Study on the effects of notch tip and crack tip plasticity on small fatigue crack growth

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ABSTRACT

The experimental investigation and modelling of short fatigue crack propagation in single edge notch specimens of a low strength aluminum alloy were carried out to characterize effects of notch-tip plasticity, crack-tip plasticity and crack closure on short fatigue crack growth within notch plastic zone. The applied loads were intentionally chosen to generate an enough large notch plastic zone where a short fatigue crack initiates and propagates. Different matches of testing conditions, specimens with notches and removing notches after pre-cracked at the stress ratio of R=0, were employed to clarify the influence of notch plastic zone, crack tip plastic zone, and crack closure on short crack growth behaviour. The experimental results show that small crack growth either in notch specimen or in smooth specimen has the common trend: first deceleration then acceleration. The analytical results show that plasticity and plasticity induced crack closure make the different contribution to small crack propagation at different growth stages. It is clear that crack-tip plasticity and notch-tip plasticity influence small crack growth via both plasticity and plasticity induced crack closure mechanisms. The high plastic stress and strain ahead of crack tip due to notch root plasticity or crack tip plasticity directly enhance crack driving force, thereby resulting in fast crack growth; while residual plastic strain due to notch-tip plasticity or crack-tip plasticity left behind crack tip would result in a transition of normalized crack opening stress from closure-free zone at the beginning to saturated zone around notch-tip plastic zone boundary. It can be concluded that the effects of notch-tip plasticity and crack tip plasticity on small fatigue crack growth are tow-hold, plastic deformation in the front of crack tip at maximum load increases crack growth driving force due to the increase in plastic component, while plastic deformation left in the wake of crack tip at minimum load decreases crack driving force due to the decrease in effective components.

Keywords: Notch tip plasticity, Crack tip plasticity, Plasticity induced crack closure, Short fatigue crack growth.

INTRODUCTION

Since small fatigue crack issue was first addressed by Pearson [1], considerable efforts have been expended in the investigation and analysis of its abnormal growth behavior, and it has been found that the majority portion of total fatigue life would often be spent with small crack growth stage. As almost all engineering structures and components contain geometric notches or other notch-like features, and these stress raisers have been recognized to be a main site for small fatigue crack initiation, propagation, and even final failure, the study of the fatigue behavior of notched members has been of prime interest to many researchers and engineers in various fatigue small crack problems. It is well documented that the observed growth of small cracks emanating from notches have remarkably similar trend: first deceleration and then acceleration. It is first known that concentrated stress gradient ahead of notch root is a direct reason to cause decrease in fatigue small crack growth rate at notch, since a decrease in local plastic strain decreases occurs simultaneously. The second reason is most often proposed, i.e., crack closure. Meantime, a variety of mechanism and corresponding analytical methods for fatigue small growth emanating notch root have been introduced. However, the difficulty in testing and analyzing short fatigue crack growth is still existing and becomes evident when considering the growth of short fatigue crack emanating from plastic notch field. Owing to difficulties in experimental measurement, there are few experimental results available. Furthermore, the two main models for a short crack embedded in notch plastic zone have been proposed, which are plastic shear displacement model due to Miller [2], to account for plasticity only, and crack closure model due to Newman [3], to consider crack closure only. As a result these approaches are still open to discussion from an academic perspective, and additionally represents an area where a contribution to the practical use of these results in engineering application can be made.

Accordingly, one main objective of this study is to show the major role of notch tip and crack tip plasticity in accounting for the abnormal growth behavior of short fatigue crack. The results reported here were obtained as a part of our extensive study on the effects of notch root plasticity and crack tip plasticity on small crack nucleation and propagation. This paper is only restricted to the initiation and growth behavior of short fatigue cracks on low strength aluminum alloy.

EXPERIMENTAL PROCEDURE AND ANALYTICAL PROGRAM

Material, specimen, and experimental procedures

The test material is 5005 aluminum alloy with a yield stress of σ_{ys}=128 MPa and a Young's modulus of 60 GPa as-provided rolled sheet 3 mm thick. Its chemical composition is shown in Table 1. Single edge U-shape-notched (2 mm deep with the radius of 0.7 mm) fatigue specimens with the length of 150 mm, thickness of 3 mm and widths of 20 and 24 mm were prepared. All specimens were mechanically polished, followed by an electrolytic polishing both to remove the residual stresses which may be introduced by rolling and machining processes, and to provide a smooth surface for microscope examination and video recording. Prior to testing, the special fixtures gripping the specimen were carefully aligned with specimens to prevent rotational and lateral bending.

Table 1. Chemical composites of AA5005 (wt%)

Mg	Si	Fe	Mn	Cu	Cr	Zn	Al
1.10	0.30	0.70	0.20	0.20	0.10	0.25	Balance

The fatigue crack propagation tests were performed at a frequency of 10 Hz in sinusoidal waveform pulsating tension loading mode with a stress ratio of R=0, by an Instron 8501 servo-hydraulic testing machine at room temperature in air under constant load control. The applied maximum stresses were deliberately chosen as 0.40, 0.55 and 0.70 of σ_{ys}, or as corresponding local stresses of 1.75σ_{ys}, 2.41σ_{ys} and 3.07σ_{ys} to introduce tensile notch plastic zones, and reversal notch plastic zones with different sizes. At least four specimens were tested at each condition of stress amplitude and specimen configuration. The cracking and propagation at different deformation stages were recorded by an imagine recording and measurement system, which consists of 50× microscope, CCD, video recorder, personal computer and imaging analyzer. In order to clarify the influences of notch root plastic field, crack tip plasticity and crack closure on growth behavior of short fatigue crack, the comprehensively comparative studies were carried on by adopting different matches of testing conditions, specimens with notches and removing notches after pre-cracked The difference of crack growth rates between short and long cracks may represent the effect of crack tip plasticity and crack length-dependent crack closure, while the difference of short crack growth rates between notch and smooth specimens may represent notch root plasticity effect. A series of fatigue tests were carried out to understand the growth behavior of short fatigue cracks from either notch specimens or smooth specimen obtained via removing notch left a short crack or long crack, including: (1)Short fatigue crack growth from notch specimen. This is to assess the effect of notch root plasticity on short crack growth under the high applied stress. (2)Short fatigue crack growth from smooth specimen without residual stress field, which were realized by removing specimen notch and the original notch root plastic field but leaving the specimen with short crack only. This is to evaluate the large crack tip plasticity effect on short crack growth. (3) Long fatigue crack growth. In order to compare short crack growth behavior with that of long crack, the tests of long fatigue crack growth were carried out to establish a baseline crack growth data. The long crack specimens were obtained by pre-cracking on notch specimen and fatiguing short crack.

Analytical program

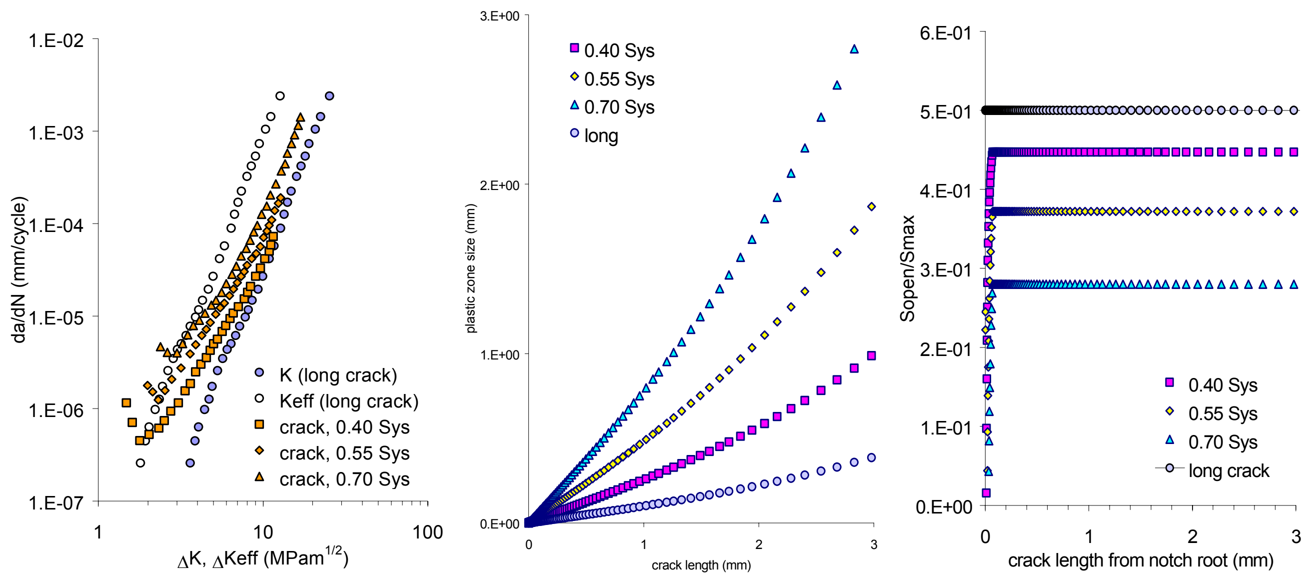
A general commercial finite element method code ANSYS 54 was chosen to make elastic-plastic finite element analysis of stress/strain distribution ahead of notch root, notch plastic field, and crack closure. Due to the geometric symmetry of the specimen only half of the specimen was used. The meshes were composed of a two dimensional, six-node triangular isoparametric elements and represented a rectangular plate with a crack emanating from single edge U shape notch of a root radius 0.7 mm. The material model employed elastic/perfectly-plastic property with von Mises yield criterion. The number of nodes and elements were 2369 and 4920, respectively, for the notch specimen. Since it has been recognized that under high applied stress levels the crack tip plasticity has a key influence on accelerated small fatigue crack growth, in this work the crack tip plastic zone size was determined using analytical approaches based on Dugdale model.

RESULTS AND DISCUSSIONS

Comparison of growth behavior between short and long fatigue cracks

The growth rates of short cracks (through-thickness crack, $a\approx0.1\sim0.2$ mm) in notch-removed specimens against stress intensity factor range, ΔK, are shown in Fig.1(a), as a comparison to that of long through-thickness crack (a>2mm). The results after accounting for crack closure, in term of ΔK_{eff}, are also shown in Fig.1(a). Inspection of short fatigue crack growth data in Fig.1(a) reveals that at the same applied K levels, the growth rates of the short cracks in three different stress levels exceed those of corresponding long cracks by up to one order of magnitude; even those of crack closure corrected long cracks. The latter implies that along with crack closure, there must be other factor to accelerate small crack growth.

The numerical results of crack tip plastic zone size are showed in Fig.1(b), and indicate that the ratio of crack tip plastic zone size to crack length is dependent on applied stress levels. It is as small as 0.1 at $0.25\sigma_{ys}$ loading level (in figures σ_{ys} is denoted by Sys), but gradually rises from 0.26 at $0.40\sigma_{ys}$, 0.49 at



(a) Crack growth rates (b) Crack tip plastic zone sizes (c) Crack opening stresses

Fig. 1 Comparison between short and long crack $0.55\sigma_{ys}$, to 0.8 at 0.70 σ_{ys}.

The calculation of the ratio of crack opening stress(S_{open}) to the maximum applied stress(S_{max}), i.e. the crack closure degree, as a function of crack length *a*, is shown in Fig.1(c). The initial crack would not close. As the crack grows, however, the newly created crack surfaces close and the crack opening stresses rapidly rise over less than 0.1 mm and reaches a stable value for large crack growth.

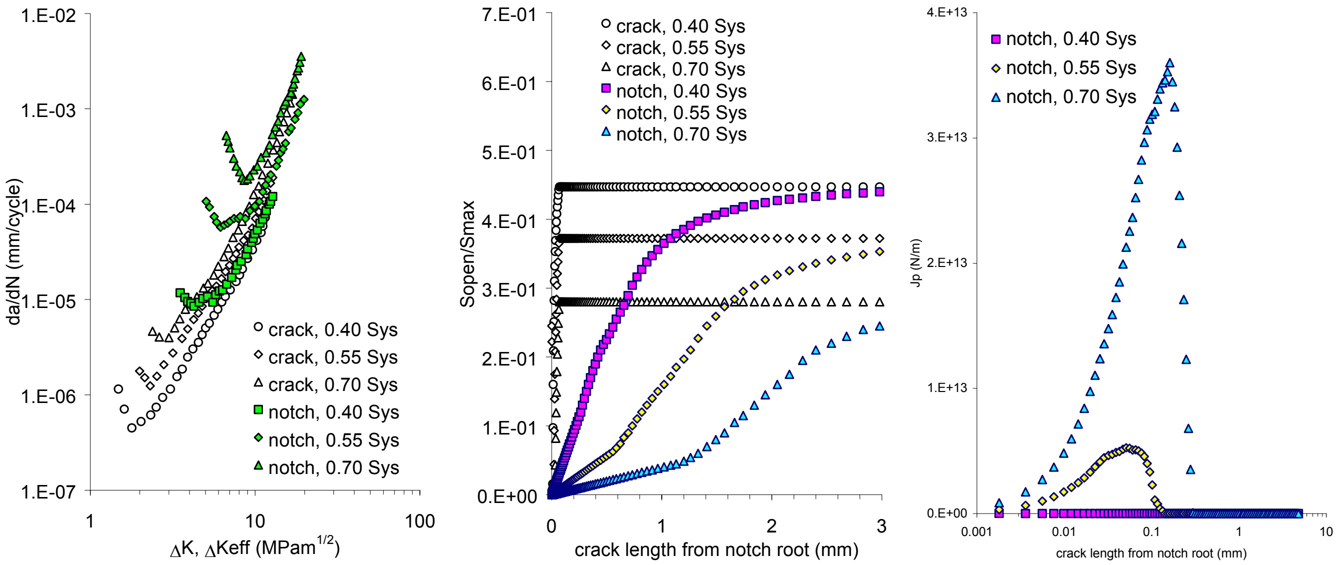
1) Effect of crack tip plasticity on growth behavior of small and long cracks from smooth specimens
An important reason generating small crack growth acceleration from smooth specimens is the crack tip plasticity. The current results shown in Fig. 1(a) indicate that with an increase in applied stress level, the corresponding difference between short and long crack growth rates also rises, this coincides with the increase in the ratio of crack tip plastic zone size to crack length. Physically, large crack tip zone size will result in large plastic deformation, and corresponding fast crack growth. This is consistent with many other experimental results. Rice [4] has quantitatively shown that when the applied stress reaches $0.5\sigma_{ys}$, the calculated ratio of plastic zone size to crack length will increased from the small scale yielding condition. Further, it has been shown experimentally by Ritchie [5] that accelerated short crack growth does not necessarily result simply from lager crack tip zone size than crack length, even when crack tip plastic zone size is far less than small crack length (10 μm:200 μm), so-called anomalous behavior still occurred.

2)Effect of crack closure on growth behavior of small and long cracks from smooth specimens
Closure or, more properly, the absence of crack closure, has been frequently suggested as a reason for the accelerated growth of very small cracks in unnotched members. The Fig.1(a) showed that all short crack growth rate data fall between baselines of long crack growth rates against ΔK and ΔK_{eff}, where ΔK_{eff} is the effective stress intensity factor range. Transition of the crack closure as shown in Fig.1(b) should be a main reason, since the initial gradual reduction in growth rate of short cracks is consistent with the corresponding progressive increase in crack opening stress. Another reason is the lower saturated crack opening stress with increasing stress levels, leading the entire short fatigue crack growth curve shift towards the left. However, it can be found that well beyond crack closure transition zone of 0.1 mm, short crack growth data from smooth (notch-removed) specimens are very close to or even exceed to free-closure corrected long crack growth data especially at high stress level. This suggests that beyond crack closure transition zone, other should become dominant factor to affect short crack growth.

Comparison of short crack growth between notch specimens and notch removed smooth specimens
The comparison of short fatigue crack behavior including crack closure degree between notch specimens and notch-removed specimens are shown in Fig.2. Fig.3 shows the numerical results of variation of notch root plasticity zone size under different loading levels of maximum stress. From Figs. 2 and 3, it is characterized that there are three typical stages for fatigue crack propagation: (1)crack initiation zone; (2) small crack propagation zone (within notch plastic zone); and (3)long crack propagation zone (out of notch plastic zone), respectively corresponding to (1)closure-free zone; (2)closure transition zone; and (3)closure saturated zone.

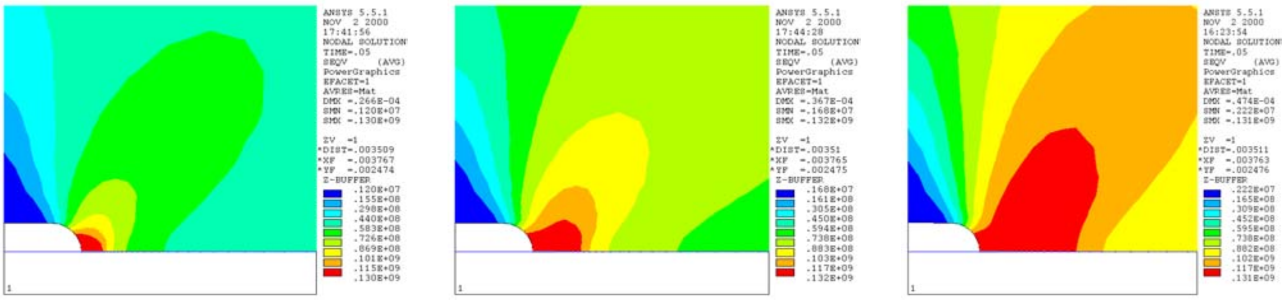
1) Effect of notch root plasticity on small crack initiation
As shown in Fig. 2, at a given load level the short crack initiated from notch root plastic field grows at a much higher rate than that of smooth specimen (i.e. notch-removed specimen), and the growth rate increases with raising loading level. In addition, the crack growth driving force for the short crack in notch specimen is very high, thus resulting in fast crack growth. Analytical results shown in Fig.2(c) manifest that the plastic components of J-integral, J_p, caused by notch plasticity, are strongly dependent on applied stress levels. For example, J_p is zero at $0.40\sigma_{ys}$, but J_p is non-zero positive value at $0.55\sigma_{ys}$, and much more higher at $0.70\sigma_{ys}$. While crack closure level is near zero at crack initiation, thereby producing very high initial crack driving force and corresponding initial crack growth rate. It is noted that such a non-zero cyclic plastic component due to notch plasticity exists only when applied stress level is larger than half yielding stress, or local stress at notch root is larger than 2 times yielding stress, a condition of producing reversed notch plastic zone. And such a plastic component due to notch plasticity is, of course, absent for smooth specimen.

Another factor often ignored is the surface influence on crack initiation. Small cracks invariably initiate at specimen surface where plane stress conditions prevail and material flow resistance or yield stress is reduced compared to the bulk, so resulting in a plastic zone size that is larger compared to those found in the interior which is subjected to plane strain conditions. It should be noted that such a surface effect is particularly important for crack initiation as it greatly enhances plastic deformation at crack tip within surface layer, though it is still not available to accurately describe stress and strain on surface layer of micro-scale, for example, a grain size, which is is independent of applied stress. There are many experimental evidences that short surface fatigue crack grow very much more quickly than short through fatigue crack growth, even if allowing for crack closure effect.



(a) Crack growth rate (b)Crack opening stress (c)Plastic component of J-integral

Fig. 2. Comparison of short fatigue crack growth between notch specimens and smooth specimens



(a) 0.397 mm at $0.40\sigma_{ys}$ (b) 0.912mm at $0.55\sigma_{ys}$ (c) 2.05mm at $0.70\sigma_{ys}$

Fig.3 Variation of notch plastic field sizes under different loading levels of maximum stress

Further, plastic strain sharply drops over a short distance, slightly larger than reversed notch plastic field. Meantime, surface effect also reduces quickly since its range is on a micro-scale. While crack closure begins to increase but slowly due to reversed plastic yielding, which is the same as a low crack closure level at R=-1 due to reversed plastic yielding. Therefore, the decrease of growth rate and the presence of 'dip' in crack growth curve is directly attributable to the decrease in tensile and reversed notch plastic strain, resulting a minimum point in the crack propagation curve at about boundary of reversed plastic strain. So, this is a reversed plasticity and surface affected region.

2) Effect of notch root plasticity on small crack propagation

Out of reversed plastic field, notch root plasticity effect decreases, while crack tip plasticity has very quickly increased up to a content where crack tip plastic zone boundary is coincident with the original notch plastic boundary. It implies that the crack tip self-generated plasticity begins to dominate crack tip field. On the other hand, crack closure stress increases with increasing crack tip plasticity, but it is still low.

Thus, at this stage, increase in crack tip plasticity is mainly responsible for median short crack slow growth, while notch root plasticity is also one important affecting factor.

3)Plasticity effect on long crack propagation region

Comparing Figs. 2 and 3, it can be seen that when a short crack approaches the boundary of notch root plastic and elastic field, as expected, notch root plasticity effect on crack growth is disappearing, instead elevated notch elastic stress/strain influence on crack growth is appearing. Crack closure degree begins increasing faster due to quick decreasing of notch elastic stress and strain, and reaches to stable value little beyond original notch plastic field. After then, the crack closure degree basically keeps constant. Thus effective crack driving force is no longer reduced by crack closure, and crack propagation becomes faster, and another transition point occurs. At this region, notch elasticity has great influence on crack growth, and fast transition of crack closure causes a transient point.

CONCLUSIONS

1) Short fatigue crack growth from smooth specimens is much faster than long fatigue crack, caused by both large crack tip plasticity and crack tip plasticity induced crack closure.
2) Crack tip plasticity and plasticity induced crack closure are dominant at crack initiation at smooth specimen, while crack tip plasticity is governing at short crack propagation as crack opening stress reaches a saturated level after a short distance.
3) Short fatigue crack growth from notch specimens is much faster than short fatigue crack growth from smooth specimens, caused by both notch plasticity induced component of crack driving force and notch plasticity induced crack closure.
4) Notch plasticity effect is dominant in reversed notch plastic zone; slightly beyond the reversed notch plastic zone, the crack tip plastic zone boundary coincides with the notch plasticity boundary and crack tip plasticity becomes important; a little bit beyond the tensile notch plastic zone, plasticity induced crack closure is determinative where crack closure transition is faster and finally reaches a stable level.
5) Surface effect on short fatigue crack initiation and very early propagation is very important.

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