PLANE STRAIN FRACTURE TOUGHNESS DETERMINATION FOR MAGNESIUM ALLOY

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ABSTRACT

A stress intensity factor K was used as a fracture parameter to determine the true material property, i.e. plane strain fracture toughness K_{IC} 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 K_C 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 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. Calculation of the minimum thickness requirement for plane strain condition and the size of the shear lips of the fracture surface validate the obtained K_{IC} 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√m and for AZ91C in the T6 condition was 11 MPa√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 ΔK level to obtain constant crack growth rate. The stress intensity factor value for SENB specimen was calculated according to the following equations:

$$K_Q = \frac{3PS}{2BW^{3/2}} f\left(\frac{a}{W}\right) \tag{1}$$

Geometrical factor,

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

Where,

P = load, [N], S = span length, [40 mm], *B* = specimen thickness, [mm], *W* = specimen width, [10 mm] and a = crack length, [mm].

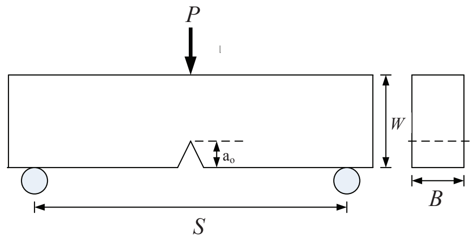

FIGURE 1
Geometry of the SENB specimen fracture test as per ASTM.

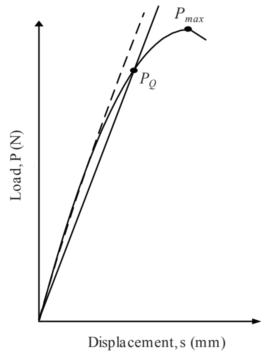

FIGURE 2
Types I of load-used in displacement records (ASTM E399, 2008)

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_{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 σ_y is the yield stress.

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

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.

TABLE 1
Fracture toughness value for different thickness of magnesium alloy

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

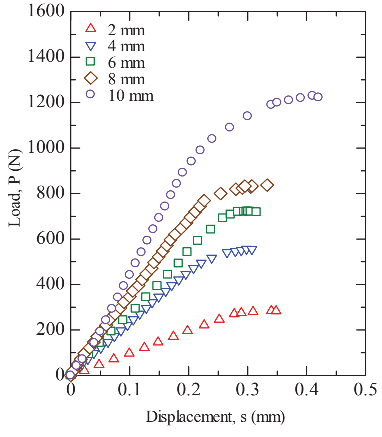

FIGURE 3
Load-displacement curve for 2, 4, 6, 8 and 10 mm thickness of AZ61 magnesium alloy.

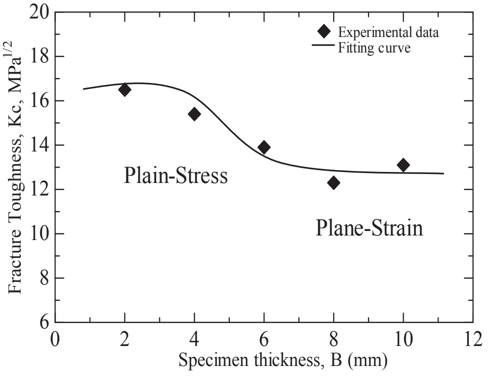

FIGURE 4
Effect of thickness on fracture toughness for AZ61 magnesium alloy.

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 shinning 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.

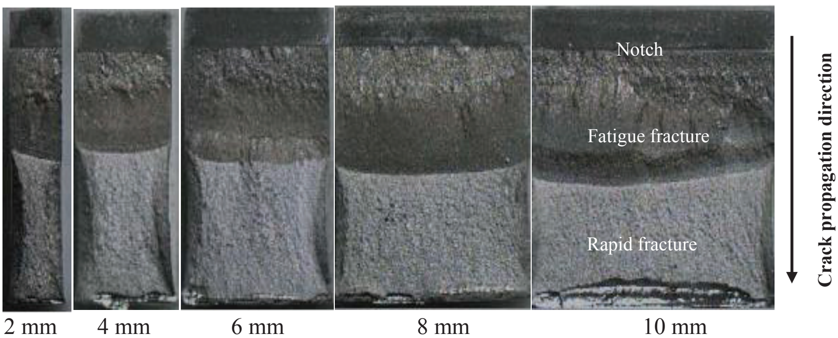

FIGURE 5
Overview of fracture surface for sample 2 mm, 4 mm, 6 mm, 8 mm and 10 mm.

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.

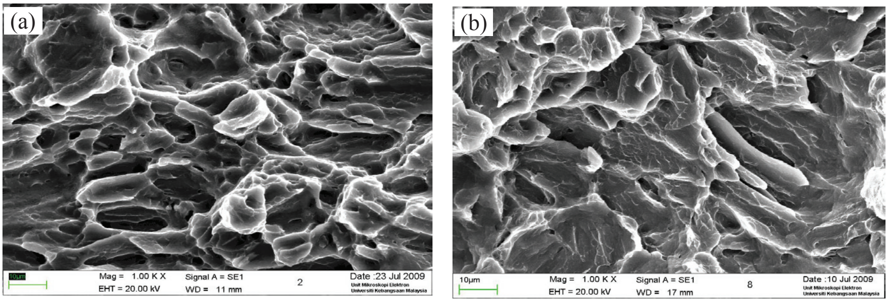

FIGURE 6
SEM observation on fracture surface in the middle of tested samples

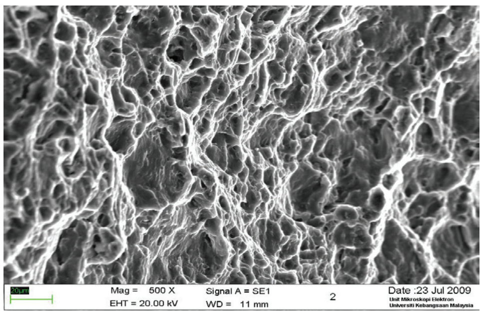

FIGURE 7
SEM observation on the shear lip area of the tested

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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