J Mater Sci (2007) 42:3552–3556
DOI 10.1007/s10853-007-1559-0

Effect of crystal orientation on the ductility in AZ31 Mg alloy sheets produced by equal channel angular rolling

Yong Qi Cheng · Zhen Hua Chen · Wei Jun Xia

Received: 27 November 2005 / Accepted: 18 September 2006 / Published online: 18 February 2007

Abstract Shearing deformation was applied to AZ31 magnesium alloy sheets by a new concept processing, so-called equal channel angular rolling (ECAR) processing for the development of a different crystal orientation compared with the as-received sheets. The results indicated that deformation behavior was changed obviously and a clear yield phenomenon appeared followed by a clear work hardening state region after ECAR processing. And the elongation-to-failure of the ECARed specimens exhibited over 24%, which was almost twice larger than that of the as-received specimens. All of these can be owing to the modification of the crystal orientation.

Introduction

The mechanical properties of a wrought magnesium alloy are affected by the basal texture [1–5] because the critical resolved shear stresses for the non-basal slips are much higher than that for basal slip near the room temperature [6]. Iwanaga et al. reported that the reduction of basal plane texture brings about good deep drawability from room temperature to warm temperature below 175 °C [7]. However, primary processing for producing sheets such as symmetrical rolling generally gives rise to a strong basal plane texture [8, 9], and this leads to a very limited ductility near the room temperature. While the asymmetric rolling, such as single roller drive rolling [10] and differential speed rolling (DSR) [11, 12] can introduce shear strain, which can fabricated the difference texture compared with the symmetric rolling. The DSR has already been applied to produce the AZ31 magnesium alloy sheets and shown that the orientation of basal plane in the rolling plane could be weakened to a certain extent, but which only made the *c*-axis incline 5° from the normal direction toward the rolling direction and the mechanical properties of the sheets at ambient temperature was not improved greatly [11].

In the present study, a new concept processing, so-called equal channel angular rolling (ECAR) [13] was adopted to produce AZ31 magnesium alloy sheets, which was able to produce magnesium alloys sheets with non-basal plane crystal orientation because of the shearing deformation in a continuous manner. The current study represents an attempt to reproduce the vast improvement in ductility in AZ31 magnesium alloy sheets using ECAR processing and a closer examination of the proposed connection between the induced crystal orientation and the tensile behavior of ECAR processed sheets.

Experimental procedure

The chemical composition of AZ31 magnesium alloy sheets with 1.6 mm in thickness used in this study was Mg–3Al–0.8Zn–0.4Mn (in wt.%), which produced by unidirectional hot rolling.

The ECAR device was illustrated in Fig. 1. The ECAR mould was posited on the ordinary twin-roll hot rolling mill with the diameter of the rolls of Ø360 mm.

Y. Q. Cheng · Z. H. Chen (✉) · W. J. Xia
School of Material Science and Engineering,
Hunan University, Changsha 410082, China
e-mail: cyqfirst@163.com

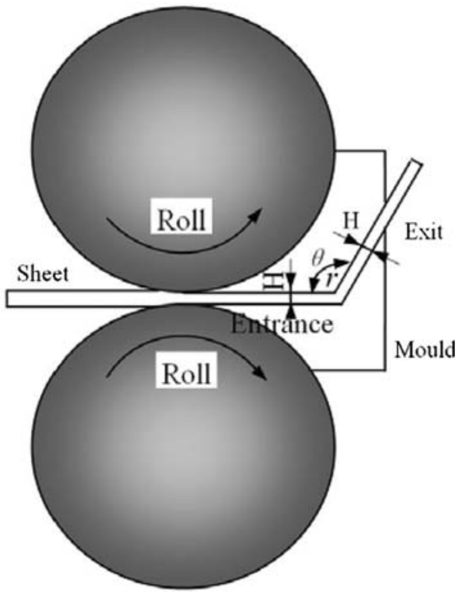

Fig. 1 A schematic of the ECAR device

The gap of the twin-roll was a constant value of 1.5 mm. And the channel height of the entrance and exit of the mould was both 1.6 mm. The oblique angle (Φ) of the ECAR channel was set to 115° with the curvature angle of 0° and the oblique radius (*r*) was 2 mm with the curvature radius of 0 mm.

Sheets with the dimensions of $600 \times 120 \times 1.6$ mm^3 (length × width × thickness, respectively) were cut from the as-received sheets with the long axis parallel to the rolling direction and fed into the ECAR machine. The feeding speed was 0.43 m/s, which equaled to the rolling speed.

To study the influence of ECAR processing on the ductility of AZ31 sheets, the as-received sheets were processed by ECAR processing for four passes. Before each pass, the sheets were pre-heated in a resistance furnace at a sheet temperature of 723 K for 5 min, while the twin-roll and the ECAR mould were not pre-heated. During the ECAR procedure, the rolling direction and the positive nominal direction of the sheets were both unchanged in each pass. The twin-roll and ECAR channels were lubricated by soap.

The X-ray diffraction spectra were recorded for the present AZ31 magnesium alloy sheets in order to examine the crystal orientation. Tensile specimens with a gauge of 15 mm length, 3.5 mm width and ~1.5 mm thickness were electro-discharged machined with the tensile axis parallel to the rolling direction. Tensile tests were performed at room temperature under a constant cross-head speed condition (0.5 mm/min). The fracture surface after tensile tests were observed by scanning electron microscopy (SEM) using a JEM-6700F.

Results and discussion

The optical microstructures of the rolling surface for the as-received specimen and the ECARed one are shown in Fig. 2. It can be seen that the as-received specimen exhibits equiaxed grains with the straight and smooth boundary and a few twins exists in some grains. The grains in the ECARed specimen are inhomogeneous and there are lots of twins in the ECARed specimen. The average grain size is 7.5 μm for the as-received specimen and 11.3 μm for the ECARed one. The grain size was not refined indicating that the recrystallization did not take place during ECAR processing because of the lower temperature of the ECAR mould when the sheets passed through the corner of the mould, which also led to the existence of twins. And the microstructure of ECARed specimen after one pass also indicates that the grains are not refined as shown in Fig. 3a. Another reason for which produced amount of twins can be owing to the higher ECAR speed. Furthermore, the reason for which the grains coarsened after ECAR processed is that the grains grew up during the repeated heating at 723 K for 5 min associated with the multiple rolling passes.

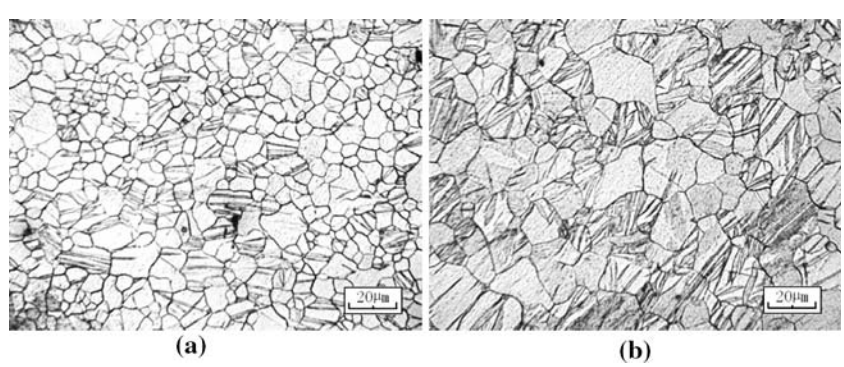

Fig. 2 Microstructures of AZ31 magnesium alloy sheets (**a**) as-received and (**b**) ECARed

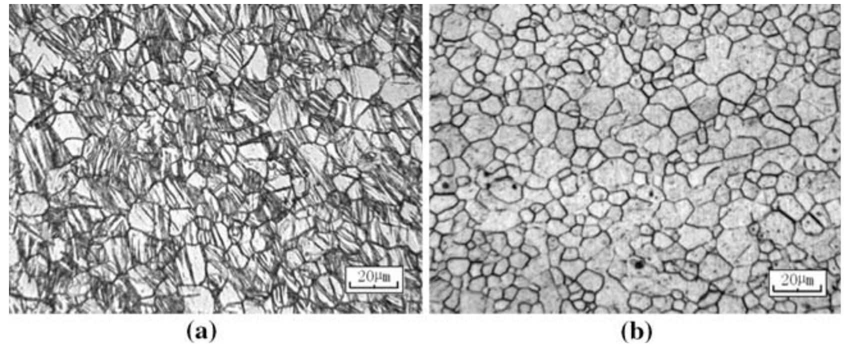

Fig. 3 Microstructures of AZ31 magnesium alloy sheets (**a**) produced by ECAR after one pass and (**b**) followed by annealing at 723 K for 5 min

As shown in Fig. 3b, twins in the one-passed specimen followed by annealing at 723 K for 5 min disappeared completely and the grains grown up slightly.

Figure 4 shows XRD spectra of the as-received specimen and the ECARed one of two sections perpendicular to the normal direction and rolling direction. It is clearly observed in Fig. 4a that the basal plane in the as-received specimen strongly depends on the rolling direction. On the other hand, the magnitude of the peak in the ECARed specimen is similar to each other for the two directions. Thus, it is suggested that the distribution of basal plane is possibly similar to each other for the two directions in ECARed specimen, which implies the specimen with basal plane in most grains inclines ~45° against the rolling plane. It also indicates that the shearing deformation was applied to the sheets during the ECAR procedure.

A group of typical results of tensile tests at room temperature of the as-received specimens and ECARed ones of AZ31 magnesium alloy sheets are shown in Fig. 5. Although ultimate tensile stress indicates similar values for both of the specimens, a clear yield phenomenon and an obvious improvement in the tensile ductility could be observed for the ECARed specimens compared with the as-received specimens. For the as-received specimens, failure occurs at an elongation of below 14% in these specimens. While for the ECARed specimens, all of the tested specimens fractured at an elongation over 24%.

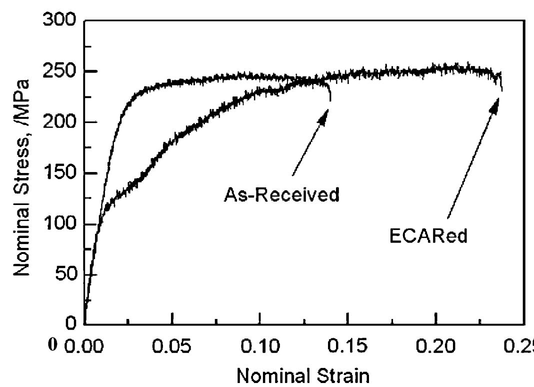

Fig. 5 Nominal stress–strain relations for the as-received sheets and ECARed ones of AZ31 magnesium alloy

Since the ECARed specimen with basal planes in most grains inclined ~45° against the rolling plane, basal slip would easily occur because maximum shear force occurs on the plane inclined at 45° to the tensile direction when the tensile direction parallel to the rolling direction. The clear yield phenomenon and lower yield stress for ECARed specimen would be associated with the fact that many portion of basal planes were more favorably oriented for slipping, as shown in Fig. 4b, which agrees with those processed by

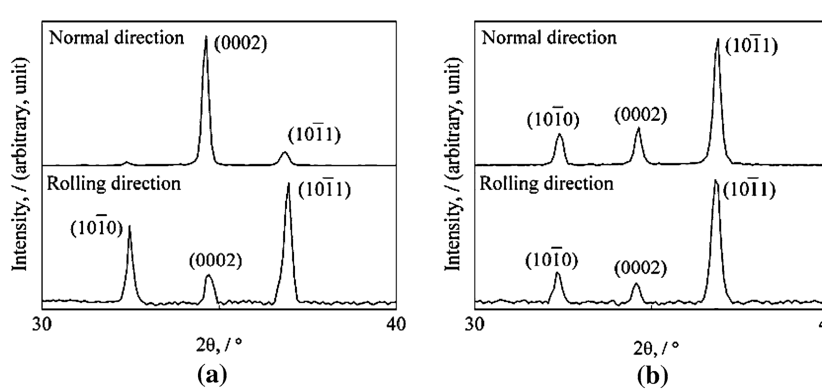

Fig. 4 X-ray diffraction spectra of AZ31 magnesium alloy sheets (**a**) as-received and (**b**) ECARed examined for two sections perpendicular to the normal direction and rolling direction, respectively

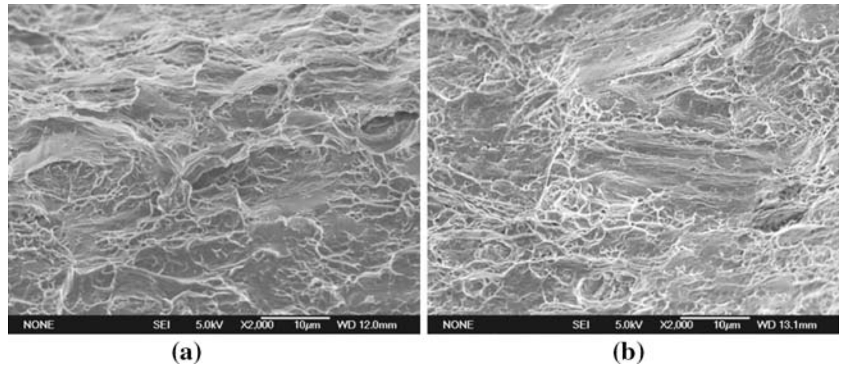

Fig. 6 Typical SEM micrograph of the fracture surfaces after tensile tests (**a**) as-received and (**b**) ECARed

ECAE in previous reports [1, 2, 14, 15]. For the same reason, the ultimate tensile stress should also be reduced and the coarsening grains could also induce the lower stress according to the Hall–Petch relationship as shown in Fig. 2b. However, the ultimate tensile stress was similar for both types of the specimens, which can be attributed to the work hardening behavior owing to the dislocation interactions during the tensile tests. Moreover, the amount of twins existed in the ECARed specimen may be another reason for the similar ultimate tensile stress in both types of specimens, because twins can be a source of work hardening by microstructure refinement as well as blocking of mobile dislocations [16]. And the evidently increased tensile ductility of ECARed specimens can be related to the large strain hardening after yielding. The strain hardening is attributed to the activation of two or more slip planes as the consequence of rotation of slip planes [17, 18] induced by the ECAR process. Furthermore, twinning in magnesium alloys is also another reason for the high ductility for ECARed specimen compared with the as-received one. When the majority of grains *c*-axis close to the tensile stress axis, a very strong signature of the $\{10\bar{1}2\}$ tensile twinning mode takes place [4, 19, 20]. So, it is easily occurring twinning deformation for ECARed specimen than as-received one, owing to the tilted angle between *c*-axis and tensile direction.

Compared with the as-received specimens, an obviously uniform deformation character for the ECARed ones is exhibited after tensile fracture, which also proved that the positive function of non-basal plane texture on the ductility. The typical SEM micrographs of the fracture surface are shown in Fig. 6: (a) As-received specimen and (b) ECARed specimen. It can be seen that the fracture surface of as-received specimen had cleavage facets and cleavage steps in Fig. 6a, which relates to deformation by mechanical twinning. This indicates that the predominant fracture mode is cleavage. While in Fig. 6b, more cleavage facet can be seen in local areas due to the twinning deformation caused by the modified crystal orientation for ECARed specimen and some bar-like morphologies were observed which indicates that the predominant fracture mode changes quasi-cleavage. This transition of the operative mechanisms of fracture may be related to the different crystal orientation.

Conclusion

Simple shearing deformation was applied to AZ31 magnesium alloy sheets by ECAR for the development of different crystal orientation compared with the as-received sheets. X-ray diffraction spectra suggested the ECARed specimen with basal plane in most grains inclined ~45° against the rolling plane, which was obviously different for the as-received sheets. During tensile test, the obvious yield phenomenon with a low yield stress and the elongation-to-failure exhibited over 24% of the ECARed sheets which was almost twice larger than that for the as-received sheets, contributing to the modification of crystal orientation caused by ECAR processing.

References

1. Mukai T, Yamanoi M, Watanabe H, Higashi K (2001) Scripta Mater 45:89
2. Watanabe H, Takara A, Somekawa H, Mukai T, Higashi K (2005) Scripta Mater 52:449
3. Yoshida Y, Cisar L, Kamado S, Kojima Y (2003) Mater Trans 44:468
4. Agnew SR, Horton JA, Lillo TM, Brown DB (2004) Scripta Mater 50:377
5. Kim WJ, An CW, Kim YS, Hong SI (2002) Scripta Mater 47:39
6. Couret A, Cailiard D (1989) Phil Mag A59:783
7. Iwanaga K, Tashiro H, Okamoto H, Shimizu K (2004) J Mater Process Tech 155–156:1313
8. Perez-Prado MT, Valle JA, Contreras JM, Ruano OA (2004) Scripta Mater 50:661

9. Valle JA, Prado MT, Ruano OA (2003) Mater Sci Eng A 355:68
10. Chino Y, Mabuchi M, Kishihara R, Hosokawa H, Yamada Y, Wen C, Shimojima K, Iwasaki H (2002) Mater Trans 43:2554
11. Watanabe H, Mukai T, Ishikawa K (2004) J Mater Sci 39:1477
12. Kim SH, You BS, Yim CD, Seo YM (2005) Mater Lett 59:3876
13. Cheng YQ, Chen ZH, Xia WJ, Fu DF (2005) Chin J Nonferrous Met 15:1369
14. Kim HK, Kim WJ (2004) Mater Sci Eng A 385:300
15. Somekawa H, Mukai T (2005) Scripta Mater 53:541
16. Koike J, Ohyama R, Kobayashi T, Suzuki M, Maruyama K (2003) Mater Trans 44:445
17. Koike J, Ohyama R (2005) Acta Mater 53:1963
18. Koike J, Kobayashi T, Mukai T, Watanabe H, Suzuki M, Maruyama K, Higashi K (2003) Acta Mater 51:2055
19. Agnew SR, Tomé CN, Brown DW, Holden TM, Vogel SC (2003) Scripta Mater 48:1003
20. Murr LE, Meyers MA, Niou CS, Chen YJ, Pappu S, Kennedy C (1997) Acta Mater 45:157