law, the twin crystal is very easy to appear, the twin crystal nucleus occurs in most grains, and thus the twin activation volume fraction is relatively high. Therefore, the activation volume of radial twins during the plastic deformation of AZ31 magnesium alloy rods is higher than that of axial twins[23–25].

Fig. 10 shows the distribution of grain boundaries and the

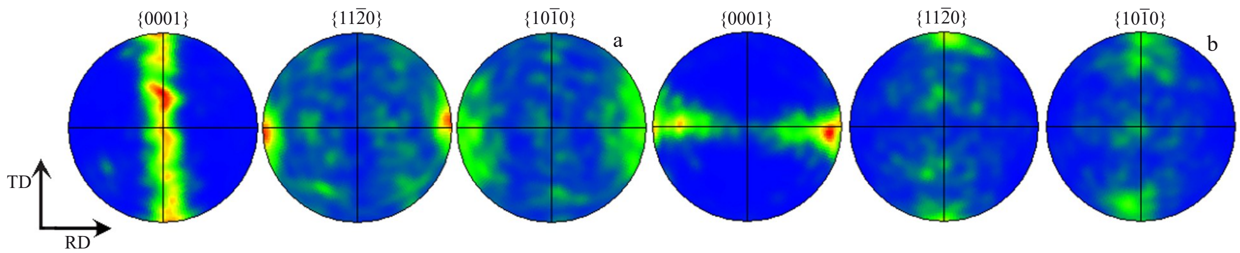

Fig.7 Experimentally obtained axial (a) and radial (b) polar plots at a true strain of 0.12

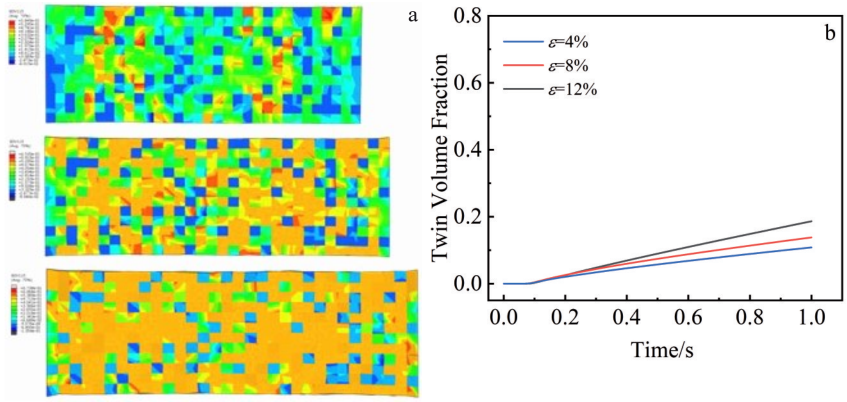

Fig.8 Twinning variation law in axial stretching process under different strains: (a) activation volume and (b) integral number curves

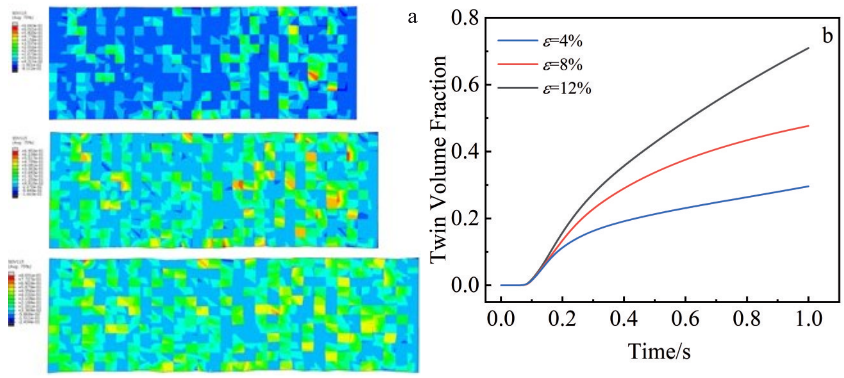

Fig.9 Twinning variation law of radial stretching process under different strains: (a) activation volume and (b) integral number curves

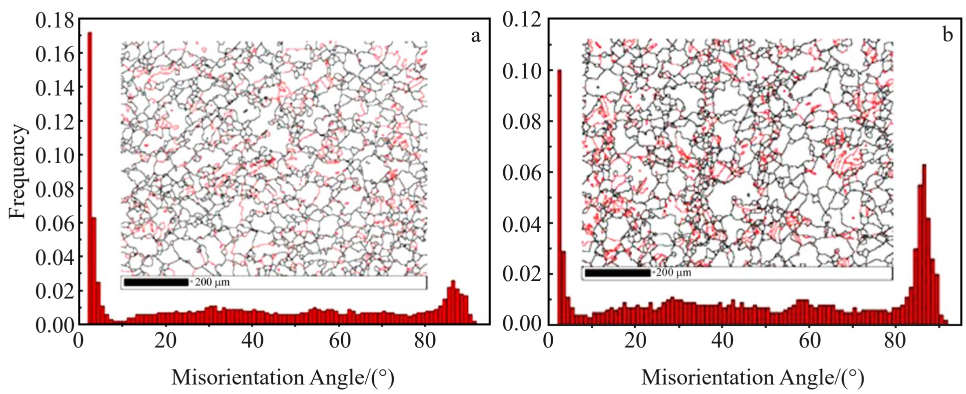

Fig.10 Grain boundary distribution and grain boundary orientation difference when the axial (a) and radial (b) uniaxial tensile strain is 0.12

histogram of grain boundary orientation difference at the axial stretching and radial stretching strain of 0.12, where the small-angle grain boundaries are from 2° to 5° and the large-angle grain boundaries are above 15°, which are indicated by red and black solid lines, respectively. Comparing Fig. 10a and Fig. 10b, it can be seen that the peaks of small-angle grain boundaries for radial stretching are relatively low due to the occurrence of twinning, which makes the small-angle grain boundaries absorb dislocations to transform into large-angle grain boundaries.

4 Conclusions

1) Through the tensile orientation control, the AZ31 magnesium alloy extruded bar exhibits obvious anisotropy during plastic deformation, high radial yield strength and tensile strength, and low axial yield strength and tensile strength.

2) During tensile plastic deformation, twinning is suppressed in axial stretching and the volume fraction of twin activation is low, while in radial stretching, twinning is extremely easy to produce and the volume fraction of twin

activation is high.

3) The deformation mechanism during the plastic deformation of the axial specimen is dominated by slip, which makes the {0001} polar map change less throughout the deformation process, and the radial specimen is activated because of a large number of tensile twins, which makes the polar density of the {0001} prismatic surface texture gradually shift in the positive and negative directions of RD, and the grain *c*-axis turns to the direction perpendicular to the loading axis.

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拉伸取向控制对AZ31镁合金孪生和织构演化的影响

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摘　要：以室温单轴拉伸实验与晶体塑性有限元相结合的方法，通过拉伸取向控制，研究了AZ31镁合金拉伸变形过程中孪生行为、织构演化规律、塑性各向异性之间的关系。基于率相关晶体塑性本构理论，建立了滑移和孪生机制耦合的具有不同取向的晶体塑性本构模型，引入孪晶体积分数研究孪生对AZ31镁合金塑性变形过程中织构演变和力学性能的影响。结果表明，2种不同取向的样品在塑性变形过程中呈现出明显不同的织构演变规律，表现出明显的各向异性。轴向拉伸时孪生被抑制，孪晶激活体积分数低，径向拉伸时孪晶极易产生，孪晶激活体积分数高。轴向试样在整个塑性变形过程中｛0001｝极图偏移较小，径向试样因大量拉伸孪晶的开启，使得｛0001｝棱柱面织构的极密度逐渐向RD的正反方向发生明显偏移。

关键词：AZ31镁合金；孪晶；晶体塑性有限元；织构演化；力学性能

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