JMEPEG (2008) 17:15–19
DOI: 10.1007/s11665-007-9103-6

1059-9495/$19.00

Improvement of Drawability at Room Temperature in AZ31 Magnesium Alloy Sheets Processed by Equal Channel Angular Rolling

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(Submitted March 30, 2006; in revised form December 12, 2006)

A new rolling process, so-called as equal channel angular rolling (ECAR) process, for fabricating the magnesium alloy sheets with an enhanced formability at room temperature is introduced. The ECAR device was designed so that it could feed the sheet with the preheated temperature of 673 K in a continuous manner at a relatively high speed of 0.43 m/s. A significant amount of the shear deformation could be achieved by passing the sheet through the mold with the oblique angle of 115°. The x-Ray spectra were examined to analyze the crystal orientation of the sheets, which indicates that the crystal orientation with non-basal plane was fabricated after ECAR processing. The grain was not refined and plenty of twins were brought out because of the low-shear deforming temperature. The high stress and low ductility for the ECARed specimens can be related to the presence of twins. In spite of having the similar optical microstructure, the elongation to failure for the ECARed specimens after annealing was above 33%, which was larger than that of about 20% for the as-received/annealed specimens. And the drawability for the ECARed/annealed specimens with the Erichsen value of 6.24 mm and the limiting drawing ratio of 1.6 can be obtained, which is improved dramatically than that of 4.18 mm and 1.2 for the as-received/annealed specimens, respectively. These can be related to the rotation of (0002) basal plane toward the rolling direction because of the shear deformation induced by ECAR process.

Keywords crystal orientation, drawability, equal channel angular rolling, magnesium alloy sheets, tensile properties

1. Introduction

In order to extend the application of magnesium alloys, it is required to develop rolling technologies for mass production of high performance magnesium alloys sheets. Critical requirements for the magnesium alloys sheets are not only high strength, but also high drawability. It is known that the drawability of magnesium alloys sheets can be improved greatly at elevated temperature (Ref 1, 2). However, the drawing process at elevated temperature is not favor of the industrialized production, which will be improving the costing and decreasing the efficiency. Although grain refinement gives rise to both high strength and high ductility (Ref 3, 4), normally rolled magnesium alloys with fine-grained microstructure often exhibit poor drawability at room temperature (Ref 5), which can be owing to the intense texture of (0002) basal plane parallel to the rolling plane (Ref 3, 4).

Iwanaga et al. (Ref 6) reported that reduction of (0002) basal plane texture dramatically improves Erichsen value from 4.9 to 7.4 mm and brings about good deep drawability with the limiting drawing ratio of 1.4 at room temperature. And others reports (Ref 7-13) showed that the ductility of magnesium alloys produced by equal channel angular extrusion (ECAE) can be increased greatly due to control of texture. So, it can be concluded that the drawability can be improved through the controlling texture. It is reported that the (0002) texture intensity of rolled AZ31 alloy is reduced by differential speed rolling (DSR) (Ref 14, 15), which results an improvement in press formability (Ref 16). However, the reduction of (0002) texture by DSR is very limited. At present, several continuous shear deformation processes, such as Conshearing (Ref 17, 18), C2S2 (Ref 19, 20) and ECAR (Ref 21, 22) were proposed and used to fabricate aluminum alloy sheets, which indicates that it is feasibility to act the shear deformation on the sheets. These studies suggest that the texture of magnesium alloys sheets can be changed in essential and the drawability of rolled Mg alloys at room temperature may be improved.

Recently, we have adopted a modified equal channel angular rolling (ECAR) process (Ref 21, 22), which based on the ECAE process, providing repeated shear deformation on magnesium alloys sheets and changing the crystal orientation of the sheets (Ref 23, 24). In the present study, ECAR is carried out on AZ31 magnesium alloy sheets and the drawability of these magnesium alloy sheets at room temperature is investigated by the Erichsen tests and deep drawing tests.

2. Experimental Procedure

The as-received sheets of AZ31 magnesium alloy with the dimensions of 800 × 120 × 1.9 mm^3 (Length × Width × Thickness) were prepared by unidirectional hot rolling, whose chemical

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composition was Mg-3Al-0.8Zn-0.4 Mn (in wt.%). The sheets were heated at 673 K for 3 min, and then rolled at the ECAR device with an ECAR mold having the oblique angle (θ) of 115°, the oblique radius (*r*) of 2 mm and the channel height (*H*) of 1.8 mm. The ECAR device was illustrated in Fig. 1. And the gap of the twin-roll was set as a constant value of 1.78 mm in order to feed the sheet into the channel successfully and reduce the friction force between the sheet and the channel. The feeding speed into the ECAR channel was a constant value of 0.43 m/s, which was equal to the radial velocity of the rolls. The twin-roll and the channel were not pre-heated and the channel was lubricated by graphite grease. The ECAR deformation was performed in one pass. Then, the as-received sheets and ECARed sheets recrystallization annealed at 573 K for 1 h. So, four types of sheets, namely, the as-received sheets, the as-received/annealed ones, the ECARed ones and the ECAR/annealed ones were investigated in the present study.

The crystal orientation of the sheets was investigated by x-Ray spectrum. Also, microstructure of the sheets was observed by optical microscopy. Mechanically grounded specimens to half of the thickness were used in order to analyses the microstructure and measure the crystal orientation at center through a thickness. Tensile tests were performed at room temperature at a constant cross-head speed of 0.5 mm/min in order to understand the tensile deformation behavior. The gauge length and width of the tensile specimens were 15 mm and 3.5 mm, respectively. The tensile direction was parallel to the rolling direction.

The square blank with 60 × 60 mm^2 (Length × Width) was machined from the sheets for Erichsen tests. Erichsen tests using hemispherical punch with a diameter of ø20 mm were carried out at room temperature to investigate the press formability of the sheets, and the Erichsen value, which was the punch stroke at fracture initiation, was recorded by the controlling computer. The punch speed was about 5 mm/min and the blank holder force was 10 kN. The circular blank with different diameters was machined from the sheets for deep drawing tests. Deep drawing tests were conducted with a punch speed of about 5 mm/min at room temperature on the Erichsen tests machine. The blank holder force was set as a constant value of 2.9 kN during the deep drawing tests. The dimensions of tools used for the deep drawing tests were summarized in Table 1. And the lubricant for Erichsen tests and deep drawing tests was the olefin.

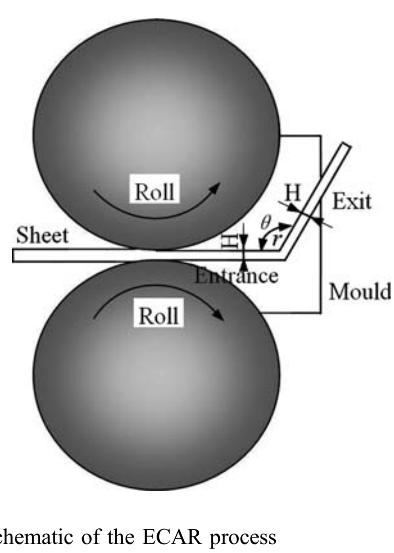

Fig. 1 A schematic of the ECAR process

3. Results and discussion

The strain during ECAR was simulated by means of the rigid-plastic finite element method (FEM) code DEFORM-2D. The FEM simulation in Fig. 2 shows the deformation in the corner of mold channel during one pass of ECAR. Changes of the shape of the FEM elements indicate that the shear deformation is not uniform through the sheet thickness, in particular at the sheet surface. It can be seen that the oblique radius (*r*) is not only broadening the shearing area but also leading to the nonuniform shear deformation at the top surface, which can be proved by FEM simulation using an oblique radius of 0 mm. These are similar with the results obtained by others (Ref 25). But it is necessary for the oblique radius to fabricate the sheet successfully, which has proved experimentally. As is clear from the experimental results, the uniform shear deformation is also observed to occur near the bottom surface. Such a uniform deformation observed from the bottom surface is due to the presence of the dead zone located at the outer corner of the mold as indicated by the arrow in Fig. 2, where the sheet fails to make contact with the mold. And the same phenomenon was also observed during the experiment. However, close to the center layer of the sheet quite uniform shear deformation prevails. Therefore, the analysis of texture and microstructure during ECAR is focused on the center of the sheets and the influence of uniform deformation on the deformation behavior is not considered provisionally at the present study.

Considering the existence of the oblique radius and dead zone, the equivalent strain induced by ECAR mold is about 0.56 according to the formula given out by Luis Pérez (Ref 25). So, it can be seen that this value is lower than that of 0.74 calculated from the equivalent strain formula provided by Iwahashi (Ref 26). And the shear strain is only 0.93 corresponding of the shear angle of 43°, which is also

Table 1 Dimensions of tool used for deep drawing tests

Punch diameter, mm	30.0
Punch shoulder radius, mm	8.0
Die hole diameter, mm	34.2
Die shoulder radius, mm	6.0

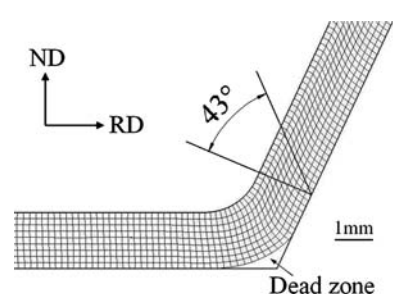

Fig. 2 Two-dimensional FEM simulation showing shear deformation during ECAR

smaller than the value according to the formula of $\gamma = 2\cot(\theta/2)$ for ECAE process.

XRD spectra of the as-received and ECARed specimens before and after annealing of a section in deferent plane are shown in Fig. 3. It can be seen that the as-received specimen presents strongly crystal orientation of (0002) basal plane with a high peak value of (0002) plane in the section perpendicular to the normal direction. On the other hand, the distribution of the diffract peak for the ECARed specimen is similar with each other in both sections except to the intensity values, which implies the ECARed specimen with basal plane in most grains inclines ~45° against the rolling plane (Ref 7). These are associated with the shear angle and the deformation mechanism of magnesium alloys according to the easiest deformation mechanism (Ref 27), which means that the basal plane trends to parallel to the shear plane during the ECAR process. After annealing, the crystal orientation for both types of sheets was not changed obviously except the intensity of the peak as shown in Fig. 3, which is consistent with the conclusions drawn by others reports (Ref 28, 29).

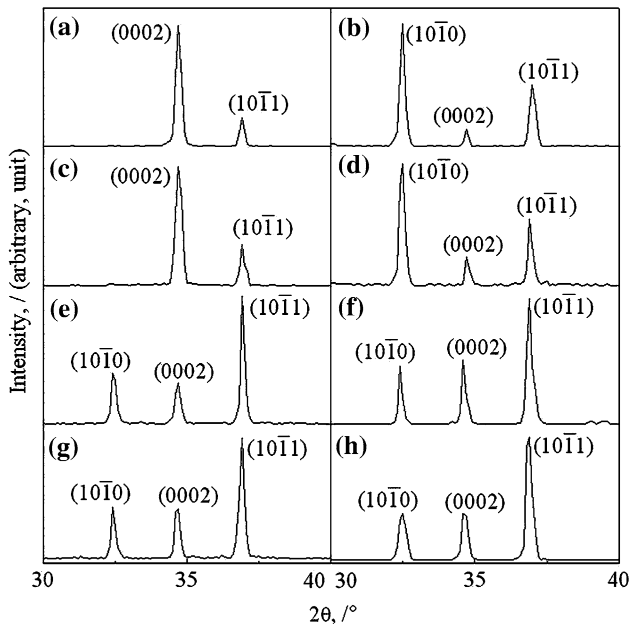

Fig. 3 Crystal orientation of the sections perpendicular to the normal direction (ND) and rolling direction (RD) measured from the as-received specimen and the ECARed one. (a) As-received, ND; (b) As-received, RD; (c) As-received/annealed, ND; (d) As-received/annealed, RD; (e) ECARed, ND; (f) ECARed, RD; (g) ECAR/annealed, ND; (h) ECAR/annealed, RD

Figure 4 shows the optical microstructure of the as-received specimen and the ECARed one before and after annealing parallel to the rolling plane. The average grain size is 11.3 μm for the as-received specimen and 10.5 μm for the ECARed specimen, showing that the grain size is hardly affected by the ECAR process. However, the quantity of twins is increased greatly. And these indicate that the dynamic recrystallization did not take place during the ECAR processing, which may be related to the low temperature when the sheet passed through the mold corner because of the cold rollers and die. On the other hand, the microstructure is homogeneous and the grain size is similar with each other for both types of the specimens and slightly refined after annealing without the presence of twins, which is due to the static recrystallization.

The typical nominal stress-strain relations for AZ31 magnesium alloy sheets at room temperature obtained from these specimens at the rolling direction are shown in Fig. 5. It can be seen that the ECARed specimen exhibits a higher strength than that of the as-received one and the elongation to failure is similar with each other. After annealing, the elongation for the ECARed/annealed specimen is above 33%, which is twice than that of the ECARed specimen. However, it is not improved so largely for the as-received specimen. These can be contributed to the presence of twins and the rotation of (0002) basal plane. The change of crystal orientation makes basal plane slip more

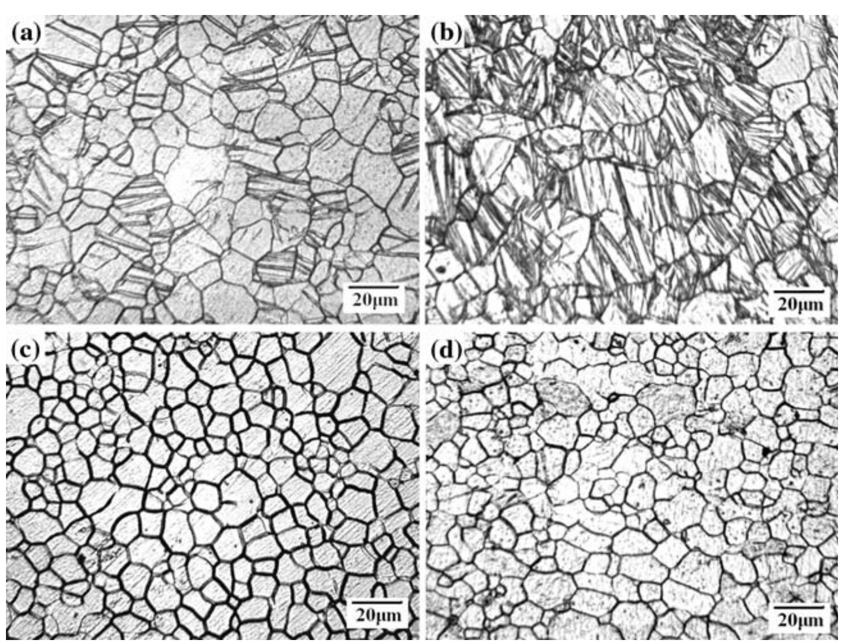

Fig. 4 Optical microstructure for AZ31 magnesium alloy sheets. (a) As-received; (b) ECARed; (c) As-received/annealed; (d) ECAR/annealed

easily according to the slip theory for magnesium alloys (Ref 30). Furthermore, the twins can act as a source of work hardening and induce a concentration of stress, leading to the high stress and low ductility, which may be one reason for the ECARed specimen with high strength and poor ductility in despite of the modified crystal orientation. On the other hand, the modified crystal orientation will lead to take place of twinning easily, which can be seen from the optical microstructure near the tensile fracture as shown in Fig. 6. And it is known that the twinning deformation can provide additional independent slip systems, which can enhance the ductility (Ref 31). Moreover, a low yield ratio (yield strength/tensile strength) and a large strain hardening phenomenon exhibit for the ECARed specimen and ECARed/annealed one, which will be favor of the improvement of drawability (Ref 6).

So, the formability tests were only carried out on the sheets after annealing. The Erichsen tests indicate that the maximum cupping value for the ECARed/annealed specimen is 6.24 mm, while 4.18 mm for the as-received/annealed sheet. Figure 7 shows photographs of two cups formed at room temperature with a drawing ratio 1.2 for the as-received/annealed sheets and 1.6 for the ECAR/annealed sheets, respectively. And no earing is observed for the deep drawing, which may be related to the high working hardening exponent and the relatively small drawing depth (Ref 32). Moreover, a special phenomenon is observed that the fracture for the as-received/annealed sheets often appears at the shoulder of the cup, while the fracture takes place at the edge of the flange for the ECAR/annealed sheets, which needs to be investigated for further. Anyway, it is conclusively demonstrated that the formability of AZ31 magnesium alloy sheets at room temperature can be improved greatly by ECAR process because of the modified crystal orientation, which will be discussed for further in elsewhere (Ref 33).

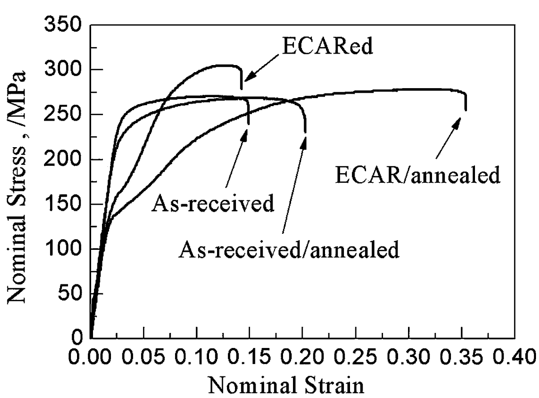

Fig. 5 Nominal stress-strain curves for AZ31 magnesium alloy sheets

4. Conclusions

Equal channel angular rolling is carried out on AZ31 magnesium alloy preheated at the temperature of 673 K for 3 min and followed by recrystallization annealing at 573 K for 1 h. The drawability of the magnesium alloy sheets is investigated by the Erichsen tests and deep drawing tests at room temperature. The results are concluded as follows.

(1) The grain size is 11.3 μm for the as-received specimen and 10.5 μm for the ECARed specimen, and plenty of twins for the ECARed specimen bring out because of the lower deforming temperature.
(2) The high strength and low ductility for the ECARed specimen can be related to the existence of plenty of twins.
(3) After annealing, the twins disappear and the ductility is improved greatly for the ECARed specimen, which can be owing to the modified crystal orientation.
(4) Although the optical microstructure is similar with each other, the drawability for the ECARed/annealed specimens with the Erichsen value of 6.24 mm and the limiting drawing ratio of 1.6 can be obtained, which is improved dramatically than that of 4.18 mm and 1.2 for the as-received specimens, respectively. Therefore, it is likely that the crystal orientation has a visible effect on the drawability for AZ31 magnesium alloy sheets at room temperature.

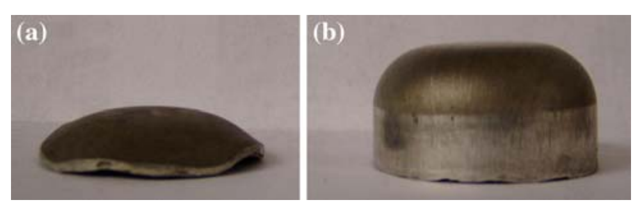

Fig. 7 The specimens after the deep drawing test at room temperature. (a) As-received/annealed; (b) ECAR/annealed

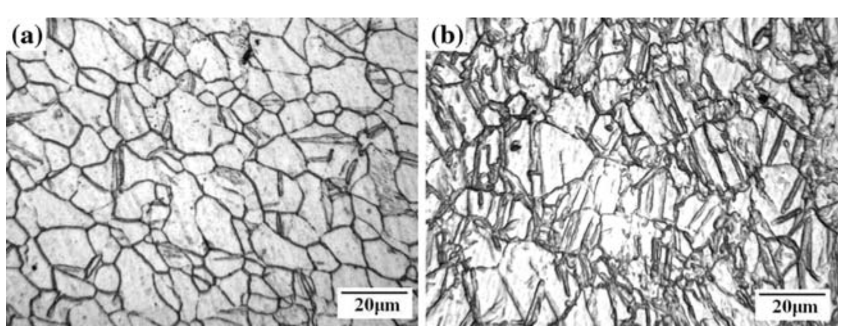

Fig. 6 Optical microstructure of the rolling plane after tensile tests at room temperature for (a) the as-received/annealed specimen and (b) the ECAR/annealed one

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