Magnesium Technology 2013
Edited by: Norbert Hort, Suveen N. Mathaudhu, Neale R. Neelameggham, and Martyn Alderman
TMS (The Minerals, Metals & Materials Society), 2013

TEXTURE DEVELOPMENT IN AN EXTRUDED MAGNESIUM ALLOY DURING COMPRESSION ALONG THE TRANSVERSE DIRECTION

D. Sarker, D.L. Chen
Department of Mechanical and Industrial Engineering, Ryerson University, 350 Victoria Street, Toronto, Ontario M5B 2K3, Canada

Keywords: compression, twin, strain-hardening, orientation, texture.

Abstract

Wrought magnesium alloys generally exhibit a certain extent of mechanical anisotropy at room temperature because of the presence of texture. In the present study the work hardening behavior and texture evolution of an extruded AM30 magnesium alloy were studied after compression along the transverse direction (TD) at varying strain levels. The initial samples were chosen to have a strong basal texture with the basal planes parallel to the extrusion direction. During compression a stage of accelerated work hardening characterized by an increasing work hardening rate appeared, and the *c*-axes of the grains were observed to re-orient parallel to the compressive loading direction. With increasing compressive strain extension twins first formed and then disappeared at higher strains.

Introduction

Magnesium alloys are the lightest structural material and therefore are promising for the application in the transportation industry to reduce vehicle weight and increase fuel efficiency [1, 2]. However, their widespread application in industry is impeded because of their poor room temperature ductility, and strong plastic anisotropy, which are due to the hexagonal close-packed (hcp) crystal structure of these materials. The anisotropy of the mechanical properties is mainly due to the development of sharp crystallographic texture during plastic deformation. Generally the rolled/extruded magnesium alloy shows a strong basal texture with most basal planes aligned parallel to the rolling/extrusion direction [3]. The basal texture formed in the extruded material influences the plastic anisotropy as well as the activation of slip and/or twinning during deformation.

Magnesium possesses limited deformation modes available for slip parallel to the *c*-axis and twinning occurs to accommodate the imposed strain [4-6]. Depending on the crystal orientation they accommodate plastic deformation by *c*-axis extension or contraction and form extension twins or contraction twins, respectively. The formation of extension and contraction twins re-orients the crystal lattice by 86.3° and 56.2°, respectively, and contributes to texture evolution [4, 7-9]. Thus the anisotropy in mechanical property results from the combination of initial strong texture and twin formation depending on the crystal orientation.

The occurrence of deformation twinning in magnesium alloys has been widely reported in the literature [10-18], however, its precise influence on the mechanical behavior and texture evolution under monotonic and cyclic loading have not yet been well understood. All studies show the change of initial basal texture with deformation condition. Systematic studies on the texture formation during deformation of magnesium alloys are still absent. The studies on the relationship between the crystallographic texture and plastic deformation mechanisms in wrought magnesium alloys would provide the important information for the general understanding of the plastic deformation of polycrystalline materials with hcp structures, and are beneficial for optimizing alloying composition and forming processes to produce high-performance wrought magnesium alloys. The aim of the present work was to provide further insights into the role of twinning in the texture evolution and deformation mechanisms of an extruded AM30 magnesium alloy.

Experimental

A recently-developed 7 mm thick extruded AM30 magnesium alloy plate was selected in the present study. Cylindrical specimens with a diameter of 5 mm and height of 8 mm were machined with the cylinder (compression) axis parallel to the transverse direction (TD). Compression tests were first conducted until failure using a computerized Instron machine at a strain rate of 1.25×10^{-4} s^{-1} and at room temperature. To observe the microstructural change with texture evolution, some samples were tested at 4.3% strain and some were stopped before failure. X-ray texture analysis was performed using a multi-functional PANalytical X-ray diffractometer. The pole figures were calculated using MTEX toolbox by measuring incomplete pole figures between Ψ=0 to 75° in the back reflection mode using Cu-Kα radiation at 45 KV and 40 mA. A set of five pole figures (i.e., $\{10\bar{1}0\}$, {0002}, $\{10\bar{1}1\}$, $\{11\bar{2}0\}$, $\{10\bar{1}3\}$) were used to calculate the orientation distribution function (ODF) using the MTEX toolbox. To present ODF, Bunge notations of the Euler angles were used. For the microstructure characterization, the deformed samples were cut along the compression axis using a slow diamond cutter, cold-mounted, ground, polished, and etched using acetic picral solution containing 4.2-g picric acid, 10-mL acetic acid, 10-mL H_2O, and 70-mL ethanol to examine the evolution of deformation twins during compression. It should be noted that in evaluating the stress-strain curves and strain-hardening rates, the machine deformation itself was eliminated using a calibration curve to obtain the actual or net deformation of test samples.

Results and Discussion

The initial pole figure of extruded AM30 Mg alloy is shown in Fig.1a. The pole figure showed an intense basal texture where the *c*-axis of the hcp unit cell was basically perpendicular to the ED. Similar texture was observed in a rolled AZ31B-H24 Mg alloy [17-19]. A twin-free microstructure of undeformed metal is shown in Fig.1b. The schematic view in Fig. 1c illustrates the orientation of samples used in the present study, where the cylindrical axis was parallel to the transverse direction, which was essentially perpendicular to the c-axis of most grains.

The stress-strain curve and strain-hardening rate of AM30 magnesium alloy during compression along the TD are shown in Fig.2 (a) and (b), respectively, where a compressive yield strength of ~96 MPa was obtained, which was considerably lower than the tensile yield strength of ~189 MPa [12]. This was attributed to the occurrence of twinning during compression which will be discussed later.

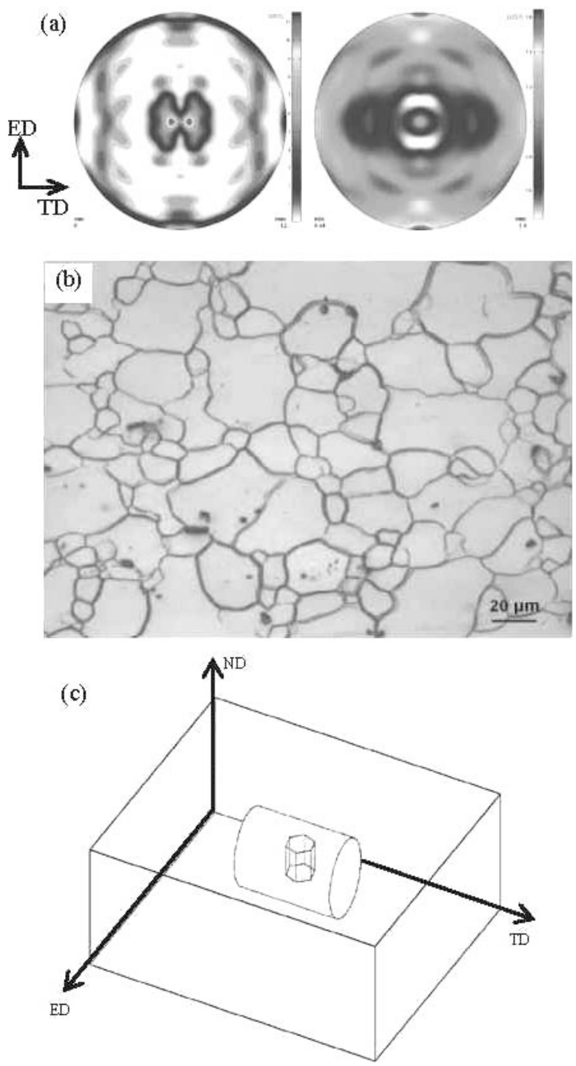

Figure 1. (a) Initial (0001) and (10 0) pole figures of as-extruded AM30 magnesium alloy, (b) a typical microstructure of undeformed extruded AM30 magnesium alloy, (c) a schematic diagram showing the orientation of the compressive samples parallel to the transverse direction (TD).

The stress-strain curve of AM30 extruded alloy exhibited a skewed shape (Fig.2 (a)), which was very different from the normal tensile (or compressive) curves of most metals with cubic crystal structures. This could be better seen based on the change of strain hardening rate $d\sigma/d\varepsilon$ (where σ is true stress) with respect to true strain ε, where three stages of strain hardening could be more clearly discerned (Fig.2(b)). Stage A was characterized only by a slight decrease in the strain hardening rate up to a compressive true strain of approximately 3%, followed by Stage B with a fairly strong increase in the strain hardening rate up to ~6.5% compressive true strain, and then Stage C with an decreasing strain hardening rate again until failure. A similar trend in the change of strain hardening rate has also been observed in AZ31 magnesium alloy [20] and in the extruded AM30 magnesium alloy during compression along ED [21].

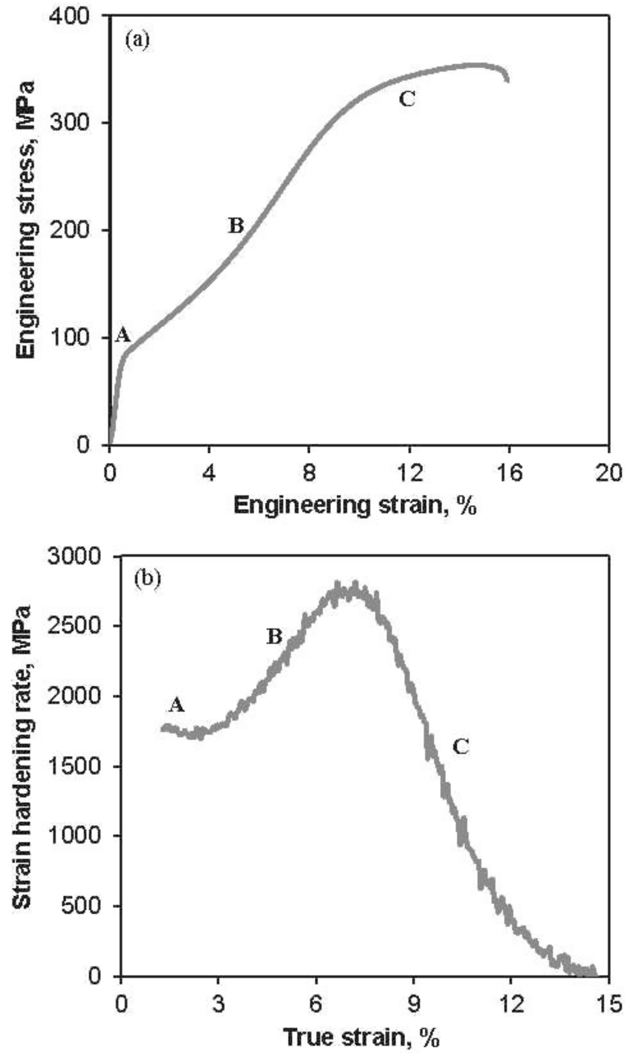

Figure 2. (a) A typical compressive stress-strain curve and (b) strain hardening rate as a function of true strain in the extruded AM30 magnesium alloy with compression axis parallel to the transverse direction.

To understand such a flow stress characteristic, the microstructural development of the samples compressed to varying strain amounts was examined and shown in Fig. 3, where the loading direction was indicated. The microstructural changes with the imposed strains of 4.3% and 12.9%, respectively, are illustrated in Figs. 3a and 3b. At a strain level of 4.3%, within the strain hardening range of stage B (Fig. 2(b)), the presence of twins was clearly visible. This observation was in agreement with the previous studies of Jiang *et al.* [22], where the tensile twins in an AZ31 magnesium alloy was reported to occur in a strain range of 2-4%. On further straining, just before failure, most twins became invisible in 3b.

The texture results are presented Fig. 4 in terms of the pole figures. The pole figures were measured from the deformed samples after compression tests at different strain amounts. In Fig. 1(a), the as extruded base metal (0% strain) shows a strong basal texture, which means that {0001} basal planes in most grains were parallel to the ED with $\{10\bar{1}0\}$ planes around the circumference of the pole figure. At a strain of 1.5% as shown in Fig. 4(a), some (0001) poles rotated towards the TD, while the pole figure still showed some intensity at the center similar to the initial texture (Fig. 1(a)). $\{10\bar{1}0\}$ poles rotated from periphery and started to concentrate at the center. A gradual change of intensity distribution was also observed after compressive deformation at a strain of 4.3% in Fig. 4(b) with more intense (0001) poles toward TD and $\{10\bar{1}0\}$ poles around the center. The (0001) poles of most grains rotated to the TD after a strain of 12.9% along TD with an obvious preferred distribution of prismatic $\{10\bar{1}0\}$ poles at the center, as shown in Fig. 4(c).

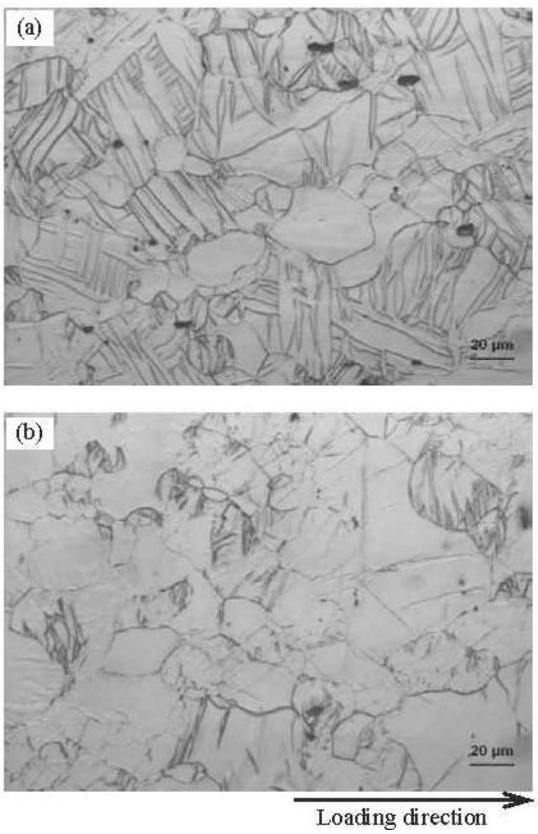

Figure 3. Microstructure changes after compressive deformation of the samples oriented in the transverse direction at a strain level of (a) 4.3%and (b) 12.9%.

This texture evolution was related to the microstructure development or the twin formation with increasing compressive strain level. The microstructure of compressed sample shown in Fig. 3a, corresponding to a strain of 4.3%, was completely different from the initial microstructure shown in Fig. 1(b). A lot of twins formed at the compressive deformation. This observation was consistent with the previous observations [22, 23], where the extension twins were reported to first occur in a strain range of 2-4%. With increasing strain levels, the extension twins appeared to thicken quickly, usually to cover each grain and their boundaries disappeared. This was again in good agreement with the previous observations [16, 22, 23]. Extension twinning was seen to play a predominant role in the texture evolution in the early stages of compression along the TD. The occurrence of extension twinning during compression along the TD, caused grains to rotate by ~86° and led to *c*-axis parallel to the TD. This is clearly seen in the evolution of the pole figures shown in Fig. 4, where the (0001) poles rotated always against the compressive direction, i.e., the TD in the present study (Fig. 4a-c).

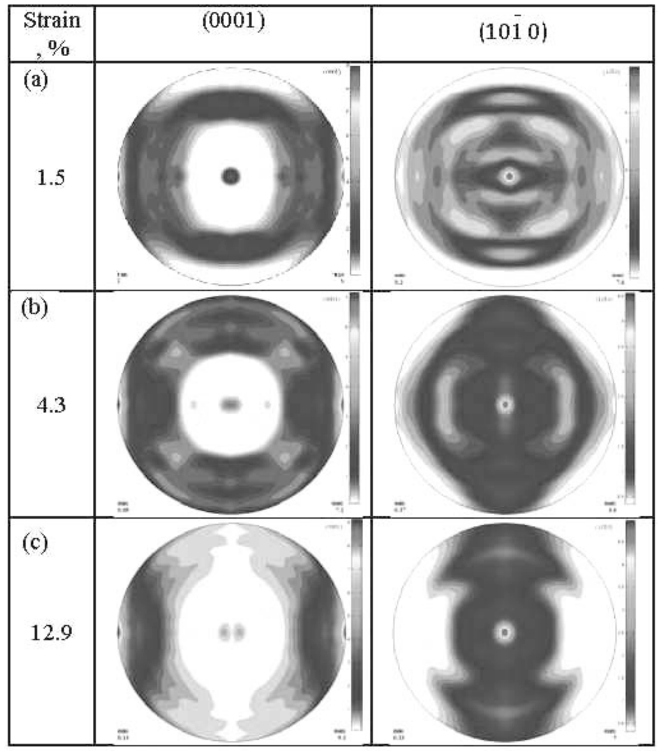

Figure 4. Pole figures measured from the compressed samples oriented in the transverse direction at a strain amount of (a) 1.5%, (b) 4.3% and (c) 12.9%.

Conclusions

The present study demonstrates the concurrent change in both the texture and deformation characteristics of extruded magnesium alloy AM30. With increasing strain during compression extension twins first formed and then disappeared at higher strains. The extension twinning played an important role in accommodating the compressive deformation as the hexagonal *c*-axis lay perpendicular to the loading direction. The low yield stress, rapid texture changes with increasing compressive strain amounts observed can be explained by the high twinning activity. As a consequence, the *c*-axes of the grains were oriented parallel to the compressive loading direction.

Acknowledgements

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC), Premier's Research Excellence Award (PREA), NSERC-DAS Award, AUTO21 Network of Centers of Excellence, and Ryerson Research Chair program for providing financial support. The authors also thank, Dr. A. Luo, General Motors Research and

Development Center for providing the test materials, and Q.Li, A.Machin, J.Amankrah, and R.Churaman for assisting in the experiments.

References

1. T.M. Pollock, "Weight Loss with Magnesium Alloys," *Science*, 328 (2010), 986-987.
2. E. Aghion, B. Bronfin, and D. Eliezer, "The role of the magnesium industry in protecting the environment," *Journal of Materials Processing Technology,* 117 (2001), 381-385.
3. B. H. Lee, S. H. Park, S. G. Hong, K.T. Park, and C.S. Lee, "Role of initial texture on the plastic anisotropy of Mg–3Al–1Zn alloy at various temperatures," *Materials Science and Engineering A,* 528 (2011), 1162–1172.
4. L. Jiang, J.J. Jonas, A.A. Luo, A. K. Sachdev, and S. Godet, "Influence of {10-12} extension twinning on the flow behavior of AZ31 Mg alloy," *Materials Science and Engineering A,* 445-446 (2007), 302-309.
5. S.B. Yi, C.H.J. Davies, H.G. Brokmeier, R.E. Bolmaro, and J. Homeyer, "Deformation and texture evolution in AZ31 magnesium alloy during uniaxial loading ," *Acta Materialia*, 54 (2006), 549–562.
6. S. Sandlöbes, S. Zaefferer, I. Schestakow, S. Yi, and R.G. Martinez, "On the role of non-basal deformation mechanisms for the ductility of Mg and Mg–Y alloys," *Acta Materialia*, 59 (2011), 429-439.
7. M. Knezevic, A. Levinson, R. Harris, R.K. Mishra, R.D. Doherty, and S.R. Kalidindi, "Deformation twinning in AZ31: Influence on strain hardening and texture evolution," *Acta Materialia*, 58 (2010), 6230–6242.
8. A.A. Salem, S.R. Kalidindi, R.D. Doherty, and S.L. Semiatin, "Strain hardening due to deformation twinning in α-titanium: mechanisms," *Metallurgical and Materials Transactions A,* 37A (2006), 259-268.
9. C.H. Cáceres, P. Lukác, and A. Blake, "Strain hardening due to {10-12} twinning in pure magnesium," *Philosophical Magazine*, 88 (2008), 991-1003.
10. A. Jiang, A. Godfrey, W. Liu, and Q. Liu, "Microtexture evolution via deformation twinning and slip during compression of magnesium alloy AZ31," *Materials Science and Engineering A*, 483-484 (2008), 576-579.
11. Y.T. Zhu, X.L. Wu, X.Z. Liao, J. Narayan, L.J. Kecskes, and S.N. Mathaudhu, "Dislocation–twin interactions in nanocrystalline fcc metals," *Acta Materialia*, 59 (2011), 812-821.
12. S. Begum, D.L. Chen, S. Xu, and A.A. Luo, "Strain-controlled low-cycle fatigue properties of a newly developed extruded magnesium alloy," *Metallurgical and Materials Transactions A*, 39 (2008), 3014-3026.
13. S. Begum, D.L. Chen, S. Xu, and A.A Luo, "Low cycle fatigue properties of an extruded AZ31 magnesium alloy," *International Journal of Fatigue*, 31 (2009), 726-735.
14. S. Begum, D.L. Chen, S. Xu, and A.A. Luo, "Effect of strain ratio and strain rate on low cycle fatigue behavior of AZ31 wrought magnesium alloy," *Materials Science and Engineering A* 517 (2009), 334-343.
15. X.Z. Lin, and D.L. Chen, "Strain controlled cyclic deformation behavior of an extruded magnesium alloy," *Materials Science and Engineering A*, 496 (2008), 106-113.
16. M.R. Barnett, "Twinning and the ductility of magnesium alloys Part I: "Tension" twins," *Materials Science and Engineering A,* 464 (2007), 1-7.
17. Y.C. Xin, M.Y. Wang, Z. Zeng, M.G. Nie, and Q. Liu, "Strengthening and toughening of magnesium alloy by {10-12} extension twins," *Scripta Mater*, 66 (2012), 25-28.
18. L. Wu, S.R. Agnew, Y. Ren, D.W. Brown, B. Clausen, G.M. Stoica, H.R. Wenk, and P.K. Liaw, "The effects of texture and extension twinning on the low-cycle fatigue behavior of a rolled magnesium alloy, AZ31B," *Materials Science and Engineering A,* 527 (2010), 7057-7067.
19. S.H. Park, S.G. Hong, J.H. Lee, and C.S. Lee, "Multiple twinning modes in rolled Mg–3Al–1Zn alloy and their selection mechanism" *Materials Science and Engineering A,*532 (2012), 401-406.
20. B.S.Wang, R.L.Xin, G.J.Huang, and Q.Liu, "Effect of crystal orientation on the mechanical properties and strain hardening behavior of magnesium alloy AZ31 during uniaxial compression," *Materials Science and Engineering A,* 534 (2012) 588-593.
21. D. Sarker and D.L. Chen, "Detwinning and strain hardening of an extruded magnesium alloy during compression," *Scripta Materialia* 67 (2012), 165–168.
22. A. Jiang, A. Godfrey, W. Liu, and Q. Liu, "Microtexture evolution via deformation twinning and slip during compression of magnesium alloy AZ31," *Materials Science and Engineering A* 483-484 (2008), 576-579.
23. L. Jiang, J.J. Jonas, R.K. Mishra, A.A. Luo, A.K. Sachdev, and S. Godet. "Twinning and texture development in two Mg alloys subjected to loading along three different strain paths" *Acta Materialia*, 55 (2007), 3899-3910.