PLANE STRAIN FRACTURE TOUGHNESS DETERMINATION FOR MAGNESIUM ALLOY

Mohd Ahadlin Mohd Daud¹, Mohd Zulkifli Selamat², Zainuddin Sajuri³

¹Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka, Locked Bag 1752, Pejabat Pos Durian Tunggal, 76109 Durian Tunggal, Melaka.

³Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor

ABSTRACT

A stress intensity factor K was used as a fracture parameter to determine the true material property, i.e. plane strain fracture toughness KIC of AZ61 magnesium alloy using a single edge notch bend (SENB) specimen in accordance to ASTM E399 testing method. Five different specimen thicknesses of 2 to 10 mm were used in the test. A sharp fatigue pre-crack was initiated and propagated to half of specimen width at a constant crack propagation rate of about 1 x 10⁻⁸ m/cycle before the specimen was loaded in tension until the fracture stress is reached and then rapid fracture occurred. The fracture toughness Kc values obtained for different thicknesses showed that Kc value decreased with increasing specimen thickness. The highest Kc value obtained was 16.5 MPa√m for 2 mm thickness specimen. The value of Kc became relatively constant at about 13 MPa√m when the specimen thickness exceeds 8 mm. This value was then considered as the plane strain fracture toughness KIC of AZ61 magnesium alloy. Calculation of the minimum thickness requirement for plane strain condition and the size of the shear lips of the fracture surface validate the obtained KIC value.

KEYWORDS: Stress intensity factor, Fracture Toughness, Thickness, Shear lips Magnesium alloy.

1.0 INTRODUCTION

In recent decades, magnesium alloys have gained great attention by automotive industry players for their promising application as structural materials. The major application benefit is the weight reduction due to their low density which consequently lead to fuel saving. Other advantages of magnesium alloy are high specific strength, good in casting, machining and recyclability (Mordika, 2001). European car maker such as Volkswagen and
BMW have introduced the application of wrought magnesium alloys in several automotive components [Duffy, 1996 and Schumann et al., 2003]. For structural application, it is important to ensure the mechanical properties of magnesium alloys satisfy both reliability and safety requirement. The main mechanical properties of AZ61 such as tensile strength and modulus of elasticity are well known, but some other important parameters such as fracture toughness are still unknown. There are some data on the fracture toughness $K_{IC}$ value for magnesium alloy that was reported by (Hidetoshi et al., 2005) and (Barbagallo et al., 2004) respectively. They reported that the fracture toughness $K_{IC}$ value for as-extruded AZ31 was 15.9 MPa$\sqrt{m}$ and for AZ91C in the T6 condition was 11 MPa$\sqrt{m}$. However, to the best authors knowledge, there is no detail work done to determine the plane strain fracture toughness of AZ61 magnesium alloy. It is very important for engineers to know the fracture parameter before use the material in real applications. Therefore, the objective of this study is to determine the plane strain fracture toughness for extruded AZ61 magnesium alloy using several specimens’ thickness.

2.0 EXPERIMENT PROCEDURE

The specimen used for fracture toughness test was single edge notch bend (SENB or 3 point bending) specimen as shown in Fig. 1. Specimen geometry was selected according to ASTM E399 standard. The specimen was then polished with 500 to 1500 grit emery papers to obtain smooth surface. The pre-cracking was attained at pre-cracking growth rates less than $10^{-8}$ m/cycle until the crack reaches half of the width of the specimen. Pre-cracking were carried out on a pneumatic fatigue testing machine (14 kN maximum capacity). The pre-cracking were performed at frequencies 10 Hz and using sinusoidal loading form. Stress ratio $R=0.1$ was applied in pre-cracking procedure at room temperature. The pre-cracking was performed at a constant $\Delta K$ level to obtain constant crack growth rate. The stress intensity factor value for SENB specimen was calculated according to the following equations:

$$K_0 = \frac{3PS}{2BW^{3/2}} f\left(\frac{a}{W}\right)$$

Geometrical factor,

$$f\left(\frac{a}{W}\right) = 1.93\alpha^{1/2} - 3.07\alpha^{3/2} + 14.53\alpha^{5/2} - 25.11\alpha^{7/2} + 25.8\alpha^{9/2}$$

Where,

$P =$ load, [N], $S =$ span length, [40 mm], $B =$ specimen thickness, [mm], $W =$ specimen width, [10 mm] and $a =$ crack length, [mm].
A secant line through the origin with slope of 95% of the initial elastic loading slope was used to determine the conditional maximum load value. For validation of maximum fracture load $P_{\text{max}}$, the principle type of load displacement record as shown Fig. 2 was used for comparison as recommended by ASTM E399. To identify the validity of the plane strain fracture toughness value, Eq. (3) was referred. Here, $a$ is a crack length, $B$ is the minimum thickness that produces a condition where plastic strain energy at the crack tip is minimal, $K_C$ is the fracture toughness of the material and $\sigma_y$ is the yield stress.

$$a, B \geq 2.5 \left( \frac{K_C}{\sigma_y} \right)^2$$  \hspace{1cm} (2)

### 3.0 RESULT AND DISCUSSION

Figure 3 showed the load-displacement curves for 2, 4, 6, 8 and 10 mm thickness specimens. All load-displacement curves exhibited type I load-displacement record as shown in Fig. 2. $P_Q$ is determined to be the valid value of maximum fracture load for calculation of fracture toughness. The mode-1 stress intensity factor at fracture $K_Q$ was calculated using Eq. (1) based on the $P_Q$ value obtained. The calculated values in Table 1 were then plotted in a $K_C$ versus thickness relation curve as shown in Fig. 4. The results showed that the highest $K_C$ value obtained was 16.5 MPa√m for 2 mm thickness specimen. The value of $K_C$ became relatively constant at about 13 MPa√m when the specimen thickness exceeds 8 mm. This value was then considered as the plane strain fracture toughness $K_{IC}$ of AZ61 magnesium alloy. The shear lip ratio value for validation of $K_{IC}$ is below 0.1 (Anderson, 2005). The shear lip ratio for 8 and 10 mm specimen thickness were 0.1 and 0.08, respectively. Therefore, plane strain fracture toughness $K_{IC}$ value was valid for specimen thickness more than 8 mm.
Macroscopic observation of fracture surfaces of the specimens clearly showed two discrete
indicated that the samples were fracture in plane stress condition.
lip zone. This indicates that the plane strain conditions are achieved. For 2, 4 and 6 mm thickness
samples, the fracture surface of the fatigue fracture region looks rough and shiny with limited shear
propagation due to fatigue while the rapid fracture region with shining appearance shows the
The direction of the crack propagation was clearly determined. The fatigue crack initiated from the
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TABLE 1
Fracture toughness value for different thickness of magnesium alloy

<table>
<thead>
<tr>
<th>Specimen thickness, B (mm)</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{\text{max}} ) (kN)</td>
<td>0.285</td>
<td>0.557</td>
<td>0.722</td>
<td>0.838</td>
<td>1.210</td>
</tr>
<tr>
<td>( P_Q ) (kN)</td>
<td>0.280</td>
<td>0.520</td>
<td>0.700</td>
<td>0.790</td>
<td>1.100</td>
</tr>
<tr>
<td>Fracture toughness, ( K_C ) (MPa√m)</td>
<td>16.5</td>
<td>15.4</td>
<td>13.9</td>
<td>12.0</td>
<td>13.1</td>
</tr>
<tr>
<td>Shear lip ratio</td>
<td>0.43</td>
<td>0.33</td>
<td>0.18</td>
<td>0.10</td>
<td>0.08</td>
</tr>
<tr>
<td>Condition</td>
<td>Plain-Stress</td>
<td>Plane-Stress</td>
<td>Plane-Stress/Mixed Mode</td>
<td>Plane-Strain</td>
<td>Plane-Strain</td>
</tr>
</tbody>
</table>

![FIGURE 3](image)

**FIGURE 3**
Load-displacement curve for 2, 4, 6, 8 and 10 mm thickness of AZ61 magnesium alloy.

![FIGURE 4](image)

**FIGURE 4**
Effect of thickness on fracture toughness for AZ61 magnesium alloy.
Macroscopic observation of fracture surfaces of the specimens clearly showed two discrete regions. These two distinct regions are shown in the optical micrograph of Fig. 5. The boundaries of these regions are well distinguished between the fatigue fracture region and rapid fracture region. The direction of the crack propagation was clearly determined. The fatigue crack initiated from the notch and propagated parallel on both side. The fatigue fracture region indicated the gradual crack propagation due to fatigue while the rapid fracture region with shining appearance shows the unstable crack propagation and characterized by fast crack features. For 8 and 10 mm thickness samples, the fracture surface of the fatigue fracture region looks rough and shiny with limited shear lip zone. This indicates that the plane strain conditions are achieved. For 2, 4 and 6 mm thickness samples the rapid fracture region looks rough and shiny with large amount of shear lip zone which indicated that the samples were fracture in plane stress condition.

Figure 6 shows the fracture surface of 2 mm and 8 mm thickness samples after fracture toughness test. The images were taken from the middle of sample thickness. Figure 6(a) showed the fracture surface of 2 mm thickness sample were relatively rough feature with the presence of many ductile dimples which may resulted from shear loading. Overview of the fracture surface revealed that almost half of fracture area was dominated by shear lip. Detail observation of the shear lip area is shown in Fig. 7. It is suggested that plastic zone size developed during the loading of 2 mm thickness sample was very big. For plain strain fracture toughness validation, the plastic zone size should be not more than the allowable area of \((1/6\pi)(K_{IC}/\sigma_y)^2\) or 2% of the crack length.
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Figure 6(b) showed cleavage fracture surface associated with river pattern was observed dominated the fracture surface of 8 mm thickness sample. This shows that the sample was failed in brittle manner with limited plastic deformation. Small ratio of shear lip area validates the sample fracture in plain strain condition.

4.0 CONCLUSION

Plain strain fracture toughness of AZ61 magnesium alloy was investigated. Based on the results obtained, the findings are concluded as follows:

1. Fracture toughness value, \( K_C \) for AZ61 magnesium alloy decreased with the increasing of specimen thickness. The \( K_C \) value became relatively constant at the specimen above 8 mm.
2. The critical plane strain fracture toughness, \( K_{IC} \) of extruded AZ61 magnesium alloy was 13.0 MPa√m.
5.0 ACKNOWLEDGEMENTS

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6.0 REFERENCES


