JOURNAL OF MATERIALS SCIENCE 32 (1997) 4673–4677

Effect of notch geometry on short fatigue crack growth in 8090 Al–Li alloy

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The short-crack propagation behaviour of 8090 Al–Li alloy under different ageing conditions has been investigated. The effect of notch geometry on short fatigue crack growth was also studied. The results show that the geometrical configuration of the notch significantly affects the growth behaviour of the short crack, the growth rates of notched short cracks being much higher than those of long cracks at the same stress intensity factor range ΔK level. The orientations of the specimens had a stronger effect on the growth rate of long cracks than on that of short cracks.

1. Introduction
Al–Li alloys with high strength, low density and good low-temperature properties are considered to be the most attractive material to replace some of the conventional aluminium alloys in future aircraft generations. In comparison with the competing composite materials, Al–Li alloys offer many advantages for the aircraft industry. As reported elsewhere [1, 2], the fatigue crack growth properties are superior to those of the traditional aluminium alloys because of the high modulus, reversibility and planarity of slips, as well as crack-tip shielding. However, the superior fatigue crack growth resistance of Al–Li alloys has been based largely on standard tests with through-thickness cracks. These results have provided some basic data for understanding the crack growth mechanism, but they do not evaluate well the fatigue resistance of alloys under service conditions. For example, the fatigue life of many critical components is controlled by short or small cracks under variable amplitude loading. Short cracks in Al–Li alloys were found [3–5] to propagate at stress intensity factor range ΔK levels far below the threshold ΔK_{th} for long cracks and at rates as much as two to three orders of magnitude faster than long cracks at nominally equivalent ΔK levels. The unusual behaviour of short fatigue cracks in Al–Li alloys has already become an obstacle for their engineering application [6]. The growth behaviour of short cracks at notches is strongly affected by the geometric configuration of the notches [7]. The present work compared the growth behaviour of short cracks which initiated from two notches with different root radius.

2. Experimental procedure
The actual chemical composition (wt%) of the 8090 alloy used for the present investigation is 2.55Li, 1.55Cu, 1.13Mg, 0.13Zr and the balance aluminium. The material was supplied in the form of 1.3 mm thick plate and machined into single-edge V-notch specimens of 120 mm × 25 mm × 1.3 mm in size. Both sharp notches with a root radius, ρ, of 0.2 mm and blunt notches with a root radius, ρ, of 1.0 mm, were selected. The depth of notches, D, was 3 mm.

The specimens were solution treated in a salt bath at 530 °C for 30 min, quenched in water, and subsequently aged at room temperature for 600 h, at 190 °C for 1, 16, and 90 h, resulting in naturally aged (NA), underaged (UA), peak-aged (PA) and overaged (OA) conditions, respectively. The corresponding mechanical properties are listed in Table I and the morphology of δ'-phase is shown in Fig. 1.

Fatigue crack propagation tests were conducted on a Schenck servo-hydraulic machine in laboratory air using a load ratio R of 0.2 and a frequency of 50 Hz. The crack initiation and early propagation from notches were monitored using a travelling microscope with magnification of 100. When a crack length of 2 mm was reached, the crack was regarded as a long crack and the near threshold crack growth rates were obtained by the load-shedding scheme.

3. Results
3.1. Differences between long and short fatigue crack growth behaviour
The growth rate of a short crack emanating from a sharp notch, as a function of ΔK, is shown in Fig. 2 for both UA (a) and PA (b) conditions. The data for the corresponding long cracks are also shown for comparison. Similar to the results reported previously [5], the growth rates of the short cracks are much higher than those of the long cracks at equivalent ΔK below ΔK_{th}, and then decrease and again increase with increasing ΔK, displaying a "trough-like" behaviour [8]. It can also be seen from Fig. 2 that the specimen orientations have a strong effect on the growth rate of long cracks but less effect on that of short cracks.

TABLE I Tensile mechanical properties

Ageing conditions	Yield strength, σ_{ys} (MPa)	Ultimate tensile strength, σ_{UTS} (MPa)	Elongation δ (%)
Naturally aged (NA)	278	422	1.08
Underaged (UA)	345	491	5.7
Peak-aged (PA)	431	536	7.8
Overaged (OA)	298	449	7.1

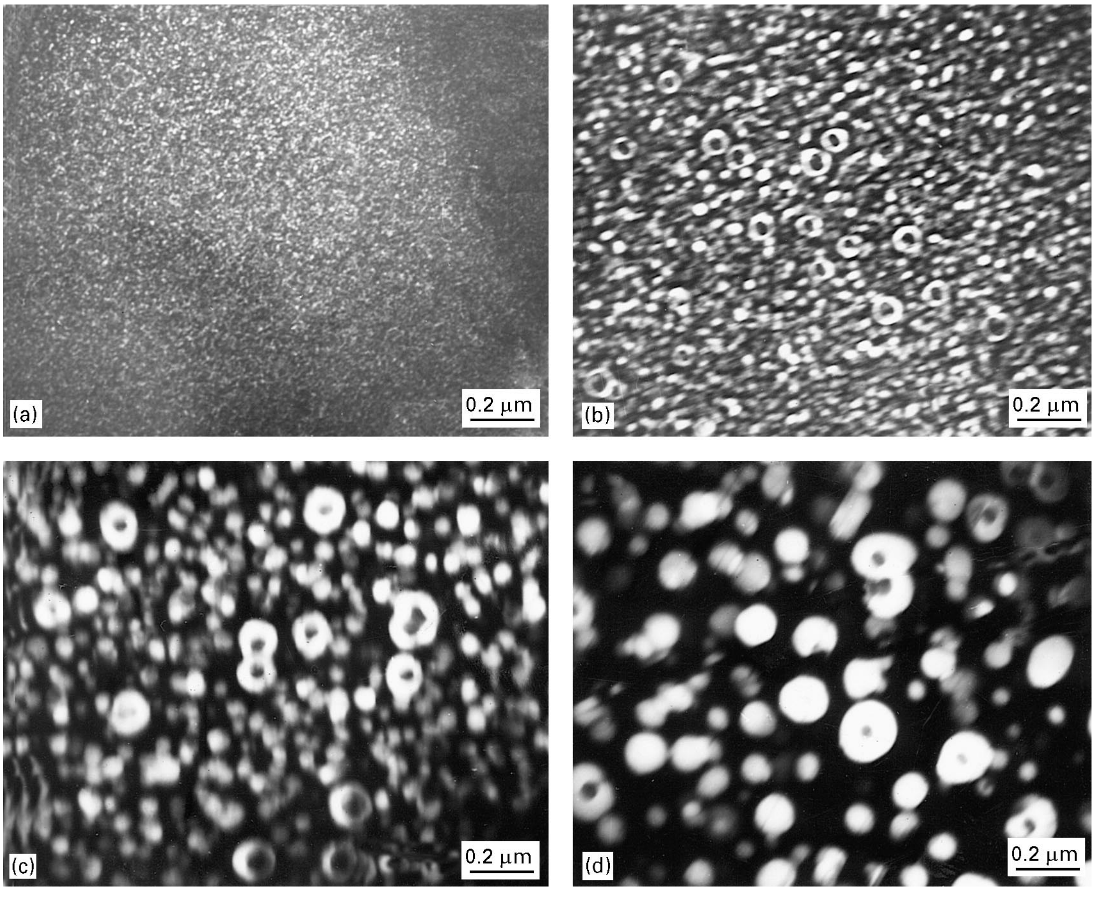

Figure 1 Transmission electron micrographs of δ′-phase after various ageing treatments: (a) naturally-aged (NA), (b) underaged (UA), (c) peak-aged (PA), and (d) overaged (OA).

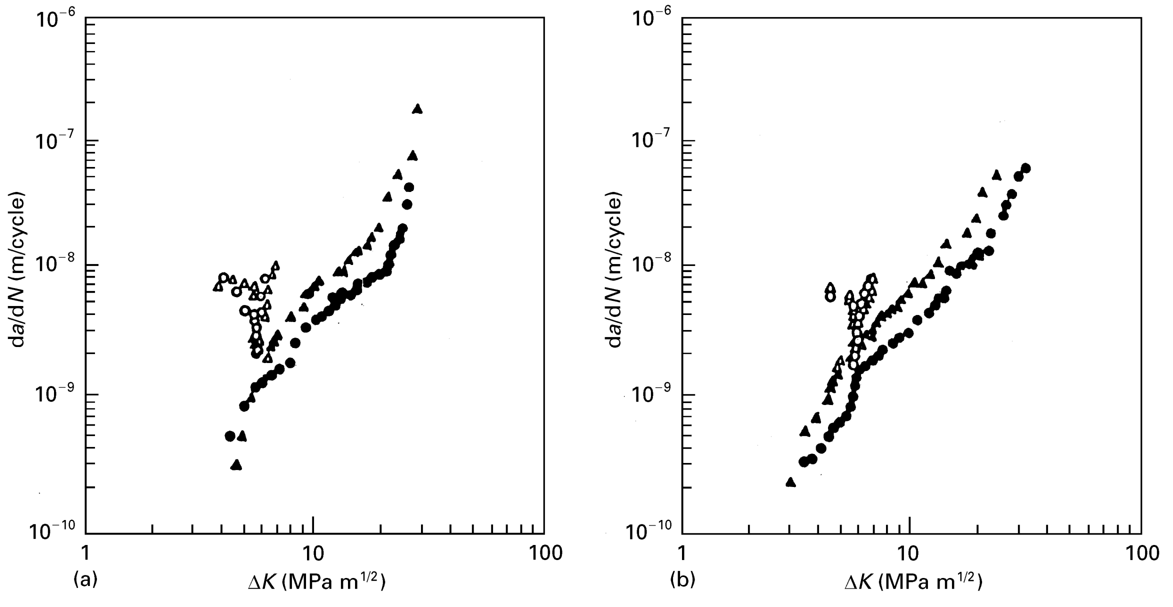

Figure 2 Comparison of growth rates of (▲, ●) long and (△, ○) short cracks emanating from a sharp notch in (a) underaged and (b) peak-aged specimens: (△, ▲) TL, (○, ●) LT.

3.2. Effects of notch geometry on short-crack growth

When fatigue cracks emanate from notches, the initial growth of the nascent cracks can be significantly influenced by the plastic deformation occurring at the root of the notch. Therefore, the geometric configuration of the notches must show strong effects on the growth behaviour of the cracks emanating from the notches. The crack growth behaviour of short fatigue cracks emanated from sharp notches and from blunt notches is shown in Figs 3 and 4, respectively. The influence of specimen orientations and ageing conditions on the short crack growth behaviour is also illustrated. It is clear from Fig. 3 that the short cracks from sharp notches display a "trough-like" behaviour for all ageing conditions in the present investigation. The minimum value of the crack growth rate occurs at almost the same ΔK level (corresponding to a crack length of 450 μm) for UA, PA and OA conditions, but it corresponds to a higher ΔK for the NA condition. It can be seen from the comparison of Fig. 3a and b that there is no significant influence of the specimen orientation on the crack growth behaviour for all ageing conditions except natural ageing. In the case of the NA condition, the crack in a specimen with TL orientation can propagate at a much higher rate than that with LT orientation under a same ΔK level.

The crack emanating from a blunt notch behaves quite differently. As can be seen from Fig. 4, the crack grows initially at an almost constant rate. After the crack reaches a certain length of about 360 μm the crack growth rate increases progressively with

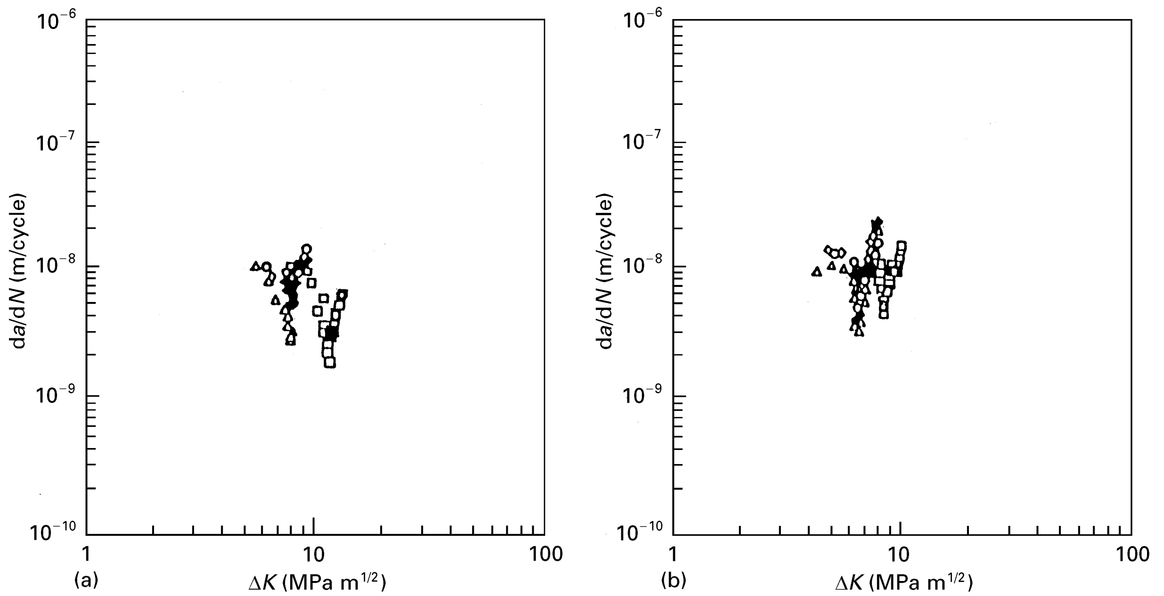

Figure 3 Crack propagation behaviour of short fatigue cracks initiated from sharp notches in differently aged specimens: (a) LT, (b) TL. (◇) OA, (○) PA, (△) UA, (□) NA.

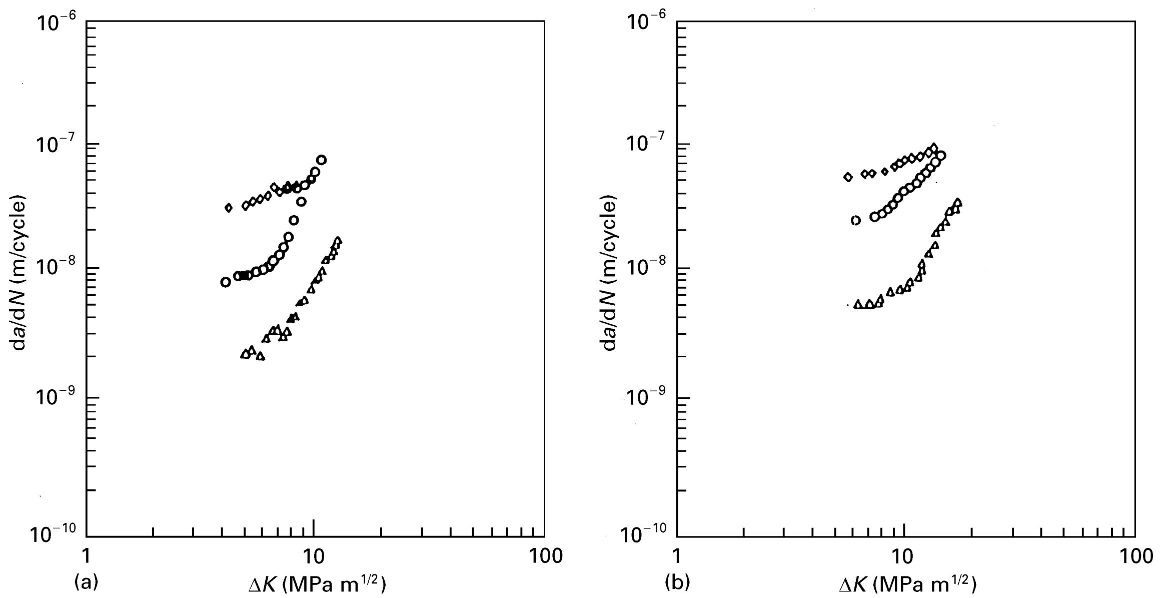

Figure 4 Crack propagation behaviour of short fatigue cracks emanated from blunt notches in (◇) OA, (○) PA and (△) UA conditions: (a) LT, (b) TL.

increasing the crack length and ΔK level. The "trough-like" behaviour has never been observed for a short crack emanating from blunt notches. In addition, both ageing treatments and specimen orientation strongly affect the crack growth behaviour when the crack emanates from a blunt notch. Similar to the results reported for long cracks [1, 5], the crack growth rate decreases in the order of OA, PA and UA conditions. However, the differences in the crack growth rate between the three ageing conditions reduce gradually with increasing ΔK level or crack length. It can also be seen from Fig. 4 that the specimen in the LT orientation shows a higher short-crack growth resistance as compared to the specimen in the TL orientation for each ageing condition in the present study.

4. Discussion

It is difficult to explain all the experimental results mentioned above. Here we would rather focus our attention on the influence of the notch geometry. Fig. 5 schematically shows a notch of depth D and root radius ρ. A crack of length l is propagating from the tip of the notch. In the present investigation, $D = 3$ mm, and $\rho = 0.2$ mm for sharp notch and $\rho = 1$ mm for blunt notch. The notch field size, L, can be estimated from the formula $L = 0.21(D\rho)^{1/2}$. Therefore, $L = 0.17$ mm for a sharp notch and $L = 0.367$ mm for a blunt notch.

Several models have been proposed for the prediction of the deceleration of short-crack growth in notch fatigue. The commonly used argument is that the initial growth of the crack which is totally submerged in the stress field of the notch can be significantly affected by the plastic zone of the notch (see Fig. 5). However, as indicated above in the present investigation, the short crack from a sharp notch exhibits a deceleration of growth over a length of 0.45 mm (450 μm) which is much larger than the notch field size (0.17 mm). In the case of a blunt notch, the retardation of the short-crack growth remained until a crack length of 0.36 mm (360 μm) was reached, which is almost the same size as that of the notch field (0.367 mm). Therefore, the notch stress/strain field does not provide convincing description of the growth behaviour of short cracks emanating from notches.

The stress intensity factor range of a short fatigue crack can be described as [9]

$$\Delta K = K' \Delta\sigma [\pi(l + l_0)]^{1/2} \tag{1}$$

where $\Delta\sigma$ is the far-field stress range, l_0 is a critical crack size below which ΔK_{th} decreases with decreasing crack length [10]. It is given by

$$l_0 = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_e}\right)^2 \tag{2}$$

where $\Delta\sigma_e$ is the fatigue limit of a smooth bar. K' in Equation 1 is the stress concentration factor. K' varies from $K'_{max} = 1.12K_t$ (where K_t is the theoretical stress concentration factor) to K'_{min} at the notch field boundary. Here [9]

$$K'_{min} = [(l + l_0 + D)/(l + l_0)]^{1/2} \tag{3}$$

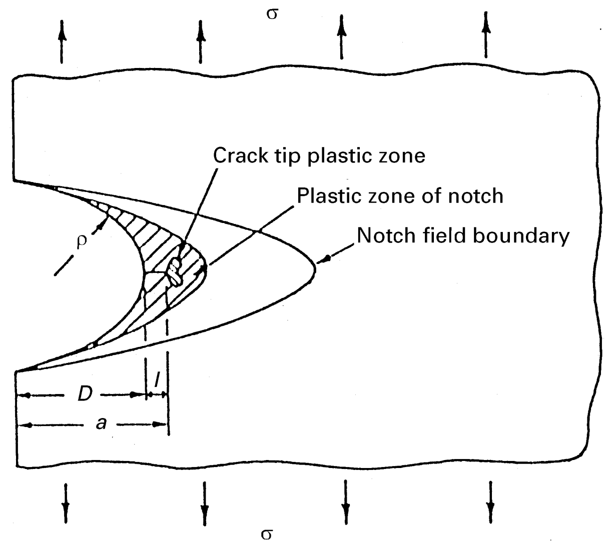

Figure 5 Schematic representation of a short crack emanating from a notch and the associated strain field of a notch.

TABLE II The values of maximum and minimum stress concentration factors within sharp and blunt notch fields for different states of specimens

Sharp notch ($D = 3$ mm, $\rho = 0.2$ mm), $K'_{max} = 5.19$		Blunt notch ($D = 3$ mm, $\rho = 1$ mm), $K'_{max} = 3.07$	
Specimens	K'_{min}	Specimens	K'_{min}
UA, TL	3.87	UA, TL	2.90
UA, LT	3.63	UA, LT	2.81
PA, TL	4.03	PA, TL	2.95
PA, LT	4.00	PA, LT	2.94
OA, TL	4.12	OA, TL	2.99
OA, LT	4.04	OA, LT	2.96
NA, TL	2.95		
NA, LT	2.65		

Table II lists K'_{max} and K'_{min} of two notches in variously aged specimens. It is interesting to note that K' remains almost unchanged within the stress field of a blunt notch and thus ΔK in Equation 1 varies only with a small amount of increase in crack length l. This is in good agreement with the experimental results shown in Fig. 4. However, there is a significant difference between K'_{max} and K'_{min} for a sharp notch. As a result, ΔK and then da/dN decrease when a short crack grows within the sharp-notch field. As indicated above, the sharp-notch field size is only 0.17 mm, but the minimum da/dN occurs at a crack length of 0.45 mm which is far beyond the notch field. The further decrease in da/dN beyond the notch field is presumably due to the crack closure effect.

5. Conclusions

1. The growth rates of notched short cracks are much higher than those of long cracks at the same ΔK level. The specimen orientation has a stronger effect on the growth rate of long cracks than that of short cracks.

2. The geometrical configuration of the notch significantly affects the growth behaviour of the short crack. The short crack emanating from a sharp notch

displays a "trough-like" behaviour. The minimum da/dN occurs at a crack length of about 0.45 mm which is far beyond the notch field. However, the short crack initiating from a blunt notch grows slowly within the notch field and then faster beyond the notch field. No "trough-like" behaviour was seen.

3. The existence of a strain field associated with notch-tip deformation during fatigue is not the only factor which decelerates the growth of the short crack from notches. Other factors, for example, crack closure, must be taken into account to explain, satisfactorily, the growth behaviour of the short crack from notch.

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Received 8 December 1995
and accepted 10 March 1997