Fatigue Crack Propagation Behavior and Fracture Surface Analysis under Two-step Loading in Aluminum Alloy

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(Received 7 December 2007; accepted 30 March 2009)

As a retardation of fatigue crack propagation occurs under two step loading such as high to low loading, it is difficult to estimate the fatigue life in variable loading conditions. Therefore, the mechanism of retardation was investigated by changing the ratio of two-step loading in aluminum alloys in this paper.

It is found in this study that acceleration of crack growth following low-to-high load change is not apparent in this investigation, there exists a uniquely-shaped fracture surface with some width (about 50–200 μm) right angle to the crack growth direction at the load-change area under high-to-low load change. This area shows some swelling, with no striation but minute and distinct unevenness.

When \( R = 0 \) and \(-1\), if maximum load decreases to 80%, crack retardation does not occur even though the crack growth rate falls slightly. When \( R = 0.1 \), by varying low load in small increments (50%, 45%, 43%, and 40%) the number of cycles of crack retardation were investigated. The varying rate is in proportion to the number of cycles of crack retardation.

This study proposed a crack growth model wherein the plastic zone formed by tensile stress was compressed by the surrounding elastic zone, and the crack does not open immediately under tensile stress load.

**Key words:** Crack propagation, Fracture surface analysis, Retardation, Two-step loading, Striation, Crack closure phenomena

1. Introduction

It is well known that Paris’ law can be applied to predict the fatigue crack growth rate (FCGR) under constant loading and the FCGR differences between various stress ratios can be explained by one master curve, if we use the effective stress intensity factor range \( (\Delta K_{eff})^{1-5} \). However, because loading history on real moving machines can be varied and complicated, the results mentioned above cannot be applied to all cases. Miner’ law can often predict fatigue life, but sometimes these predictions do not exactly coincide with actual fatigue life\(^{6-8}\). The main reason for this discrepancy may be attributed to retardation or complete stop, when the load is changed from high to low\(^{9-10}\). In this paper, the authors investigated qualitatively and quantitatively, the crack retardation and the
crack arrest under two-step loading. FCGR was measured by the replica method; then a scanning electron microscope (SEM) was used to observe the fatigue fracture surfaces and to measure striation spacing on the fracture surfaces.

2. Materials and experimental procedure

The material used in this experiment is 2017-T4 Al alloy whose chemical composition and mechanical properties are given in Table 1. Because of its high strength and light weight, this material has been used as a structural material in aircrafts. The specimen used in this experiment is a compact tension specimen (CT specimen), as shown in Fig. 1. The distance from the loading axis to the notch tip is 14 mm.

Using a hydraulic-servo fatigue machine, we have conducted with four different loading ratio $R = P_{\text{min}} / P_{\text{max}} = -1$, 0, 0.3, and 0.5, fatigue tests. Fig. 2 and Fig. 3 show four different loading patterns and loading reduction patterns for $R = 0$ and $-1$, respectively. The crack growth configuration was investigated for the specimen cycled to $10^6$, under decreasing

Table 1  Mechanical properties and Chemical composition of 2017–Al T4 Alloy of Al alloy.

<table>
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<th>$\sigma_{0.2}$ (MPa)</th>
<th>$\sigma_B$ (MPa)</th>
<th>$\psi$ (%)</th>
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<td>2017–T4 Al Alloy</td>
<td>270</td>
<td>435</td>
<td>23.8</td>
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<th></th>
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<th>Cu</th>
<th>Mg</th>
<th>Mn</th>
<th>Si</th>
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<tr>
<td>2017–T4 Al Alloy</td>
<td>Bal.</td>
<td>3.7</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Fig. 1  CT specimen (mm).

Fig. 2  Load pattern.

Fig. 3  Reduction of maximum load.
maximum load to 80%, 70%, 50%, and 40%. Moreover, we investigated the case of R=0.1, under decreasing maximum load to 50%, 45%, 43%, and 40% for up to 10^8 cycles.

Crack length was measured by means of both the replica method and optical micrograph. Crack length was defined as the projection length to the loading direction. Striation spacing was measured by SEM.

3. Experimental result

3.1. The relationship between da/dN and ΔK under low-to-high load variation

Fig. 4 shows the relationship between FCGR measured by means of the replica method and ΔK, stress intensity factor range. Fig. 5 shows the relationship between striation spacing measured by SEM and ΔK. Comparison between Figs. 4 and 5 clearly reveals a strong correlation between da/dN and striation. That is to say, even when changing low load to high load, FCGR can be estimated by measuring striation spacing on the fracture surface. To see this more clearly and the results are shown, constant amplitude fatigue tests were also conducted and the result are shown in Fig. 4 and 5. In Fig. 4 and 5, where the results of da/dN vs ΔK relations for R = -1, R = 0 and R = 0.5 are shown by double-dashed dotted line, dashed dotted line and dotted line, respectively. By comparing the results of the constant amplitude fatigue tests, we conducted that Paris' law can be applied to the results of low-to-high load change.

3.2. Fractography of the fracture surface after low-to-high load change

Fig. 6 shows SEM fractographs of the fracture surface immediately after low-to-high load change where R = -1 and 0. The two photos reveal that striation spacing conforms to that at constant amplitude immediately following load change. In this study, acceleration phenomena were not observed.

3.3. The relationship between crack length and number of cycles after high-to-low load change

The fatigue tests, where maximum load changed from high-to-low, were conducted for R = 0 and −1 at the point where crack length is about 5 mm. The appearance of the crack growth was investigated by varying the ratio of low-to-high load (80%, 70%, 50%, and 40%).

As shown in Fig. 7, for all R's when the maximum load decreased to 80%, crack retardation did not occur even though the crack
growth rate decreased somewhat after changing the load. When the maximum load dropped to 70%, the crack retardation became obvious immediately after load change. Then, after some number of cycles, crack growth appeared. After some amount of crack growth, the crack growth rate recovered to the level at constant maximum load. When $R = 0$ and the maximum load was decreased to about 50%, no crack growth appeared after $10^6$ cycles. However, when $R = -$ 1 and a different phenomena was observed, i.e. even when maximum load was decreased to 50%, complete crack arrest was not apparent but at 40% decrease of maximum load, complete crack arrest was realized.
By varying the low load to 50%, 45%, 43%, and 40%, the cyclic number of crack arrest was investigated. As shown in Fig. 8, the cyclic number of crack arrest increased, in inverse proportion to reduction rate of high to low load change.

3.4. The relationship between $\frac{da}{dN}$ or $s$ and $\Delta K$ for a 70% maximum load decrease

Maximum load was decreased to 70% to investigate the $\frac{da}{dN} - \Delta K$ relationship and striation spacing $-\Delta K$ relationship where $R = -1, 0, 0.3$ and 0.5. Fig. 9 shows the relationship between FCGR measured by the replica method and the stress intensity factor range ($\Delta K$). Fig. 10 shows the relationship between $\Delta K$ and striation spacing measured by SEM.

As shown in Fig. 9, in all cases of R’s crack stops immediately following load change, and crack growth appears after some number of cycles and then FCGR increases, and FCGR finally coincides with that of constant maximum load.

As shown in Fig. 10, SEM measurements of striation spacing reveals the results identical to those of Fig. 9. Though very small striation could not be measured, striation spacing exceeding 0.1 $\mu$m could be measured and agreed with crack growth rate at constant amplitude.

3.5. Fracture Surface Fractography for variable high-to-low load

Fig. 11 shows the SEM photos of the specimen under load change with $R = -1$. This figure reveals a large striation corresponding to the specimen before load change, and these fracture surfaces of the unique morphology on the right corresponding to immediately after load change. The width of unique morphology is

The load changing point

\[
R = -1, P_{\text{max}} = 4.9kN \rightarrow 2.94kN
\]
about 50 μm ~ 200 μm and it is aligned perpendicular to the direction of crack growth. Fig. 12 shows an enlarged SEM photo indicated by □ in Fig. 11, when after load change, the area swells somewhat and there is no striation, although some minute bumps are apparent. This phenomenon may be due to some very fine plastic deformation, which does not exist on a fracture surface involving one crack per a single stress cycle. The unevenness and crack growth rate of this unique fracture surface morphology are both less than 0.01 μm and less than 10^{-8} m/cycle, respectively. These heights and rates are very short and small. Thus, this unique fracture morphology is similar to the very fine fracture one in ODA (optical dark area) or FGA (fine granular area), often observed in a specimen with super long-life fatigue.

After this unique fracture morphology like ODA or FGA, there exists a fracture morphology involving one crack per one cycle of external stress, which is consistent with Paris’ law.

3.6. Crack retardation phenomena under high-to-low load change

The crack-arrest phenomenon is thought to be crack closure in the plastic region, created by local high load stress after load change. That is to say, if tensile stress is increased, the crack does not open immediately; further, unless the tensile strength exceeds a given level, the crack can not open. Therefore, after high-to-low load change, while the crack is passing through this plastic zone, crack arrest or retardation may occurs.

The crack retardation zone shown in Figs. 11 and 12 may be associated with the plastic zone at the crack tip. And, since this plastic zone may be related to the range of maximum stress intensity factor, it is possible that this portion is connected by the difference between Kmax values of high load and that of low load. Therefore, the relationship between the difference in Kmax for each R is in proportion to the width of retardation. Matsuoka et al. and Tanaka et al. investigated this relationship in detail and proposed a model for its mechanism. One of their results is that if high load is decreased to 50%, the crack arrest should occur. Their result agrees with the results described in our experiment.

4. Discussion

4.1. Elber’s formula

Elber defined effective stress intensity factor’s range as equation (1) and the opening ratio U for an aluminum alloy was reported as equation (2).

\[ \Delta K_{	ext{eff}} = K_{\text{max}} - K_{\text{op}} = U \times \Delta K \]  
(1)

\[ U = 0.5 + 0.4R, \text{ for } -0.1 > R > 0.7 \]  
(2)

Elber explained the phenomena wherein the crack tip did not immediately open, even if tensile stress is increased, as a product of crack closure. However, this theory cannot be applied easily because it is difficult to measure crack closure at the crack tip under variable loading.

One reason why a crack does not open immediately, even under additional tensile stress at the crack tip, is that the plastic zone lengthens vertically and it is compressed by the surrounding elastic zone. When maximum load is decreased to 50% for R=0, crack stopped thoroughly. This result agrees with Elber’s formula.

4.2. Crack growth model

Crack growth formation in the second stage advances according to striation formation. In the case of high-to-low load change, crack
retardation and crack arrest occurred. S. Suresh explained this phenomena as plasticity effect. Therefore these phenomena can be explained as follows: if a plastic zone is formed by tensile stress at the crack tip, this plastic zone is strengthened in the direction of load axis and, even under zero applied tensile stress, does not shrink because of the plastic deformation. However, as the surrounding elastic zone returns to its previous position, if tensile stress is at zero, this plastic zone is compressed by the surrounding elastic zone. Therefore, under additional tensile stress, the crack does not open immediately. In fact, the crack does not open until tensile stress exceeds the residual compressive stress by the surrounding elastic zone.

The phenomena of crack retardation and crack arrest can be explained by the residual compressive stress of the surrounding elastic zone on the plastic zone.

If the value of the tensile stress is similar to the value of the compressive stress, even though tensile stress may not correspond to compressive stress, crack growth appear again after some number of cycles. But if the tensile stress is very small in comparison to the surrounding compressive stress, crack will not grow regardless of the number of cycles. This phenomenon is considered crack arrest. The model is illustrated in Fig. 13.

1. At the first stage, because no applied tensile stress operates on the specimen, the plastic zone extends in the direction of load axis at crack tip and consequently receives the maximum compressive stress from the surrounding elastic zone.

2. At the second stage, as applied tensile stress begins to operate, the compressive stress from the surrounding elastic zone on the plastic zone at the crack tip decreases.

3. At the third stage, as applied tensile stress increases, the compressive stress on the plastic zone at the crack tip from the surrounding elastic zone becomes zero and crack tip begins to open and crack begins to propagate.

4. At the fourth stage, applied tensile stress becomes even greater and affects the plastic zone at the crack tip; the crack tip open widely and the crack propagate.

5. At the fifth stage, as applied tensile stress rises to a maximum, tensile stress on the plastic zone at the crack tip also maximizes and the crack propagate.

When applied tensile stress decreases, stage (5) changes to stage (3). Crack growth continues until stage (3). The new plastic zone begins to feel compressive stress from the

Fig. 13 The model of fatigue crack growth.
surrounding elastic zone again as stage (2) changes to stage (1). One cycle is completed.

5. Conclusion

We can make the following remarks:

1) Acceleration of crack growth following low-to-high load change is not apparent in this investigation.

2) There exists a uniquely-shaped fracture surface with some width (about 50–200 um) right angle to the crack growth direction at the load-change area under high-to-low load change. This area shows some swelling, with no striation but minute and distinct unevenness.

3) When $R=0$ and $R=-1$, if maximum load decreases to 80%, crack retardation does not occur even though the crack growth rate falls slightly. For all $R$s, if maximum load decreases to 70%, crack retardation occurs. When $R=0$ and maximum load was decreased to 50%, there was no crack growth after $10^6$ cycles was observed. When $R=-1$ and maximum load is decreased to 40%, no crack growth appeared after $10^6$ cycles.

4) When $R=0.1$, by varying low load in small increments (50%, 45%, 43%, and 40%) the number of cycles of crack retardation were investigated. The varying rate is in proportion to the number of cycles of crack retardation; when the low load was reduced to 40%, no further crack propagation appeared even after $10^8$ cycles.

5) This study proposed a crack growth model wherein the plastic zone formed by tensile stress was compressed by the surrounding elastic zone, and the crack does not open immediately under tensile stress load. Then those phenomena are explained as crack closure.

References