Rare Metal Materials and Engineering
Volume 51, Issue 10, October 2022
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Wu Yiping, Jia Yuzhen, Zhang Sha, et al. Twinning Behavior in Extruded AZ31 Alloy Under Low Strain Deformation[J]. Rare Metal Materials and Engineering, 2022, 51(10): 3574-3579.

ARTICLE

Twinning Behavior in Extruded AZ31 Alloy Under Low Strain Deformation

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Abstract: Tension parallel to the radial direction (RDT) and compression along the extrusion direction (EDC) of an extruded AZ31 Mg alloy bar were conducted under a strain rate of 10^{-4} s^{-1} at room temperature. Twinning behavior was characterized by optical microscopy (OM) and electron backscatter diffraction (EBSD). The results demonstrate that extension twins have an effect on the yield point; the yield point of the alloy under EDC is 139 MPa which is higher than 88 MPa of the alloy under RDT. With increasing strain, strain hardening rates under these two stress states show a trend of fast decline at first, and then the hardening rates under EDC start to increase obviously till fracture while that under RDT keeps almost a constant. The increase in the hardening rate under EDC is related to the formation of extension twins and the twinning texture-induced slip activity. A method to measure the twin volume fraction in grains based on EBSD results was proposed. Under RDT, the volume fraction of extension twin in (0002) grains is about 45% at the strain of 0.04.

Key words: Mg alloys; twinning; strain hardening; twin volume fraction; EBSD

Mg alloys belong to the hexagonal closed packed structure. Limited independent slip systems are initiated to adjust the homogeneous deformation at room temperature, and $\{10\bar{1}2\}$ extension twinning acts as the commonest twinning mode and dominates the primary stage of plastic deformation[1]. Extension twin is easy to nucleate when the tensile loading is applied along the *c*-axis or the contractive loading is applied vertical to the *c*-axis, commonly born in the early stage of the deformation or at small strains to coordinate the *c*-axis strain and bring about a rotation of 86.3° along a $<11\bar{2}0>$ direction[2]. The evolution of twinning under uniaxial tension and compression of Mg alloys has been extensively studied[3-6], including the contribution of extension twins to the strain after macroscopic yield, which helps control the yield strength of deformed Mg alloys with strong basic texture[7,8]. When a rolled AZ31B alloy is tensioned parallel to the normal direction and compressed along the rolled direction, twins are detected at low strains of 0.007 for tension and 0.008 for compression with the twin volume fraction measured as 5% and 11%, respectively, which indicates that the yielding of the alloy is directly related to twinning[9].

Calculation of twin volume fraction is necessary to quantitatively calculate how much plastic strain is accomplished by twinning[10]. The twin volume fraction in extruded AZ31 alloy during compression to strains of 0.008~0.015 along the extrusion axis was analyzed by EBSD. Their results showed that extension twinning contributes about 45% of the deformation and has an effect on the yielding[11]. What's more, when Mg and its alloys with sharp textures were deformed in different crystal orientations, various deformation modes can be operated due to the asymmetric nature of hcp structure[1,12]. The experimental comparison of twinning behavior under different stress states is very important to aid the microstructural design of Mg alloys.

Comparison of twinning evolution in extruded AZ31 alloy under two stress states was carried out, i.e. tension along the radial direction (RDT) and compression along the extrusion direction (EDC). Optical microscope (OM) was used to

Received date: November 01, 2021
Foundation item: Changsha University Talent Introduction Project (50800-92808); Excellent Youth Project of Hunan Provincial Department of Education (18B418, 19B055, 19C0156, 19A118); Natural Science Foundation of Hunan Province of China (2020JJ4645)
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characterize the twin structures in terms of the twinning morphology and twin number at low strain levels, and electron backscatter diffraction (EBSD) was employed to examine the twin volume fraction in (0002) grain family at 0.04 strain under RDT (grains with (0002) perpendicular to tensile direction are marked as (0002) grains, so as other grain families of $(10\bar{1}1)$, $(10\bar{1}2)$, $(10\bar{1}3)$, $(10\bar{1}0)$ and $(11\bar{2}0)$.

1 Experiment

The experimental material was extruded AZ31 alloy with a nominal composition of Mg-3wt% Zn-1wt% Al. Tensile samples were wire cut from the extruded bar such that its long (loading) axis was perpendicular to the ED. Samples for tensile tests have a gauge section of 10 mm×6 mm×0.7 mm. For compression tests, samples were cut from the rod along the ED to produce a gauge section of Φ8 mm×12 mm.

Tension and compression tests were accomplished on an Instron 30KN 5967 tester with a strain rate of 10^{-4} s^{-1} to strains of 0.01, 0.015, 0.02, 0.04 until fracture (0.15 for RDT and 0.13 for EDC) at room temperature. Comparison samples were used which were interrupted at incremental strain levels. Three samples were tested under each strain, and the average value of the test results was obtained. All metallographic samples were obtained in the middle of the tensile gauge length perpendicular to ED and in the center of middle plane parallel to ED of compressed sample, and polished for EBSD observations. The EBSD results were obtained on a LEO 1530 with a scanning step of 0.15 μm. HKL Channel 5 software was used to analyze the EBSD results, including grain orientation, texture analysis, twin type determination, etc.

2 Results and Discussion

2.1 Initial microstructure and texture of material

Testing samples for two loading conditions of RDT and EDC are illustrated in Fig. 1a. The inverse pole figure in Fig.1b shows that the main texture component of the extruded alloy is <0001>//RD. The extruded alloy has the typical extrusion texture where *c*-axes of most grains are oriented approximately along RD and perpendicular to the ED. Fig.1c shows the microstructure of the extruded alloy perpendicular to ED. As seen from it, the microstructure is mainly composed of fine equiaxed grains and several large grains with an average grain size of ~8 μm by the line method. Fig. 1d shows the EBSD orientation map of the extruded alloy, and it indicates the grain structure is the same as the result in Fig.1c.

2.2 Stress-strain curve

Fig. 2a shows the true stress-true strain curves of the extruded AZ31 alloy during tension and compression. The curve under EDC displays a similar sigmoidal shape, indicating the typical twinning-dominated deformation[9], since the activation of profuse extension twins changes the concavity in the flow curve and a rapid hardening regime[13-15]. The alloy yields at 88 MPa/0.0029 under RDT and 139 MPa/ 0.0059 under EDC. At strains higher than the yield strain, the stress under EDC increases at a higher rate and the flow stress level is obviously higher than that under RDT.

Fig. 2b presents the hardening rate as a function of true strain under RDT and EDC in order to analyze the strain hardening behavior. The hardening rates under the two conditions both decrease rapidly at first due to the easy accommodation of extension twinning to the plastic strain, reflecting in an obvious increase of the twin number and twin boundary length. Extension twinning has low critical resolved shear stress and is associated with a stress relaxation effect[5,16,17]. However, the hardening rate under RDT keeps almost constant after yielding, while the rate under EDC is followed by a slower and continuous rise until fracture which is suggested to be connected with the faster twinning rate and higher twin volume fraction. The generation and multiplication of twin boundaries inhibit the dislocation motion and

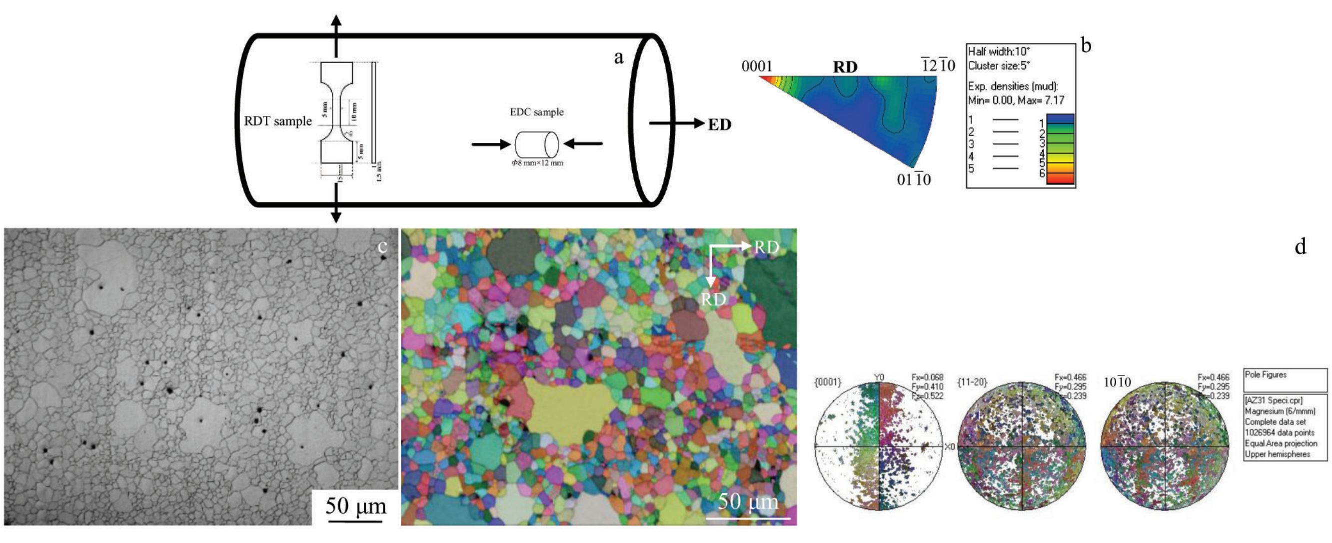

Fig.1 Extruded AZ31 alloy rod: (a) schematic illustration of the rod with tension sample oriented parallel to the RD and compression sample oriented parallel to the ED; (b) inverse pole figure; (c) OM microstructure; (d) EBSD orientation

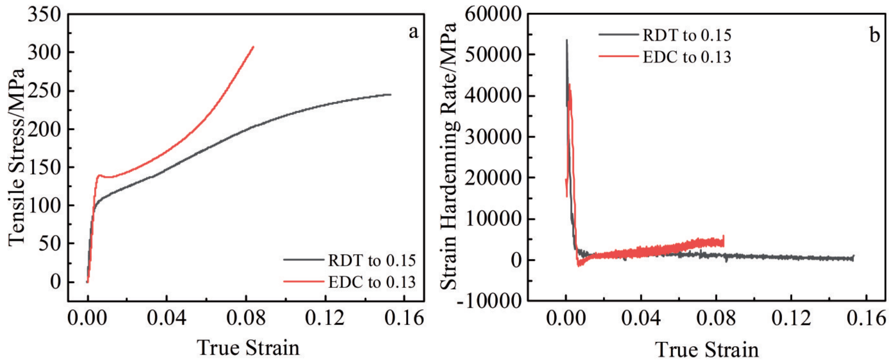

Fig.2 True stress-true strain curves (a) and strain hardening rate curves (b) of RDT and EDC samples

twinning deformation brought in the hardening effect due to a dynamic Hall-Petch mechanism[3]. Moreover, the extension twinning-induced deformation texture changes the dislocation slip activity since the twinned crystal is reoriented from a soft to a hard orientation, which also affects the hardening effect[3,18].

2.3 Microstructure evolution

Fig. 3 shows the microstructure evolution of the extruded alloy during tension deformation. The white arrows indicate twins which are preferable to form nucleus at grain boundaries due to the high local stress concentration during deformation. It is also obvious that the number of twins increases as the strain increases. When the strain is 0.01, few twins are observed and they are slender in morphology (Fig.3a). As the strain increases to 0.015, more twins are observed, but still slender (Fig. 3b). When the strain increases to 0.02 and 0.04, more twins are found. Twin growth besides twin nucleation becomes another significant contributor to the strain (Fig. 3c and 3d). Further increase in strain to 0.15 leads to extensive twins and twin coalescence, with twins parallel or intersecting (Fig. 3e). In most grains, parallel twins tend to be the same twin variants which gradually contact each other and then merge into one grain to completely consume the matrix [19, 20]. For the grain with intersected twins which belong to different twin variants, the grain is difficult to completely twin because the grain can only be divided into several small sections by these twin variants when the growth of one twin variant is restricted by other twin variants[7].

Fig. 4 shows the microstructure evolution of the extruded alloy under EDC at similar equivalent strains of 0.01 and 0.02. As shown in Fig. 4a, the number of twins is obviously more than that under RDT. In a grain with at least two lentoid twins, these twins are mostly parallel rather than intersecting and grow throughout the grain. At 0.02 strain, more twins are induced and become coarser. In particular, parallel twins in an elongated grain are formed in two directions, which is also

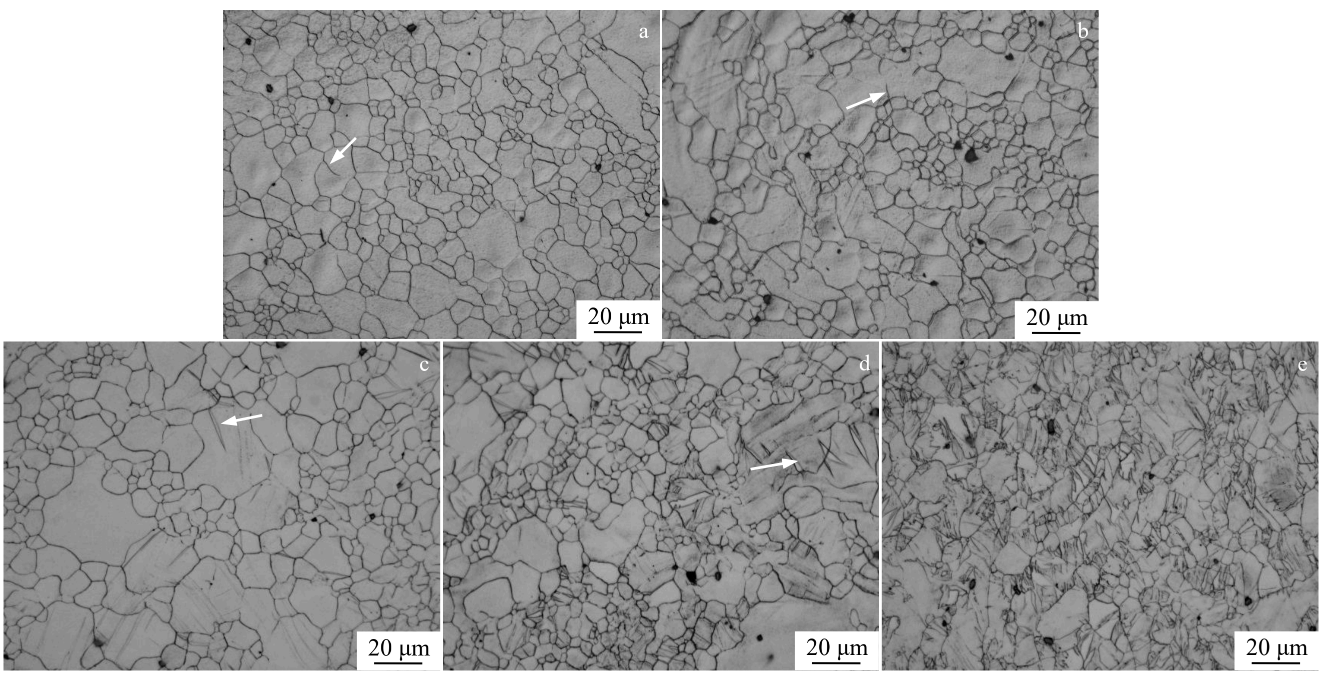

Fig.3 OM microstructures at different tensile strains: (a) 0.01, (b) 0.015, (c) 0.02, (d) 0.04, and (e) 0.15

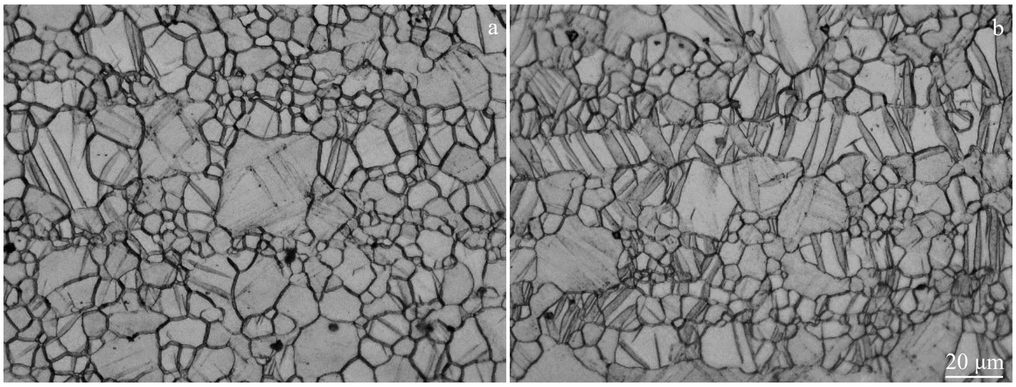

Fig.4 OM microstructures at different compression strains: (a) 0.01 and (b) 0.02

examined in Ref.[21] where about 86% (relative frequency) of extension twins have Schmid factor of 0.4~0.5 under EDC. According to Fig. 1a and 1b, *c*-axis of most grains in the original extruded alloy is oriented perpendicular to the ED, so it is expected that extension twins are more favorably induced under EDC than RDT, which will be discussed in detail later.

2.4 Calculation of twin volume fraction

The initial texture has a decisive influence on the operation of deformation modes of Mg alloys[22]. Upon compression along the transverse direction and perpendicular to the extruded direction of an extruded AZ80 Mg alloy flat bar, twinning mainly dominates the plastic deformation and activates limited basal slip for compatibility [23]. Due to the orientation change caused by the extension twins, neutron diffraction test was used to detect the volume fraction of twins. When the plastic strain exceeds 1.0%, extension twinning contributes 80%~90% of the plastic deformation until twinning is saturated by calculating the twin volume fraction in EBSD maps during compression along the extrusion direction of an extruded Mg-3Al-1Zn alloy[24]. The main texture component of the original extruded AZ31 alloy is <0001>//RD, which means that *c*-axis of grains is along the bar radial direction. Under EDC, the loading direction is perpendicular to *c*-axis of grains, and thus extension twins with high Schmid factor are mostly favorable to occur. Under the same strains of 0.01 and 0.02, more and larger twins are observed in Fig.4 compared with Fig.3a and Fig.3c. Actually, the twinning behavior under RDT is more complex and interesting than under EDC. The Schmid factor of extension twinning in different grain families of the alloy under RDT varies due to the fiber texture. Twins are the most favored in (0002) grains with basal plane normal to tensile direction since Schmid factor for extension twinning and basal slip in (0002) grains is ~0.5 and ~0, respectively; in $(10\bar{1}1)$ grains, the values are ~0.36 and ~0.026, which are ~0.43 and ~0.23 in $(10\bar{1}2)$ grains, ~0.39 and ~0.34 in $(10\bar{1}3)$ grains, while for $(10\bar{1}0)$ and $(11\bar{2}0)$ grains, all values are 0. It is concluded that grains with a low Schmid factor for twinning often show a high Schmid factor for basal slip. Thus, yielding over different grain orientation classes on one single loading direction is expected to be dominated by different deformation modes.

In this work, extension twinning is mostly favored and mainly dominates the plastic deformation under EDC; but under RDT, the case is different. For studying the relationship between extension twinning and yielding behavior under RDT, (0002) grains with the highest Schmid factor of extension twinning are chosen for further twin volume fraction calculation by EBSD at 0.04 strain. Fig.5a indicates EBSD orientation map of the alloy after 0.04 strain, where red line represents extension twin boundary. As seen from the figure, extension twins occur in both large and small grains. Some twins are parallel to each other and almost traverse the grain, while some twins terminate in the grain or are prevented from growing by other twins. Fig.5d shows that the main texture component of the alloy after 0.04 tension strain is $<10\bar{1}0>$//ED, and the original texture component of <0001> //RD is significantly weakened due to the appearance of extension twins. (0002) grains are marked as blue in Fig. 5b and its the corresponding reverse pole figure is shown in Fig.5e. Then, (0002) grains are further isolated and extracted in Fig. 5c. Once isolated based on orientation, non-twinned domains are omitted on the basis of manual identification of large irregularly shaped grains. Fig. 5f is the corresponding reverse pole figure of Fig.5c which shows the huge orientation change due to extension twinning. This sharp texture alteration has been applied by many researchers to calculate twin fraction [11].

To calculate the twin volume fraction, extension twin and the remained untwined parent part in (0002) grains need to be separated and the results are given in Fig. 6. Fig. 6a is the EBSD map of the remained untwined parent part and its corresponding inverse pole figure is shown in Fig. 6c. Extension twins and its corresponding inverse pole figure are presented in Fig.6b and Fig.6d, respectively. According to the inverse pole figure, the twin volume fraction can be calculated as the total point number of (0002) grains (72 626 points in Fig. 5f) divided by the point number of twins (32 951 in Fig. 6d). Therefore, the twin volume fraction is obtained as ~45%.

As seen in Fig. 5b, extension twins are also observed in other grains except (0002) blue grains under RDT. $(10\bar{1}3)$ and $(10\bar{1}2)$ grains are also prone to twin, but less favored, because

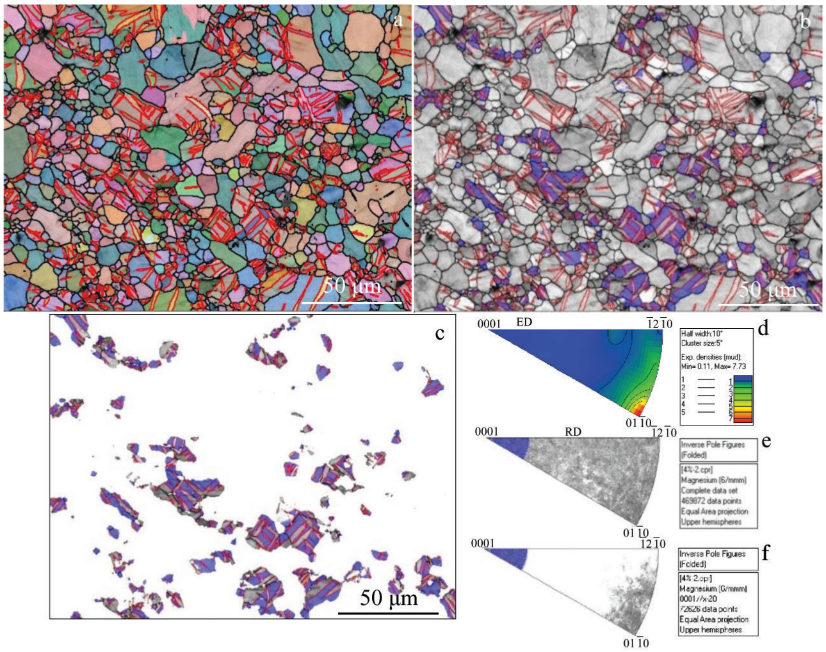

Fig. 5 EBSD orientation of extruded AZ31 alloy at 0.04 tensile strain (a~c) and corresponding IPF (d~f): (a, d) original, (b, e) (0002) grains marked as blue, and (c, f) extracted (0002) grains

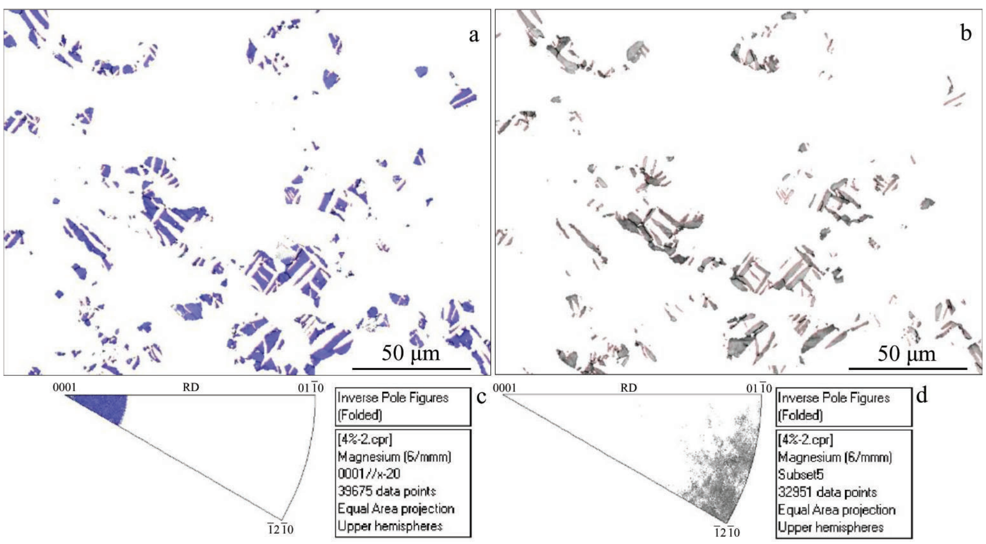

Fig.6 EBSD mapping (a, b) and IPF (c, d) of extruded AZ31 alloy after 0.04 tensile strain: (a, c) untwined matrix of (0002) grains and (b, d) extension twins

the average Schmid factor values of extension twins in these grains are lower than in (0002) grains. Plastic yielding in Mg alloys frequently involves the initiation of both slip and twinning events. In this work, the alloy yields at a stress of 88 MPa and is attributed to extension twinning under RDT, but yielding behavior in different grain families is varied due to different activation degrees of deformation mechanisms. The yielding in ($10\bar{1}2$) and ($10\bar{1}3$) grains may be accounted for the basal slip.

3 Conclusions

1) The extruded AZ31 alloy yields at 88 MPa/0.0029 under RDT and 139 MPa/0.0059 under EDC. The stress level under EDC is much higher than under RDT. The hardening rates under the two states decrease rapidly at first, while it is followed by a continuous increase under EDC and keeps almost constant under RDT.

2) The twin number under RDT is relatively lower than under EDC at the identical strains of 0.01 and 0.02. The original texture component of <0001>//RD is changed to the texture component of <$10\bar{1}0$>//ED after 0.04 tensile strain.

3) (0002) grains with the highest average Schmid factor values of extension twinning present a twin volume fraction value of ~45% at 0.04 strain under RDT.

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挤压态AZ31合金小应变变形时的孪生行为

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摘　要：在室温下对挤压态AZ31合金沿棒材径向进行拉伸变形（RDT试样）和沿挤压方向进行压缩变形（EDC试样），2种变形应变速率均为10^{-4} s^{-1}。采用金相显微镜（OM）和背散射电子衍射（EBSD）研究了变形过程中合金的孪生行为。结果表明：拉伸孪晶影响了合金的屈服点，EDC试样的屈服点为139 MPa，高于RDT试样的屈服点88 MPa。2种变形应力状态下，随应变增加，合金的应变硬化速率都是先快速下降，但EDC试样的硬化速率随后明显上升，并一直持续到断裂，而RDT试样则几乎保持稳定的硬化速率。EDC试样硬化速率的升高与合金中产生大量的拉伸孪晶以及孪晶织构诱导的滑移行为有关。基于EBSD测试结果，给出了一种计算晶粒内孪晶体积分数的方法，得出RDT试样在应变为0.04时，（0002）晶粒中拉伸孪晶体积分数约为45%。

关键词：镁合金；孪生；应变硬化；孪晶体积分数；EBSD

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