Microstructure and mechanical properties in an AZ31 magnesium alloy sheet fabricated by asymmetric hot extrusion

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\textbf{A B S T R A C T}

Hot extrusion is one of the effective methods to decrease grain size of materials. As grains are finer, the mechanical properties of materials can be improved. It was found that the grains of magnesium alloy AZ31 sheets could be reduced to 3/μm by a differential speed rolling at an elevated temperature. In the present study, one-pass asymmetric hot extrusion performed at temperature of 673 K was applied to fabricate an AZ31 magnesium alloy sheet in order to introduce great shear strain during the primary processing. The textures, microstructures and mechanical properties at room temperature along the extrusion planes from top surface to bottom surface were examined. The experimental results showed that the asymmetric hot extrusion effectively weakened the basal texture and improve the ductility at room temperature.

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\section{1. Introduction}

Room temperature ductility of magnesium alloys in the second processing strongly depends on the orientation of basal plane, because critical resolved shear stress (CRSS) of basal slip system at room temperature is much higher than those of non-basal slip systems on prismatic and pyramidal planes [1]. Primary processing, such as hot rolling and hot extrusion usually leads to a strong basal texture, which results in poor ductility at room temperature [2]. Thus, it is important to control the texture during primary processing for improvement of ductility at room temperature during second processing. Mukai et al. used ECAE method to enhance the room temperature ductility of AZ31 magnesium alloy [3]. Significant improvement in tensile elongation ~50% was achieved. Recently, other methods, such as single roller drive rolling (SRDR) and differential speed rolling (DSR) were used to introduce shear strain during processing magnesium alloys. SRDR and DSR effectively weakened basal texture and improved the ductility and formability of AZ31 magnesium alloy [4–8]. In the present study, one-pass asymmetric hot extrusion was performed to fabricate the AZ31 magnesium alloy sheet in order to introduce great shear strain during the primary processing, and the resulting microstructure, texture, and mechanical properties were studied.

\section{2. Experimental procedure}

The procedure of one-pass asymmetric extrusion, which we propose in this study, is schematically shown in Fig. 1. One-pass asymmetric extrusion can be easily conducted by an extrusion die with an angle chamfer (45° in this study) in one side. By one-pass asymmetric extrusion, a large amount of shear deformation can be introduced through the thickness of the extruded sheet by the die with an angle chamfer in one side.

The chemical composition of the as-received AZ31 billet used in this study (in mass percent) is Mg–3.02% Al–1.01% Zn–0.30% Mn. This alloy is a solution-hardened alloy with minimum precipitation. The as-received billet possessed nearly equiaxed grains around 75/μm and the diameter of the billet is 50 mm. One-pass asymmetrical extrusion was conducted by a die with 45° chamfer on one side at temperature of 673 K with the speed of extrusion 10 mm/s, resulting into a sheet of 10 mm in width and 5 mm in thickness. The microstructure of the sample was examined under optical microscopy, and average grain size was determined using intercept method. Four pole figures, \{0002\}, \{1,0,−1,1\}, \{1,0,−1,2\} and \{1,0,−1,3\} were measured by X-ray diffraction with Co K\alpha radiation up to a tilt angle of 70° using the Schultz reflection method. The orientation distribution function (ODF) was calculated from

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In order to examine distributions characteristics of textures and microstructures throughout the thickness in the asymmetrically extruded sheet, the top surface (denoted the asymmetrically extruded sheet on chamfer side), 1/4 surface (1/4S), 1/2 surface (1/2S), 3/4 surface (3/4S) and bottom surface, respectively, were selected for texture and microstructure examination, as shown in Fig. 2(up). Samples labeled A, B and C for tensile test are presented as top, center and bottom regions in the sheet, respectively, as shown in Fig. 2(below). Tensile tests were carried out along the extrusion direction (ED). The gauge length, width and thickness of the tensile specimens were 6 mm, 3 mm and 1.5 mm, respectively. Tensile specimens were prepared using electrical-discharge machining from the extruded sheet. Tensile tests were conducted using WD-3010 universal testing machine with an initial rate of \(1 \times 10^{-3} \text{s}^{-1}\) at room temperature. All tests were repeated at least three times.

### 3. Results and discussion

Optical microstructures of the ED–TD plane for different surfaces in asymmetrically extruded AZ31 alloy sheet were shown in Fig. 3. After the hot extrusion, grains were refined to smaller than 4 \(\mu\text{m}\) in all layers. Asymmetrically hot-extruded sheet had equiaxed grains, indicating that intensively dynamic recrystallization took place during extrusion process. It is noticed that there exists a slight grain size gradient along the through-thickness direction in the sheet. The average grain sizes, \(d\), of the AZ31 specimens in different surfaces were listed in Table 1.

The relationship between the average recrystallization grain size \((d)\) and the Zener–Hollomon parameter \((Z)\) during dynamic recrystallization is given by \(\ln d = A + B \ln Z\). The temperature corrected strain rate \(Z\) is given by \(Z = \dot{\varepsilon} \exp(Q/RT)\). Where \(\dot{\varepsilon}\) is strain rate, \(Q\) is activation energy for the deformation, \(T\) is temperature and \(R\) is gas constant \([9,10]\). Based on the present asymmetric extrusion processing, the strain rate throughout the thickness in the sample is not uniform. It is roughly suggested that the top layer would be imposed more strain rate than that of the bottom layer, which

<table>
<thead>
<tr>
<th>Surface</th>
<th>Grain size ((\mu\text{m}))</th>
</tr>
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<tbody>
<tr>
<td>Top</td>
<td>2.50</td>
</tr>
<tr>
<td>1/4S</td>
<td>2.66</td>
</tr>
<tr>
<td>1/2S</td>
<td>3.13</td>
</tr>
<tr>
<td>3/4S</td>
<td>3.38</td>
</tr>
<tr>
<td>Bottom</td>
<td>3.67</td>
</tr>
</tbody>
</table>

Fig. 3. The optical microstructures of the ED–TD plane of the asymmetrically hot-extruded AZ31 sheet: (a) top surface; (b) 1/4S; (c) 1/2S; (d) 3/4S; (e) bottom surface.
resulting in the smaller grain size in the top layer than that in the bottom layer according to the above equations.

The pole figures in different surfaces of the sheet processed by one-pass asymmetric hot extrusion are shown in Fig. 4. It can be easily seen from Fig. 4(a) that the texture in top surface is characterized by pronounced tilted \(\{0002\}\) basal plane towards the extrusion direction around 15°. The textures in 1/4 surface, 1/2 surface and 3/4 surface presented the similar textural characteristics.

Fig. 4. \((0 0 0 2)\) and \((1 0 , −1 , 1)\) pole figures in the asymmetrically hot-extruded AZ31 sheet: (a) top surface; (b) 1/4S; (c) 1/2S; (d) 3/4S; (e) bottom surface.
were calculated and listed in Table 2. The results indicate that ductility of sample A (top region) and sample B (center region) is greatly improved compared with sample C (bottom region). The YS of sample A exhibits near half value compared with the sample C, although the average grain size of sample A is smaller than that of sample C, indicating that the grain size is not a dominant factor for yield stress (from the perspective of the Hall–Petch relation). Therefore, the low value of yield stress in sample A compared with sample C is owing to the difference of texture in the two samples. The ultimate tensile stress of sample A exhibits almost the same value as the sample C. The mechanical properties of sample B are between the sample A and sample C.

In general, the poor ductility of Mg alloys at room temperature has been attributed to the less number of independent slip systems for a polycrystalline Mg and its alloys. The CRSS have been reported for three different slip systems in single crystal Mg [11]. According to the reported data, the CRSS of a basal slip system at room temperature is approximately 1/100 those of non-basal slip systems on prismatic and pyramidal planes. Therefore, plastic deformation in polycrystalline Mg alloys was thought to occur almost entirely by basal slip. It is well known that the yield stress scales inversely with Schmid factor \( m \) and directly with CRSS for basal slip, namely, the yield stress can qualitatively be expressed as \( \sigma_y \propto (1/m)_{\text{CRSS}} \), where \( m \) is Schmid factor or orientation factor and \( (1/m)_{\text{CRSS}} \) is critical resolved stress of single crystal for basal slip [10–12–16].

The Schmid factor \( m \) for basal slip is defined as
\[
m = \cos \chi \cos \lambda,
\]
where \( \chi \) and \( \lambda \) are angles between the stress axis and the slip plane normal and slip direction, respectively. For any value of angle \( \chi \), there exists an optimally oriented \((1,1,0)\) slip direction for a grain. This optimally oriented slip direction \( \lambda_{\text{opt}} \) is lying in the plane defined by the normal to the basal plane and stress axis, namely, the sum of the angle \( \chi \) and \( \lambda_{\text{opt}} \) equals to \( \pi/2 \). Therefore, the term of \( \lambda_{\text{opt}} \) can be expressed as \( \cos \lambda_{\text{opt}} = \cos[(\pi/2) - \chi] = \sin \chi \). Taking into account of symmetry of the \((1,1,0)\) slip direction rotated up to \( \pm \pi/6 \) about the c-axis of the optimally oriented grain, the average of the cosine function from \( -\pi/6 \) to \( \pi/6 \) can be weighted by the factor \( 3/\pi \), and obtained as \( \cos \lambda = (3/\pi) \sin \chi \). Therefore, the Schmid factor \( m \) as a function of \( \chi \) can be written as:
\[
m(\chi) = \left( \frac{3}{\pi} \right) \cos \chi \sin \chi.
\]  

Table 2
<table>
<thead>
<tr>
<th>Sample</th>
<th>YS (MPa)</th>
<th>UTS (MPa)</th>
<th>( \delta ) (%)</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>150</td>
<td>295</td>
<td>14.8</td>
</tr>
<tr>
<td>B</td>
<td>220</td>
<td>275</td>
<td>13.8</td>
</tr>
<tr>
<td>C</td>
<td>270</td>
<td>295</td>
<td>11.4</td>
</tr>
</tbody>
</table>
For the sample A, the (0002) slip planes rotated around 15° from normal direction to extruding direction, as shown in Fig. 4(a). When the stress axis is parallel to the extruding direction, the normal direction of the (0002) slip planes can be roughly considered as 15°. Thus, the ideal Schmid factor for the basal slip in the sample A can be calculated as to be around 0.24 according to Eq. (1) [17]. However, owing to the strong basal texture in the sample C, as shown in Fig. 4(e), when the stress axis is parallel to the extrusion direction, the normal direction of the most basal slip planes are nearly perpendicular to the stress axis, i.e. the angle of γ almost equals to 90°. Thus, the ideal Schmid factor for basal slip is null in the sample C. Therefore, the sample C has the largest yield stress (270 MPa), followed by sample B (220 MPa), and then the sample A (150 MPa). As seen in Fig. 5, elongation-to-failure (δ) of samples A and B is greatly improved compared to sample C, besides the effect of weakened and scattered (0002) basal texture in samples A and B, finer grain size also contributed to the improvement of ductility of those samples.

It is noticed that the sample A exhibits a remarkable strain hardening and a large uniform elongation compared with sample C and sample B, as shown in Fig. 5. The remarkable strain hardening and improving uniform elongation can be related to the modified crystal orientation. Therefore, it is suggested that the high Schmid factor for basal slip would easily lead to the operation of basal slip systems, which results in the low yield stress. Meanwhile, the easy operation of basal slip would bring out a high additional shear stress at grain boundaries (compatibility stresses) for the fine-grained polycrystalline magnesium alloys [1], which would induce the non-basal a and a+c slips as accommodation of slip deformation. When flow stress increases to some degree, twinning occurs as an additional deformation mechanism even in a fine-grained alloy. Therefore, the intense interactions of multiple deformation models would then bring about a rapid work hardening and a large uniform elongation in the present sample A. Further microstructural investigation of deformed structure is underway to clarify the deformation mechanism of the present ductile magnesium alloy.

4. Conclusions

One-pass asymmetric hot extrusion performed at temperature of 673 K was applied to fabricate AZ31 magnesium alloy sheet. The textural characteristics, microstructures and mechanical properties at room temperature throughout the thickness were examined. The results are concluded as follows:

1. Asymmetrically extruded AZ31 sample showed a fine-grained microstructure and some grain size gradient as well as inhomogeneous distribution of textures throughout thickness.

2. Asymmetric extrusion AZ31 sample showed the basal plane inclined by ~15° from the normal direction towards the extrusion direction in the top surface, and weakened and scattered basal texture in the center layer, and strong basal texture in the bottom surface of the sheet. Ductility can be improved by inclined and weakened basal texture, while yielding stress was brought down.

Asymmetric extrusion resulted in grain size and texture gradient through the thickness, therefore, it can be promisingly applied as the first deformation step in combination with asymmetric rolling.

Acknowledgement

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References