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MIXED MODE FRACTURE BEHAVIOR OF AN ALUMINUM ALLOY A6061 INVESTIGATED BY USING COMPACT TENSION SHEAR SPECIMENS

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ABSTRACT

Aluminum alloys, such as A6061-T6, are widely used in engineering components. However, detailed knowledge is needed to understand the way they respond to a fracture due to mechanical loading. Fractures occur in the structural component from crack propagation, and it is important to understand the mixed mode fracture behavior of crack growth. In this research, mixed mode fracture testing was conducted on the aluminum alloy A6061-T6 by employing a compact tension shear specimen. Crack growth behavior was investigated by applying a quasi-static loading at a constant cross-head speed using a Servopulser universal testing machine. The crack growths were observed by a Keyence digital microscope, and the critical stress intensity factors of the material were examined. Results showed that the shear type of crack initiation preceded the opening-type fracture. The dimple-type fracture on the fracture surface occurred under mode I and mixed mode with a loading angle of about 60^o and 75^o, respectively. The transition of crack initiation behavior from the opening-type fracture to the shear-type fracture occurred at a loading angle from 15^o to 30^o. The experimental data followed the maximum hoop stress criterion under mode I and mixed mode at a loading angle 60^o and 75^o, respectively, for the compact tension shear specimen. Crack propagation behavior with three small holes occurring in a *zigzag* pattern ahead of the crack tip showed that crack initiation and propagation occurred only in the opening-type fracture. The experimental data followed the maximum hoop stress criterion under mode I and mixed mode with a lower mode II component at a loading angle of 75^o. When the small holes occured *inline*, there were two types of fractures occurring: an opening fracture at crack initiation and then crack propagation caused by shear fracture.

Keywords: Aluminum alloy; Crack growth behavior; Critical stress intensity factor; Compact tension shear specimen

1. INTRODUCTION

Aluminum alloys are widely applied in the engineering of machine components, and consequently it is important to know how they respond to fractures due to mechanical loading in accordance with the American Society for Metal (ASM) l Handbook (1989). Fractures occur in the structure from fatigue cracks extending from defects in the structural component. Therefore, the behavior of the crack growth needs to be understood.

Many previous studies have tested fractures both under mode I and mode II loading as well as for mixed mode elastic-plastic fractures. However, only a few studies have examined crack

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growth behavior of the aluminum alloy under mixed mode loading, especially using compact tension shear (CTS) specimens. When plastic deformation becomes extensive, linear-elastic fracture mechanics cease to be applicable for various fracture parameters (Halbäck et al., 1994; Aoki et al., 1990). According to Knott (1980), the fibrous fracture mechanism can be divided into two extremes of behavior, *i.e.*, micro-void coalescence or fast shear. Fast shear in steel under various mixed mode loadings was recently examined by Maccagno and Knott (1992). In an Finite Element Method (FEM) analysis, Aoki et al. (1987) concluded that shear fracture in an aluminum alloy becomes more pronounced as the mode II component increases. Studies of fracture behavior of polymer alloys under various mixed mode loadings showed that crack initiation occurs in the opening-type fracture followed by the transition fracture from the opening-type to the shear-type fracture (Husaini et al., 2001; Husaini et al., 2000; Husaini et al., 1997).

In the present study, mode I and mixed mode fracture behaviors of an aluminum alloy were investigated by using a CTS specimen. Crack propagation was observed with a digital microscope. Crack initiation and propagation behavior took into account the effect of three small holes that occurred ahead of the initial crack tip.

2. EXPERIMENTAL METHODS

The experimental methods used are similar to those previously employed by Husaini et al. (1997). The material used for all experiments was the aluminum alloy A6061-T6. Mechanical properties were determined through tensile tests on a specimen 12.5 mm in diameter and about 62.5 mm in length (Table 1). Fracture tests used CTS specimens with the dimensions 90mm×148mm×8mm, as shown in Figure 1. As per Japan Society of Mechanical Engineer (JSME) standards (JSME, 1981), a fatigue crack of up to $a_o/w \cong 0.5$ was introduced in the specimen, where a_o is the pre-cracked length and w is the specimen width.

Table 1 Mechanical properties of aluminium alloy A6061-T6

Yield Strength	σ_{ys}	243 (MPa)
Shear Strength	τ	184 (MPa)
Modulus of Elasticity	E	61.1 (Gpa)
Poisson's Ratio	ν	0.33

Two other types of specimens were tested. In these tests, three holes were drilled ahead of the crack tip in a *zigzag* pattern in one specimen and in an inline pattern in the other specimen.

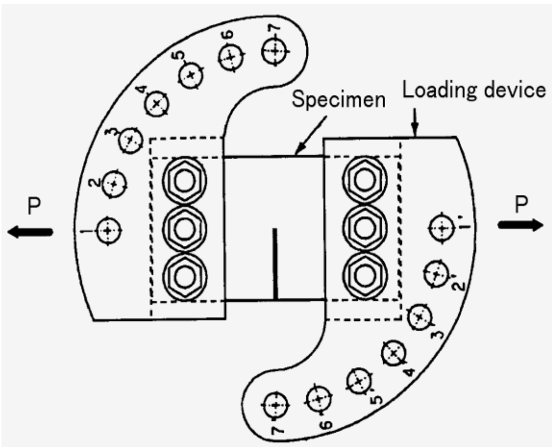
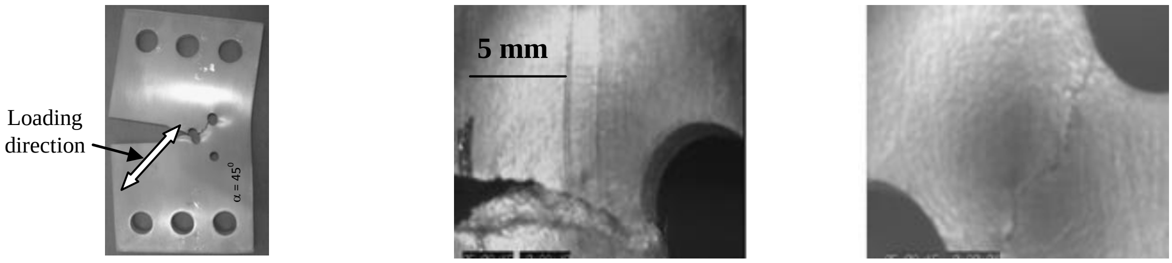


Figure 1 Configuration of a CTS specimen and the loading device for mixed mode testing

In the fracture tests, the CTS specimen was loaded under displacement-controlled conditions by a Servopulser universal testing machine attached to a special loading device (Richard et al. 1983) using a constant cross-head rate of 0.05 mm/sec. Mode I loading was conducted using the No. 1 and 1' holes, whereas mixed mode loading was carried out using six other combinations of the hole pairs. The angle between the loading axis and the crack surface was identified as α. Fracture tests were conducted in three types of CTS specimens. There were two types of specimens with small holes; one had three holes in a zigzag pattern, the other three holes in an inline pattern, were drilled ahead of the crack tip. The small holes were about 5 mm in diameter, the distance from the crack tip to the first hole was about 11 mm, and the distance between holes was about 11 mm. Fracture behavior of crack initiation and crack propagation at the crack tip was monitored by means of a Keyence digital microscope.

3. RESULTS AND DISCUSSION

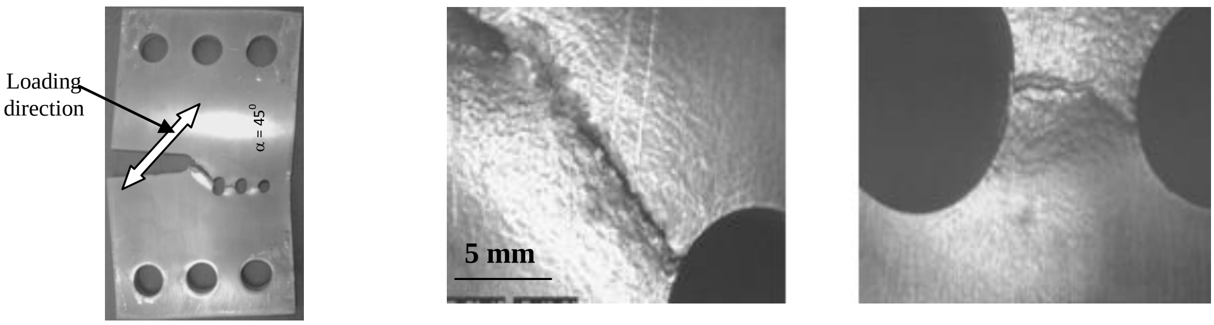
The fracture behavior of the CTS specimen with three holes in a *zigzag* pattern under mixed mode loading with a loading angle of $\alpha = 45^{\circ}$ is shown in Figure 2. From these results, it can be inferred that the shear fracture occurred due to decreases in the ligament (the distance between the crack tip and the first hole) between the holes.



(a) (b) (c)

Figure 2 Crack propagation behavior for the CTS specimen with three holes in a *zigzag* pattern ahead of the crack tip with mixed mode loading ($\alpha = 45^{\circ}$): (a) Fracture specimen; (b) crack initiation and extension behavior; (c) crack propagation caused by shear fracture

Results of the crack propagation behavior for the specimen with three holes in the *inline* pattern ahead of the crack tip under mixed mode loading with a loading angle of $\alpha = 45^{\circ}$ is shown in Figure 3.



(a) (b) (c)

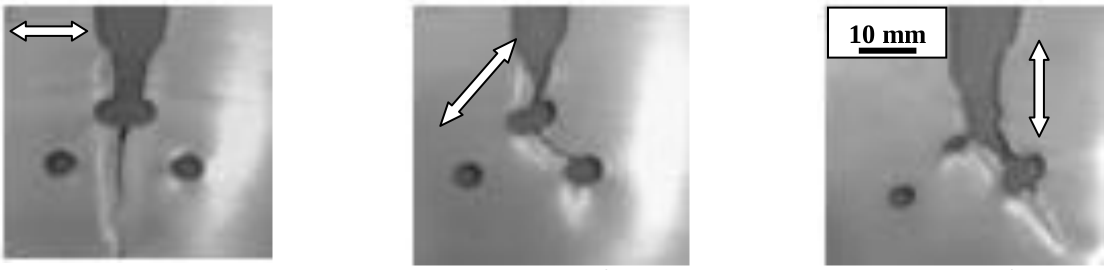
Figure 3 Crack propagation behavior for the CTS specimen with three holes in the *inline* pattern ahead of the crack tip under mixed mode ($\alpha = 45^{\circ}$): (a) Fracture specimen; (b) crack growth behavior; (c) crack propagation from shear fracture

Figure 4 shows that the crack growth direction of the fracture differed for the different loading angles. The arrow in the figure indicates the loading direction.

(a) $\phi = 0^o$ (b) $\phi = 47^o$ (c) $\phi = 72^o$

Figure 4 Crack growth directions ϕ after fracture testing: (a) Mode I, $\alpha = 90^o$; (b) mixed mode, $\alpha = 45^o$; and (c) mode II, $\alpha = 0^o$

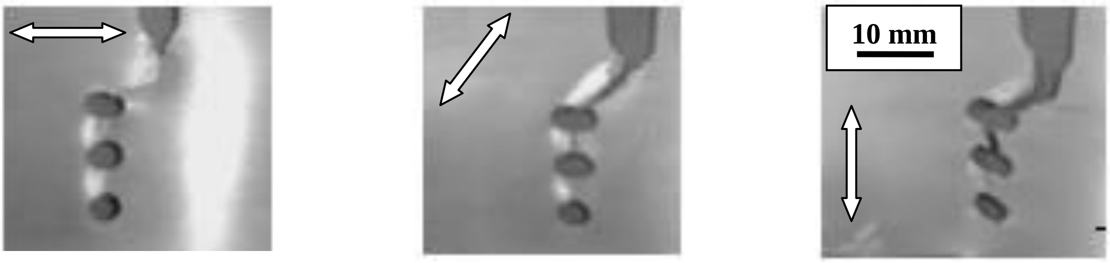
Figure 5 shows crack propagation behavior for the specimen with three holes in a *zigzag* pattern ahead of the crack tip under mode I (a), mixed mode (b), and mode II (c) loadings. The 5-mm diameter hole was introduced 11 mm ahead of the initial crack tip. Figure 5(a) shows the crack extension behavior under mode I loading that occurred in the opening-type fracture. The fracture surface near the surface of the specimen occurred with a shear lip; however, the middle of the fracture surface was flat. Fracture behavior under the mixed mode condition with a loading angle of 45^o is shown in Figure 5b. In this case, crack initiation occurred in the opening fracture. However, crack extension propagated due to the critical value of the shear stress; the shear fracture then occurred due to critical shear stress at the ligament. In the mode II loading with a loading angle of 0^o (Figure 5 c), crack initiation and propagation only occurred from shear fracture.



(a) $\alpha = 90^o$ (b) $\alpha = 45^o$ (c) $\alpha = 0^o$

Figure 5 Crack extension behavior of the specimen with three holes located ahead of the crack tip

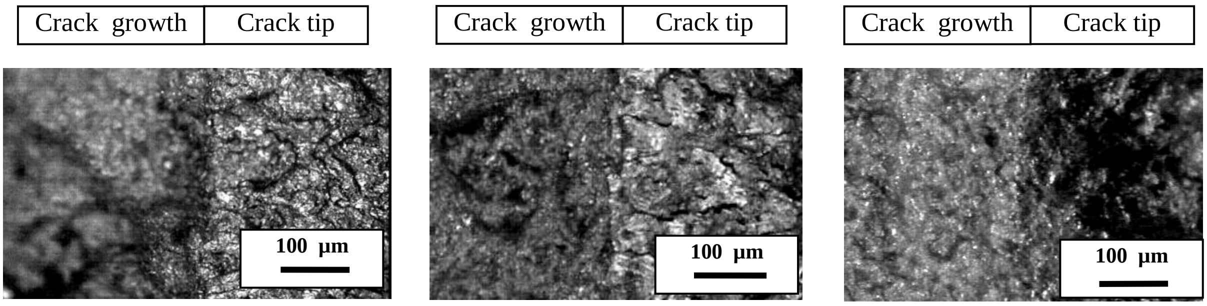
Figure 6 shows crack propagation behavior for the specimen with three holes (*inline* pattern) ahead of the crack tip. Figure 6a shows crack extension behavior under mode I loading occurred in the opening-type fracture. In the case of fracture behavior under mixed mode with a loading angle of 45^o (Figure 6b), crack initiation occurred in the shear-type fracture. Crack extension propagated via the opening-type fracture due to critical stress at the ligament. In the mode II loading with a loading angle of 0^o (Figure 6c), crack initiation and propagation occurred in two fracture processes. First, the opening-type fracture occurred at crack initiation; this was followed by the transition fracture and then the shear-type fracture, due to the decrease in the ligament between the crack tip and the holes. Therefore, the existence of small holes ahead of the crack tip decreased the ligament between the crack tip and the hole due to crack extension, after which shear-type fracture instability occurred.



(a) (b) (c)

Figure 6 Crack propagation behavior of the specimen with three holes in an *inline* pattern ahead of the crack tip: (a) Mode I, $\alpha = 90^{\circ}$; (b) mixed mode, $\alpha = 45^{\circ}$; (c) mode II, $\alpha = 0^{\circ}$

SEM observations of the fracture surface of the crack tip and the crack growth zone are shown in Figure 7. The dimple-type fracture on the fracture surface due to a lower mode II component is shown in Figures 7a and 7b. When the mode II component was dominant, crack initiation occurred as a shear-type fracture (Figure 7c).



(a) Mode I (b) Mixed mode (c) Mode II

Figure 7 SEM images of the fracture surface near the crack tip

The experimental results showed that crack initiation occurs below the maximum load. Therefore, small-scale yielding fracture criteria could be applied. According to Murakami (1987), the critical value of stress intensity factors K_I at crack initiation under mode I loading is denoted as K_{Iin}. Hereafter, a critical stress intensity factor, which was obtained by this method, will be referred to as fracture toughness K_{Iin}. In our experiment, we found that fracture toughness K_{Iin} = 27.03 MPa·√m. The critical stress intensity factors of K_{II}/K_I at crack initiation for the opening type of fracture are plotted in Figure 8.

The experimental data shown in Figure 8 relate to the CTS specimen with three holes in a *zigzag* (▲) and *inline* (■) pattern ahead of the crack tip, where both axes are normalized by fracture toughness K_{Iin}. The solid line in the figure indicates the fracture boundary curve corresponding to the maximum hoop stress criterion ($\sigma_{\theta\max.}$)as reported by Erdogan et al. (1963), where the relationship between K_I and K_{II} is given by:

$$\left(\frac{K_I}{K_{Ic}}\cos^2\theta_0 - \frac{3}{2}\frac{K_{II}}{K_{Ic}}\sin^2\theta_0\right)\cos^2\frac{\theta_0}{2} = 1, \tag{1}$$

where θ_0 denotes the direction at which hoop stress takes its maximum value, given by

$$\theta_0 = \sin^{-1}\left(\frac{\kappa}{\sqrt{1+9\kappa^2}}\right) - \tan^{-1} 3\kappa \tag{2}$$

with the mixed mode ratio, $\kappa = K_{II} / K_I$.

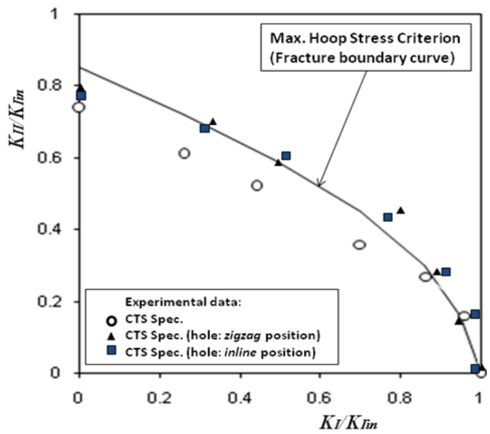


Figure 8 Plot of critical stress intensity factors under mode I, mixed mode, and mode II loadings where both axes are normalized by K_{Iin}

Figure 8 shows that the experimental data follow the maximum hoop stress criterion only under pure mode I and mixed mode loadings at loading angles of 15^o and 30^o of the mode II component for the CTS specimen. On the other hand, the results showed that when the mode II component exceeds some critical value (occurring at a loading angle from 45^o to 90^o), then the fracture resistance of the tested material decreases, as shown in Figure 8. However, the experimental data for the specimen with the hole in a *zigzag* pattern followed the maximum hoop stress criterion only under pure mode I and mixed mode loadings at a loading angle of 75^o. In contrast, the experimental results differed for the specimen with holes in the *inline* pattern. In this case, the maximum hoop stress criterion was followed only under pure mode I and mixed mode with a higher mode II component at a loading angle of 15^o.

The experimental results demonstrated that a ductile fracture is caused by initiation and coalescence of a void corresponding to local stress, as reported by Rice-Tracey (1969) and Hancock (1976). In the case of an increasing mixed mode ratio, shear strain occurs locally at the crack tip, as proposed by Aoki (1987), and this causes crack initiation of a shear-type fracture by shear stress.

4. CONCLUSION

In the mixed mode fracture tests with a loading angle of 75^o, crack propagation occurred in the opening mode. The dimple-type fracture occurred on the fracture surface due to a lower mode II component at loading angles from 60^o to 75^o. The transition of crack initiation behavior from the opening-type fracture to the shear-type fracture occurred at a loading angle from 15^o to 30^o. Since the appearance of the small hole ahead of the crack tip affected crack initiation and the propagation direction, then the crack propagated and coalesced to the hole by a shear-type fracture.

Crack propagation behavior with three small holes in a *zigzag* pattern ahead of the crack tip showed that crack initiation and propagation occurred in the opening-type fracture. However, when the small holes were in the *inline* position, two types of fracture processes occurred; first, the opening-type fracture occurred at crack initiation, and this was followed by a shear-type fracture until final failure.

5. ACKNOWLEDGEMENT

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