Deformation Mechanism of AZ31B Magnesium Alloy Under Different Loading Paths

Shuai-Feng Chen¹ · Li Zheng² · Shi-Hong Zhang¹ · Hong-Wu Song¹ · Ming Cheng¹

Received: 28 June 2015 / Revised: 1 November 2015 / Published online: 9 December 2015
© The Chinese Society for Metals and Springer-Verlag Berlin Heidelberg 2015

Abstract Deformation and texture evolution of AZ31B magnesium (Mg) alloy sheet under uniaxial tension, compression, and reverse loading after different pre-strain (compression and tension) were investigated experimentally. The results indicate that the pre-compressive strain remarkably affects the reverse tensile yield stress and the width of the detwinning-dominant stage during inverse tension process. Similar to stress-strain curve of the uniaxial compression, the curve of reverse tensile yield value also has ‘S’ shape, and its minimum value is only 38 MPa. The relationship between pre-compressive strain and the width of detwinning-dominant stage presents a linear growth, and the greater the pre-compressive strain is, the smaller the strain hardening rate of the detwinning-slip-dominant stage is. Compared with the reverse tension under pre-compression, the influence of the pre-tension deformation on the deformation mechanism of subsequent compression is relatively simple. With the increase in pre-tension strain, the yield stress of the reverse loading is rising.

KEY WORDS: AZ31B magnesium alloy; Loading path; Detwinning; Texture; Yield stress

1 Introduction

Magnesium (Mg) alloys are promising metallic materials for structural applications in electronic, automotive and aerospace fields due to their low density and high strength-to-density ratio [1]. For their hexagonal close-packed (hcp) structure, the basal slip $\langle a \rangle$ has only two independent slip systems and prismatic slip $\langle a \rangle$ and pyramidal slip $\langle a \rangle / \langle c + a \rangle$ [2, 3] are not easy to be activated for their high critical resolved shear stress (CRSS) at room temperature.

In order to coordinate the non-uniform deformation inside the grain, magnesium alloy is prone to activate $\{10\bar{1}2\}$ tension twins (TT) when load tension along the c axis direction or compression is perpendicular to the c axis [4]. Now, plastic deformation mechanism of magnesium alloy has become a hot research topic [5]. These researches mainly concentrate on activation of the slip and twinning systems and texture evolution under uniaxial loading [6, 7]. Hong et al. [8, 9] have shown that the activation of specific twin variants depending on the strain path induces a significant difference in twinning characteristics, such as twin morphology and volume fraction of twins with different compressive strain, which consequently gives rise to a totally different effect on the deformation. Song et al. [10] investigated the relative activity of the twin and slip system under different forming temperatures. It has been shown that when the temperature is above 200°, the dominate deformation mechanism is prismatic slip $\langle a \rangle$ instead of TT, and in situ EBSD was also conducted to study the

Available online at <http://link.springer.com/journal/40195>

✉ Shi-Hong Zhang
shzhang@imr.ac.cn

¹ Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

² School of Materials Science and Engineering, Shenyang University of Technology, Shenyang 110870, China

change in magnesium alloy grain orientation and mechanical behavior under compressive path [11].

Twin size will be smaller or even disappears in different loading paths, and this phenomenon is called as detwinning (DT) or untwinning. In recent years, the researches on the detwinning have attracted widespread concern [12]. Lou *et al.* [13] experimentally studied the effect of pre-strain on the yield stress of subsequent deformation under cyclic loading conditions. Wu *et al.* [14, 15] analyzed the twinning/detwinning process and strain distributions among grains by in situ neutron diffraction, which indicates that detwinning occurs during unloading process. Zheng *et al.* [16] investigated the detwinning behavior with different pre-compressive strain and discovered that detwinning similar to the twinning is governed by the Schmid factor (SF). However, it is still not clear about the relationship between the pre-strain and subsequent deformation, especially the hardening behavior during the cyclic loading.

In the present work, tension, compression, compression–tension and tension–compression experiments were conducted along the extrusion direction (ED) of the extruded AZ31B magnesium alloy sheet, which are combined with the analysis of texture evolution and change in mechanical properties. A detailed analysis of deformation mechanism under different loading paths and the effect of different pre-strain on the cyclic deformation mechanism of magnesium alloy were discussed.

2 Experimental

The material used in this article is commercial extruded AZ31B magnesium alloy, and its thickness is 8 mm. The sheets were machined into cylinder to prevent compressive instability. The detail dimensions of the specimen are shown in Fig. 1.

At ambient temperature, the mechanical behavior of tension, compression, compression–tension and tension–compression experiments were measured along ED on the INSTRON8862 under a deformation speed of 0.1 mm/min. In order to understand the effect of different pre-compressive strain on the cyclic deformation of the Mg sheets, the inverse mechanical behaviors of the sheets with different pre-compressive strains were also measured. The

Fig. 1 Dimensions of specimen (unit mm)

pole figures of {0002}, {10 $\bar{1}$ 0} were analyzed by D/Max-2500PC X-ray to trace the texture evolution. The degree range of α is 0°–70° and β is 0°–360°, 5° per step. The details of the experiments are listed in Tables 1 and 2. It should be mentioned that the ‘√’ and ‘×’ in the table, respectively, mean measuring and no measuring of the texture.

3 Results and Discussion

3.1 Deformation Process of Uniaxial Loading

The initial basic plane (0002) pole figure of extruded sheet shown in Fig. 2 is mainly parallel to ED, which can be divided into two orientation groups: One group is perpendicular to normal direction (ND), called as ND group, and the other group perpendicular to transverse direction (TD), called as TD group, and the ND group is the main component [17].

Figure 3 shows the stress–strain curves of uniaxial tension and compression. The yield stresses of tension and compression are 225 MPa (point A) and 87 MPa (point B), respectively, and the difference between both is 138 MPa, which presents apparent tension/compression asymmetry. When the sheet is compressed along ED, the activation condition of {10 $\bar{1}$ 2} TT is satisfied by the grain orientations of the ND and TD groups. The {10 $\bar{1}$ 2} TT cannot be activated by tension along the ED, and the dominated deformation mechanism is slipping.

The ‘S’ curve of the extruded sheet is related to the alternating dominant deformation mechanism of twinning and slip deformation during the compression process [3]. The plastic stage of the curve can be roughly divided into two stages: twin-dominant deformation and slip-dominant deformation. It is unable to determine the cutoff point of each stage from the stress–strain curve.

When stretched along the ED, the sheet will go through a slip hardening process after the yield point, so tensile yield point A (Fig. 3) with a strain hardening rate of $H_A = 2500$ MPa can be selected as the starting point of the slipping hardening process. By combining $H_A = 2500$ MPa with the value of strain hardening rate during compression,

Table 1 Program of unidirectional loading tests

Specimen	Strain path	Strain (%)	Texture test
No. 1	Monotonic tension	Till failure	√
No. 2	Monotonic compression	Till failure	×
No. 3	Monotonic compression	3	√
No. 4	Monotonic compression	7	√
No. 5	Monotonic compression	11	√

Table 2 Program of compression–tension and tension–compression loading tests

Specimen	Strain path	Pre-compression strain (%)	Strain of reverse loading (%)	Texture test
No. 6	Tension–compression	4	7	×
No. 7	Tension–compression	5	9	×
No. 8	Tension–compression	8	12	×
No. 9	Compression–tension	3	10	×
No. 10	Compression–tension	4	10	×
No. 11	Compression–tension	5	10	×
No. 12	Compression–tension	6	10	×
No. 13	Compression–tension	7	10	×
No. 14	Compression–tension	8	10	×
No. 15	Compression–tension	8	3	✓
No. 16	Compression–tension	8	5	✓
No. 17	Compression–tension	8	8	✓

Fig. 2 Pole figure of as-received extruded magnesium sheet **Fig. 3** Strain hardening rate curve of tension, compression and dominate deformation mechanism distribution along compression stress–strain curve

two feature points can be determined: twinning-dominant end point (point a in Fig. 3, $\varepsilon_a = 5.3\%$) and slip-dominant deformation starting point (point b in Fig. 3, $\varepsilon_b = 7\%$). Through these two feature points, compressive stress–strain curve in Fig. 3 can be divided into three stages: the twinning-dominant stage (TDS), twinning-slip transition stage (TSTS) and slip-dominant stage (SDS).

The pole figures under different compressive strain are shown in Fig. 4. During TDS, Fig. 4a shows that after 3% compressive strain along the ED, the texture changes obviously. Part of the grains in the sample have twinned, which deflect the grains to be parallel to the ED. When the compressive strain is about 5.3%, twinning has occurred in most of the grains. Macroscopic deformation cannot be coordinated by a small amount of residual TT, which needs more activated slip systems, and the material turns into TSTS.

Fig. 4 Pole figures of extruded magnesium sheet under 3% **a**, 7% **b**, 11% **c** compression strains along ED

During TSTS, part of the non-twined grain can continue the twinning deformation. Meanwhile, the activation of TT significantly changes the order of Schmid factor of different slips and accordingly affects the activation of slips during the subsequent deformation process. Moreover, the material gets a high strain hardening rate due to the hindrance produced by the twinning boundary (TB) suppresses motion of dislocations [6]. When the slipping is once started, the hardening rate will decrease rapidly. From Fig. 4b, when the compressive strain is 7%, ND group in the original material disappears completely due to

twinning. In SDS, slip system turns to be hardening saturation with compressive strain rising, and the hardening rate will become smaller, which is consistent with the deformation mechanism of fcc, bcc structure metal. In this process, the material texture remains unchanged basically.

3.2 Deformation Mechanism During Compression–Tension Process

Figure 5 shows the stress–strain curve of compression–tension with pre-compressive strain 8% along ED. It can be

seen that the tensile curve after compression is also a ‘S’ shape curve, which is similar to compression curve. In reverse tensile process, detwinning happens in twinning grains produced during compression process. Because detwinning does not need nucleation process, the CRSS value of detwinning is lower than that of twinning. The yield stress of the reverse loading is low, and there is obvious Bauschinger effect [13].

By using the same method described above with $H_A = 2500$ MPa, the stress-strain curve of the reverse tensile process can be divided into three stages with a’ and b’ as the cutoff points shown in Fig. 5: detwinning-dominant stage (DTDS), detwinning–slip transition stage (DTSTS) and slip-dominant stage (SDS).

The strain hardening rate is also shown in Fig. 5. In DDS, the hardening rate of Mg alloy decreases rapidly due to detwinning. It is noticed that the strain hardening rate of DTSTS is more than twice as that of TSTS. One reason is that the interaction between slip and DT is stronger, because more dislocations are piled up around the twinning boundary (TB) or grain boundary (GB) after the pre-compressive deformation. The other reason is the different activated slip systems between DTSTS and TSTS [7, 16, 17]. Figure 6 shows the pole figures of the samples under different reverse tension strain and 8% compression strain along ED. As shown in Fig. 6a, part of the grains have been back to the initial orientations under 3% inverse tension strain, indicating that detwinning happens in the twinned grains with a small inverse tension strain. Figure 6b indicates that most grains are back to their original orientations with 7% inverse tension strain, and the sheet has been back to the initial texture condition with an inverse tension strain of 11%, as shown in Fig. 6c.

Fig. 5 Stress–strain curve of extruded magnesium sheet during compression–tension along ED and strain hardening rate curve during reverse tension

3.3 Inverse Tensile Deformation under Different Pre-compressive Strains

Stress–strain curves of the reverse loading along the ED with pre-compressive strains from 3% to 8% are shown in Fig. 7. Overall, the effects of different pre-strain on the reverse loading are mainly discussed in three aspects: the reverse yield stress, the width of DTDS and the strain hardening rate of DTSTS.

3.3.1 Effect of Pre-compressive Strain on the Inverse Tensile Yield Stress

As shown in Fig. 7, the Mg alloy sheets in the reverse tensile process have no obvious yield point. Generally, we can define the yield point by using $R_{p0.2}$, but yield stress defined at the offset 0.2% in this experiment still locates at the rising area of stress–strain curve, corresponding to point a in Fig. 7, and also not accurate enough to describe the yield behavior of the sheets. So the yield stress is determined with a larger strain value offset 0.4% to compare the yield stress of reverse loading under different pre-compressive strain. Point b is marked in Fig. 7 [13] by this method.

The yield stress of the inverse tension also presents the ‘S’ shape, as shown in Fig. 8. The maximum value is 68 MPa, which is much lower than the yield stress of uniaxial tension (205 MPa), and even lower than that of uniaxial compression (97 MPa), which suggests that the detwinning significantly decreases the yield stress of the inverse tension.

The reverse loading yield stress is only 38 MPa with pre-compressive strain of 3%. At this stage, tensile twinning generation is relatively small, due to the small pre-compressive strain. Muransky *et al.* [18, 19] found that when pre-compressive strain is small, there will be detwinning activated by the internal stress of unloading process during the cyclic loading process of Mg alloys. This can be explained by the weak interaction between matrix and twins, and the CRSS of detwinning is low under this condition.

When the pre-compressive strain ranges from 4% to 6%, tensile twins (TT) will be produced in most of the grains. Meanwhile, the interaction between matrix and twins will be enhanced which leads to the increase in CRSS of detwinning process. So the internal stress of unloading process is not large enough to activate the detwinning process, which needs a larger reverse stress. During these strain ranges, the reverse yield stresses are stable at about 53 MPa, which may be related to the stable interaction between matrix and twins, because twinning is the dominant deformation, and the dislocation density will increase slightly with the strain rising.

Fig. 6 Pole figures under different reverse tension strains of 3% **a**, 7% **b**, 11% **c** and with 8% compression strain along ED

When the pre-compressive strain is 7%–8%, the Mg alloy goes into TSTS (see Fig. 4). At this stage, slipping will replace twinning to be the dominant deformation mode. With the dislocation density increasing rapidly, interaction between the matrix and twins makes the hardening effect significantly enhanced. It can be predicted that there are a large number of dislocation at the TB, which will impede detwinning activation and improve the yield stress in the inverse tension process.

3.3.2 Effect of Pre-compressive Strain on the Width of DTDS

The strain hardening rate of the stress–strain curves under compression–tension loading along ED with different pre-compression strain is shown in Fig. 9. We can define the starting point (point a in Fig. 9) and ending point (point b in Fig. 9) of the DTDS using the same $H_A = 2500$ MPa. The strain between the points a and b is the width of

Fig. 7 Stress-strain curves of extruded magnesium sheet under compression-tension loading along ED with different pre-compression strains

Fig. 8 Relations between yield stress of reverse tension and pre-compression strain

DTDS. As shown in Fig. 10, the pre-compressive strain and width of DTDS present a liner relationship, which can be described by the following equation:

$$\varepsilon_w = 0.697\varepsilon_{pc} - 1.80, \quad (1)$$

where ε_w is the width of the DTDS and ε_{pc} is the pre-compressive strain. With the pre-compressive strain increasing, the growth of the fraction of twinning will broaden the width of DTDS. By backstepping, if the $\varepsilon_{pc} = 2.62\%$, then $\varepsilon_w = 0$, which means that there will be no existing of DTDS when ε_{pc} is smaller than 2.62%.

3.3.3 Effect of Pre-compressive Strain on the Strain Hardening Rate of DTSTS

The strain between point b and point c in Fig. 9 stands for the DTSTS. The strain hardening rate decreases from

Fig. 9 Strain hardening rate curves of reverse tension with different pre-compressive strain along ED

Fig. 10 Relation between pre-compressive strain and detwinning-dominant deformation strain in reverse tension

17,000 MPa (with pre-strain 3%) to 7000 MPa (with pre-strain 8%) with the rising of the pre-compressive strain. As described above, during TSTS, twins with a low Schmid factor (SF) can be activated under high stress, when the pre-strain is increased. The enhanced interaction between the twins and matrix induce more dislocations piled up at the twinning boundary (TB), which results in a higher stress during the DTSTS. However, the piling up of dislocations at the TB will lead to a decrease in the strain hardening rate due to the limitation of the hardening potential. Increasing the pre-compressive strain can enlarge the fraction of these twins, which could coordinate more internal stress inside the grain during the DTSTS, and the strain hardening rate will be lower by the relaxing of the internal stress. It is worth mentioning that the maximum value of the strain hardening rate all appears near $\varepsilon = 0$, the reason of which is not clear at this time.

Fig. 11 Stress-strain curves of extruded magnesium sheet under tension-compression loading along ED with different pretension strain

Fig. 12 Relation between yield strength of reverse compression and pretension strain

3.4 Deformation Mechanism During Tension-Compression Process

Figure 11 presents the stress-strain curves of the extruded Mg alloy sheets. The tensile loading path does not satisfy the condition to activate twinning, so the slipping is the dominant deformation mechanism, which is similar with metals with bcc and fcc structure. The yield stress (using the same 0.4% off-set value) of the inverse compression under different pre-tensile strain is shown in Fig. 12, from which it can be known that the activation of twinning makes the yield stress lower than that of tension. With the pre-tensile strain increasing, the yield stress of the inverse compression grows from 120 MPa (pre-tension strain of 4%) to 150 MPa (pre-tension strain of 8%), which is 53 MPa higher than yield stress of uniaxial compression (97 MPa). The dislocations piled up

during the pre-tension are the main factor to influence the twinning process in the subsequent compressive deformation. The hindering effect will be enhanced by the increasing dislocations with a bigger pre-tensile strain, which can improve the CRSS of twinning, so the yield stress is higher with a larger pre-tensile strain.

4 Conclusions

1. Pre-compressive strain can change the yield stress and the width of twin-dominant stage (DTS) of Mg alloy remarkably. Similar to the uniaxial compression curve, the curve of tensile yield stress of inverse tension presents a 'S' shape, and the minimum yield stress is 38 MPa. It has a liner relationship between pre-compressive strain and the width of detwinning-dominant stage (DTDS). The strain hardening rate of detwinning-slip transition stage (DTSTS) decreases with the increase in pre-compressive strain.
2. Compared with the deformation of compression-tension, it is prone to understand the effect of pre-tensile strain on the subsequent compression deformation. The yield stress would increase with a larger pre-tensile strain.

Acknowledgments This work was financially supported by the National Nature Science Foundation of China (No. 51174189).

References

- [1] E. Doege, K. Dröder, J. Mater. Process. Technol. **115**, 14 (2001)
- [2] Q. Liu, Acta Metall. Sin. **46**, 1458 (2010). (in Chinese)
- [3] R. Xin, Q. Liu, Mater. China **2**, 16 (2011)
- [4] L. Jiang, J.J. Jonas, A.A. Luo, A.K. Sachde, S. Godet, Mater. Sci. Eng. A **445**, 302 (2007)
- [5] B. Song, R. Xin, N. Guo, T. Lou, Q. Yang, Chin. J. Nonferrous Met. **24**, 2699 (2014). (in Chinese)
- [6] X. Yang, L. Zhang, Y. Jiang, Y. Zhu, Chin. J. Nonferrous Met. **21**, 269 (2011). (in Chinese)
- [7] W. Ding, L. Jin, W. Wu, J. Dong, Chin. J. Nonferrous Met. **21**, 2371 (2011). (in Chinese)
- [8] S.G. Hong, S.H. Park, C.S. Lee, Acta Mater. **58**, 5873 (2010)
- [9] S.G. Hong, S.H. Park, C.S. Lee, Scr. Mater. **64**, 145 (2011)
- [10] G.S. Song, S.H. Zhang, L. Zheng, L. Ruan, J. Alloys Compd. **509**, 6481 (2011)
- [11] G.S. Song, Q.Q. Chen, S.H. Zhang, Y. Xu, Mater. Des. **65**, 534 (2015)
- [12] C. Lou, X.Y. Zhang, R.H. Wang, G.L. Duan, Q. Liu, Acta Metall. Sin. **49**, 291 (2013). (in Chinese)
- [13] X.Y. Lou, M. Li, R.K. Boger, S.R. Agnew, Int. J. Plast. **2007**(23), 44 (2007)
- [14] L. Wu, S.R. Agnew, D.W. Brown, G.M. Stoica, Acta Mater. **56**, 3699 (2008)
- [15] D.W. Brown, A. Jain, S.R. Agnew, B. Clausen, Mater. Sci. Forum **539**, 3407 (2007)

- [16] L. Zheng, S.H. Zhang, D. Helm, H.W. Song, G.S. Song, N.Y. Ye, *Rear Met.* **34**, 698 (2015)
- [17] K. Yu, S. Rui, R. Wang, C. Peng, X. Xue, *Chin. J. Nonferrous Met.* **18**, 2127 (2008). (**in Chinese**)
- [18] O. Muránsky, D.G. Carr, P. Šittner, E.C. Oliver, *Int. J. Plast.* **25**, 1107 (2009)
- [19] O. Muransky, D.G. Carr, M.R. Barnett, E.C. Oliver, P. Šittner. *Mater. Sci. Eng. A* **496**, 14 (2008)