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Effect of grain refinement on fracture toughness and fracture mechanism in AZ31 magnesium alloy

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Abstract

The effect of grain size on fracture toughness was investigated for a wrought AZ31 magnesium alloy. The grain size was refined by equal channel angular pressing (ECAP) process. Digital image correlation (DIC) was used to determine the fracture property. The fracture toughness was found to be improved by grain refinement. The fracture mechanism was examined through the progress of crack tip and the analyses of fracture surface. The fracture mechanism changed from dimple fracture to mixture of cleavage fracture and dimple fracture.

Keywords: magnesium alloy; fracture toughness; grain size; digital image correlation (DIC); fracture mechanism

1. Introduction

Magnesium alloys hold promise for lightweight structural applications in transportation industry because of their low density and high specific strength and stiffness (Mukai et al. (1997)). Many researchers have hammered themselves at improving ductility and strength of magnesium alloys through grain refinement. Equal channel angular pressing (ECAP) was proved to be an effectual process in refining grains in various Mg alloys (Mabuchi et al. (2001) and Kim et al. (2003)). The enhancements of the mechanical properties of magnesium alloy through ECAP progresses have been reported in many literatures (Ding et al. (2008) and Biswas et al. (2010)). The grain refinement
also can improve the fracture toughness in pure magnesium (Somekawa et al. (2005)). Somekawa et al. (2005) and (2006) studied the effect of texture and grain size on fracture toughness in extruded AZ31 magnesium alloy and they draw the conclusion that the fracture toughness was higher in the extruded direction than in the normal direction and the fracture toughness was investigated to be improved by ECAP process.

In this study, the fracture toughness of AZ31 alloy of different grain size was tested under static loading with the assistant of DIC technique. The progress of the crack tip was observed microscopically in the loading progress and the typical SEM micrographs of the fracture surface after fracture tests were shown to explore the fracture mechanism.

2. Experimental Procedure

2.1. Materials and specimen

The material used in the present study was a commercial Mg-Al-Zn alloy, AZ31B (with chemical composition of Mg-3.28Al-1Zn-0.44Mn in wt. %). The ECAP progress was conducted with a die having an internal angle of 90° between the vertical and horizontal channels and the outer angle of 20°. The billets were rotated in a clockwise direction by 90° to the longitudinal axis between consecutive passes, designated as route Bc. The ECAP processing was carried out at the temperature of 553K in the first two passes followed by 538K and 523K for the third and fourth passes with a constant pressing speed of 20mm/min. Hereafter, specimens with different ECAP pass was designated as ECAPed-n. The typical initial microstructures of ECAPed-n specimens were shown in Fig. 1. The ECAPed-1 sample was featured by coarse grains surrounding by many fine grains for the reason that the fine grain had just began to generate around the coarse ones due to severe plastic deformation in ECAP progress. The grain size was more symmetrical due to the accumulation of plastic strain by ECAP processing. The average grain sizes were 16.47, 6.47, 4.46 and 1.75 μm for as-received, ECAPed-1, ECAPed-2 and ECAPed-4 specimens, respectively.

Fig.1. typical microstructures of AZ31 alloy: (a) as-received, (b) ECAPed-1, (c) ECAPed-2 and (d) ECAPed-4.

Fig.2. shape and dimension of specimen: (a) tensile specimen; (b) fracture specimen.
Tensile and fracture specimens were cut from the as-received and ECAPed-n billets along the extruded direction. The shape and dimension were showed in Fig.2.

2.2. Experimental technique

Tensile tests of ECAPed-n specimen were actualized at room temperature by utilizing an electric universal tensile-compressive test machine. The specimens were loaded at a constant speed of 0.6mm/min to achieve the strain rate of $10^{-3} \, \text{s}^{-1}$. The tensile specimens with a gauge length of 11.3mm and thickness of 1mm were machined from the ECAPed-n billets and the tensile axis was parallel to the extrusion direction. At least three specimens were tested to guarantee the repeatability.

Fracture toughness tests were carried out according to ASTM-E399. The specimens were three point bending samples with approximate dimension $3\, \text{mm} \times 6\, \text{mm} \times 30\, \text{mm}$. The specimens were machined directly from ECAPed-n billets with the notch normal to the extrusion direction. A natural pre-crack was prefabricated at the tip of the notch of the specimen through fatigue crack tests. The fracture toughness tests were carried out at a clamper speed of 0.06mm/min with a camera beside to generate speckled photos to calculate the displacement field via digital image correlation (DIC) method. At least two specimens were tested to guarantee the reproducibility. The microstructure of the crack tip in the testing process was observed through optical microscope (OM). The fracture surfaces were examined by scanning electron microscopy (SEM).

Typical microstructures of the pre-crack of the fracture specimen machined from the as-received billets were shown in Fig. 4: (a) indicated the pre-crack straightly proceeded and/or propagated along the initial notched direction; (b) indicated that the pre-crack proceeded across the grains. These features were also observed in the fracture specimens machined from ECAPed-n billets.
3. Results and Discussion

3.1 Tensile property

The typical true stress and strain curves at room temperature were shown in Fig. 5. These curves indicated that the elongation of AZ31 alloy was improved with the decrease of the grain size. The yield strength of as-received specimen was higher than those of ECAPed-n ones while the ultimate tensile strength was lower. The Young’s modulus slightly decreased due to the mass dislocations formed by severe plastic deformation of ECAP progress. The results of tensile tests at room temperature were summarized in Table 1.

Table 1. The results of tensile tests at room temperature

<table>
<thead>
<tr>
<th>Specimen</th>
<th>d / μm</th>
<th>E / GPa</th>
<th>σ_y / MPa</th>
<th>σ_p / MPa</th>
<th>δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-received</td>
<td>16.47</td>
<td>41.81</td>
<td>133.46</td>
<td>241.56</td>
<td>0.08</td>
</tr>
<tr>
<td>ECAPed-1</td>
<td>6.47</td>
<td>38.84</td>
<td>111</td>
<td>239.4</td>
<td>0.113</td>
</tr>
<tr>
<td>ECAPed-2</td>
<td>4.46</td>
<td>35.87</td>
<td>127.15</td>
<td>277.2</td>
<td>0.146</td>
</tr>
<tr>
<td>ECAPed-4</td>
<td>1.75</td>
<td>32.15</td>
<td>118.76</td>
<td>259.5</td>
<td>0.161</td>
</tr>
</tbody>
</table>

Note: d was grain size, E was Young’s modulus, σ_y was yield strength, σ_p was ultimate tensile strength and δ was elongation.

Fig. 5. true stress and strain curves of AZ31 alloy at room temperature.

3.2 Fracture property

The results of fracture toughness tests were listed in Table 2. In this study, since the dimension of the three point bending sample could not satisfy the requirements of plane-strain fracture toughness, the crack tip open displacement (CTOD) was chosen to describe the fracture property of AZ31 magnesium alloy and the fracture toughness $K_C$ can be calculated through Eq.1:

$$\delta = \frac{K_C^2}{E\sigma_S}$$

Table 2. The results of fracture toughness test

<table>
<thead>
<tr>
<th>Specimen</th>
<th>W / mm</th>
<th>B / mm</th>
<th>a / mm</th>
<th>t / s</th>
<th>CTOD_c / mm</th>
<th>$K_C$ / MPam$^{1/2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-received</td>
<td>5.76</td>
<td>3.02</td>
<td>1.6</td>
<td>690.8</td>
<td>0.075781</td>
<td>21.1</td>
</tr>
<tr>
<td>ECAPed-1</td>
<td>5.9</td>
<td>2.66</td>
<td>1.58</td>
<td>1207.6</td>
<td>0.153558</td>
<td>25.5</td>
</tr>
<tr>
<td>ECAPed-2</td>
<td>5.64</td>
<td>2.66</td>
<td>1.46</td>
<td>1357.5</td>
<td>0.165552</td>
<td>28</td>
</tr>
<tr>
<td>ECAPed-4</td>
<td>6.02</td>
<td>2.88</td>
<td>1.94</td>
<td>1279.3</td>
<td>0.230405</td>
<td>28.6</td>
</tr>
</tbody>
</table>
Note: $W$ and $B$ was the width and thickness of the specimen, $a$ was the length of pre-crack, $t$ was the time when the load reached the highest value.

The time history of CTOD was calculated geometrically by Eq. 2 considered the history of the notch edge open displacement, termed as $V$ and the displacement at loading point, termed as $\Delta$.

$$\delta = V - \frac{4a}{S} \Delta$$  \hspace{1cm} (2)

Where $a$ was the crack length and $S$ was the span between the two supporting points of the three point bending sample ($S$ was 24mm in this study). The notch edge open displacement was generated through the DIC technique from the photos taken by camera stepping every twenty seconds. Fig. 6 was a typical displacement atlas in the vicinity of the pre-crack analysed through DIC data analysis software.

![Fig.6](image1.png)

Fig.6. (a) the speckle photo taken by the CCD camera (b) a typical displacement atlas in the vicinity of the pre-crack (the interested region in (a)).

From Table 2, it was found that the $c_{CTOD}$ namely, the CTOD at the critical time when the load reached the highest value increased as the grain size decreased. Considered the change of the Young’s modulus and yield strength of material due to ECAP progress, the fracture toughness $K_c$ increased from 21.1 MPam$^{1/2}$ to 28.6 MPam$^{1/2}$ when the grain size decreased from 16.47 $\mu$m to 1.75 $\mu$m. The fracture toughness tested in this study agreed well with the results achieved by Somekawa et al. (2005). In their study, the fracture toughness was 22 MPam$^{1/2}$ for AZ31 alloy with grain size of 13.5 $\mu$m. Fig. 7 showed the evolution of the crack tip. Fig. 7(a) and (b) showed that the crack opening displacement increased with the loading increase and the crack tip became obtuse without any substantial propagation. Thus, it could be indicated that a mass of plastic deformation had taken place around the crack tip. Furthermore, from the fracture surface Fig.8 (a) after the test, a lot of microvoids presented, suggesting typical mechanism of dimple fracture. Also, the size of the microvoids matched the grain size indicated...
that the microvoids were grain pullouts in the other fracture surface. However, in Fig. 7(c) and (d), the crack tip propagated (as shown by arrows in Fig. 7(d)) within the grain almost without increase of the opening displacement. Additionally, the appearances of cleavage steps and river pattern around the microvoids (Fig. 8(b)) which were smaller than the microvoids in Fig. 8(a) suggested the mechanism of mixture of cleavage fracture and dimple fracture.

Fig. 8. The typical SEM micrographs of the fracture surface after fracture toughness tests: (a) as-received and (b) ECAPed-4.

4. Summary

The fracture toughness of an AZ31 magnesium alloy processed by ECAP was investigated. The following results were obtained:

1) Based on the experimental results, the $K_c$ of AZ31B alloy was obtained to be 21.1-28.6 MPa$m^{1/2}$ with average grain size variation from 16.47 $\mu$m to 1.75 $\mu$m. As the grain size decreased, the fracture toughness of AZ31 magnesium alloy was increased.

2) The fracture mechanism of as-received AZ31 magnesium alloy was different from that of the ECAPed AZ31 alloy. For the as-received AZ31 magnesium alloy, dimple fracture were dominated. However, mixture of cleavage fracture and dimple fracture contributed to the fracture of ECAPed AZ31 magnesium alloy with fine grain size.

Acknowledgements

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References