Mode I Fatigue Crack Growth with Occasional Mode II Loading in 7075 Aluminum Alloy

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ABSTRACT. *Effect of occasional mode II loading on subsequent mode I fatigue crack growth behavior was investigated by using a thin-walled tube made of 7075-T6511 aluminum alloy. Careful observation of crack growth behavior revealed that the occasional mode II loading has two contradictory effects for crack growth behavior. The first is a retardation effect that is associated with the plastic deformation near crack tip. However, this effect is negligibly small for the crack growth life as a whole. The second is an acceleration effect caused by mode II fatigue crack growth itself. It was found that under relatively high ΔK level, the mode II crack growth was about an order magnitude faster than mode I crack growth. Therefore, to properly evaluate the effect of occasional shear loading in the 7075 alloy, the mode II crack growth should be taken into account.*

INTRODUCTION

In practical service conditions for various machine components and structures in aircrafts, automobiles and power generators *etc.*, shear loadings are occasionally mixed with cyclic tension-compression loadings. Therefore, the effect of occasional mode II loading upon mode I fatigue crack growth has been a matter of concern for various materials [1-7].

With respect to the relevant issues, Nayeb-Hashemi and Taslim [1] studied the effect of a single mode II cycle on subsequent mode I growth in the quenched and tempered AISI 4340 steel. They reported that the mode II loading causes the crack growth acceleration for a very short distance, much smaller than the transient plastic zone size. Further, Decreuse *et al.* [2] obtained similar results for S355NL steel. Sander and Richard [3] carried out a series of fatigue tests to investigate the effect of mixed mode overloading in 7075-T651 aluminum alloy. They found that a pure mode II overloading had an insignificant influence on the subsequent mode I growth. In contrast, Dahlin and

Olsson [4-6] demonstrated a marked reduction of subsequent mode I growth due to a single mode II loading in AISI 01 steel. The retardation of crack growth was also observed by Gao and Fernando [7] in the quenched and tempered low alloy steel.

The acceleration or retardation due to occasional mode II loading, if any, is attributed to the following distinct crack closure mechanisms [1, 5]: (i) roughness induced fatigue crack closure (RIFCC) caused by a mismatch between crack faces due to relative tangential displacement, and (ii) plasticity-induced fatigue crack closure (PIFCC) caused by a large stretch of material in the vicinity of the crack tip. In the literature, Dahlin and Olsson [5] analyzed the RIFCC caused by a single mode II loading based on a theoretical model developed by Budiansky and Hutchinson [8]. They successfully simulated the experimental results for AISI 01 steel and manifested that the recovery distance (*i.e.* distance for the crack growth rate to revert to its original level) is much larger than the size of the mode II induced plastic zone. On the other hand, Nayeb-Hashemi and Taslim [1] discussed the PIFCC due to mode II overloading. It is well known that mode II loading can produce a much larger plastic zone compared to mode I loading as displayed in Fig. 1, where the shapes and dimensions of the plastic zone formed by the modes I and II loadings are illustrated. It is noted that in Fig. 1, the plastic zone is calculated based on the von Mises yield condition with the elastic solutions [9]. Nayeb-Hashemi and Taslim [1] speculated that mode II overloading causes the crack growth acceleration while mode I overloading causes the crack growth retardation, both of which are closely related to the amount of plastic stretch near the crack tip as well as an interference between crack faces. According to those results and discussions, RIFCC plays a more dominant role than PIFCC in determining the behavior of subsequent mode I growth after occasional mode II loading. Nonetheless, it is not a straightforward task to justify whether the occasional mode II loading causes acceleration or retardation for the subsequent crack growth in arbitrary cases. In addition, the circumstance could be easily changed depending on some pertinent factors (*e.g.* overload ratio, material, stress ratio and *etc.*). To properly understand such a complicated phenomenon, the effects of those influencing factors need to be quantified based on the experimental facts with the aid of adequate material modeling.

In this study, our focus is on 7075 aluminum alloy that has been widely used for aircraft structures. Based on a series of observations of fatigue crack growth behaviors, the effect of shear loading and the dominating factors for fatigue crack growth behavior are discussed.

EXPERIMENTAL

Material

The study was carried out using a commercial grade 7075-T6511 aluminum alloy. The chemical composition in mass % was 0.1 Si, 0.25 Fe, 1.6 Cu, 0.06 Mn, 2.6 Mg, 0.2 Cr, 5.6 Zn, 0.01 Ti and bal. Al. The 0.2 % yield and tensile strength of the alloy was found to be 600 and 634 MPa, respectively. The average Vickers hardness, *HV*, measured with a load of 9.8 N was 184.

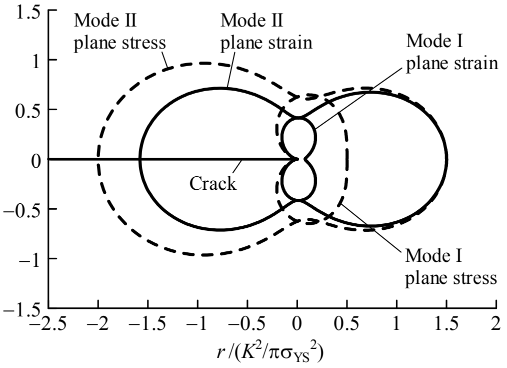


Figure 1. Shapes and dimensions of the plastic zone formed by the modes I and II loadings [9]. (r: Distance from crack tip, K: Stress intensity factor, σ_{YS}: Yield stress)

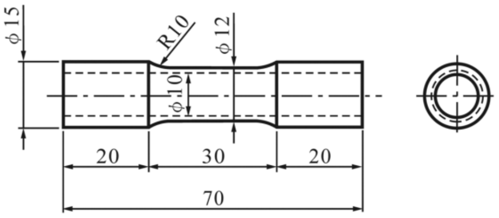


Figure 2. Shape and dimensions of specimen, in mm.

Specimen

Thin-walled tubular specimens were machined from a 16 mm-diameter round bar. Figure 2 shows the shape and dimensions of the specimen: 12 mm in outer-diameter and 1 mm in wall-thickness at the test section. The specimen surface was finished by polishing with an emery paper and then by buffing with an alumina paste. In the middle of specimen, a through hole (1 mm in diameter) was introduced as a crack starter.

Fatigue tests

Two types of servo-hydraulic fatigue testing machines, the uniaxial tension-compression type and the combined tension-torsion type, were used to apply the mode I and mode II loadings, respectively. The machines were operated at a test frequency of 0.1~10 Hz. A stress ratio R of -1 was selected both for the mode I and mode II loadings. Fatigue crack growth behavior was investigated by applying two series of loading sequences:

(i) **Sequence A**: A single mode II cycle in the middle of mode I fatigue test
At first, fatigue crack was initiated and propagated in mode I from the 1-mm drill hole under a constant amplitude tension-compression loading. After the total crack length including hole, $2a$, reached 2 mm, a single cyclic torsion was applied. Thereafter, the tension-compression fatigue test was resumed.

(ii) **Sequence B**: Mode II fatigue test after mode I fatigue test
Similar to the Sequence A, the crack was firstly propagated to the length $2a$ of 2 mm under a constant amplitude tension-compression loading. Then, the type of loading was changed to cyclic torsion, and the crack was propagated under the mode II loading.

The fatigue tests were periodically halted for microscopic observation of crack growth processes. The crack length at specimen surface was measured by using the plastic replica method.

RESULTS AND DISCUSSION

Effect of a single mode II loading on mode I fatigue crack growth (Sequence A)

Figure 3 shows an example of the crack growth curve. In the figures, ΔK_{I} indicates the mode I stress intensity factor range just before and after a single mode II cycle, and $\Delta K_{\mathrm{II\ single}}$ indicates the stress intensity factor range for the single mode II cycle. Figure 4 exhibits the fatigue crack before and after the single mode II loading. The crack path was macroscopically straight even after the shear loading. Figure 5 shows the crack growth rate, da/dN as a function of ΔK_{I}. It is noted that, in the present tests, the crack length was measured at specimen surface using the plastic replica method. The crack growth at specimen surface was microstructurally irregular, which resulted in a large scatter in da/dN data, as exhibited by Fig. 5. In the case of (ΔK_{I}, $\Delta K_{\mathrm{II\ single}}$) = (20, 20) in MPa·$\mathrm{m}^{1/2}$, the single mode II cycle had no influence on the crack growth rate (*cf.* Fig. 5(a)). On the other hand, for (ΔK_{I}, $\Delta K_{\mathrm{II\ single}}$) = (15, 25) and (10, 25) in MPa·$\mathrm{m}^{1/2}$, a little retardation, if any, was observed just after the mode II loading (*cf.* Figs. 5(b) and 5(c)). However, the retardation effect was negligibly small for the crack growth life as a whole. In fact, the observed retardation effect is much less than that in AISI 01 steel reported by Dahlin and Olsson [4-6].

As mentioned before, some studies in the literatures have shown that the crack growth retardation due to occasional mode II loading does not always occur in all the materials and loading conditions. The crack behavior may change depending on not only loading conditions, but also types of materials. For instance, with respect to mode I loading, Ishihara *et al.* [10] carried out a series of mode I crack growth tests with CT specimens and discussed the significance of PIFCC and RIFCC. They pointed out that PIFCC is favored in alloys of low modulus and relatively low yield strength. In addition, materials with a low strain-hardening rate such as 6061 aluminum alloy favor PIFCC. Steels having a higher modulus and a higher strain-hardening rate than 6061 aluminum alloy, in general, exhibit RIFCC, even though they have a comparable yield strength level to aluminum alloys. In ferritic steels, the roughness of fracture surface is larger and the crack-opening level is higher than those in aluminum alloys because of the larger grain size of the microstructure. Also in the crack closure associated with occasional mode II loading, it can be deduced that the mechanical properties and microstructures plays a key role in determining the crack retardation behavior.

Fatigue crack growth under cyclic mode II loading (Sequence B)

Figure 6 shows examples of the crack growth curves. Further, Figure 7 shows the crack growth rate, da/dN as a function of ΔK. In the figures, the open symbols represent the mode I crack growth. The closed symbols represent the mode II crack growth. After changing the loading type from mode I to mode II, the crack growth rate was significantly increased (*cf.* Figs.7(a) and 7(b)), and this is in strong contrast with Sequence A *(cf.* Fig. 5). Figure 8 exhibits the fatigue cracks before and after the changing of loading type. Under the cyclic mode II loading, no crack branching was occurred and the crack grew straight in mode II direction. Figs. 6(b) and 7(c) show the results of ΔK_{II}-decreasing test in the relatively small ΔK_{II} level, where ΔK_{II} was decreased from 15 to 7 MPa·$\mathrm{m}^{1/2}$.

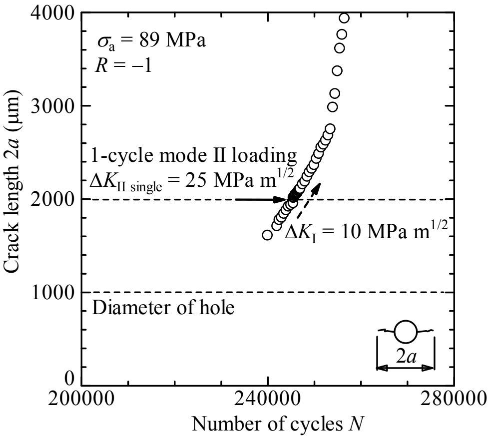
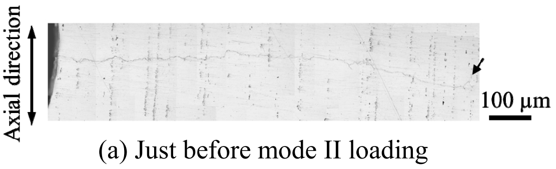
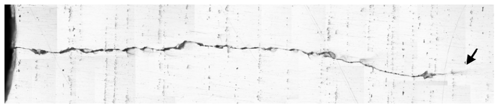


Figure 3. Crack growth curve in Sequence A. ((ΔK_I, $\Delta K_\mathrm{II\ single}$) = (10, 25) in MPa $\mathrm{m}^{1/2}$).

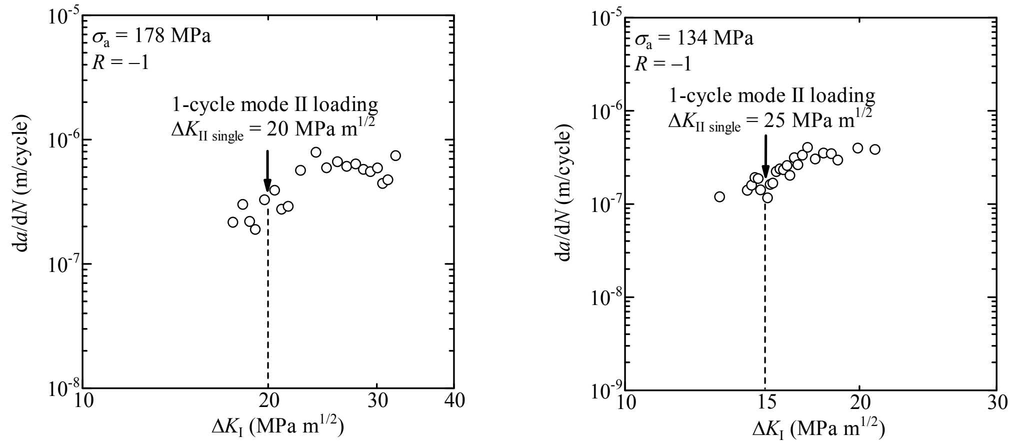


(a) Just before mode II loading



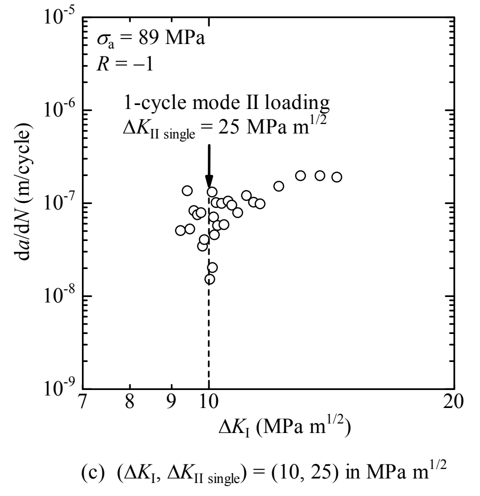
(b) Just after mode II loading

Figure 4. Fatigue cracks before and after a single mode II loading.



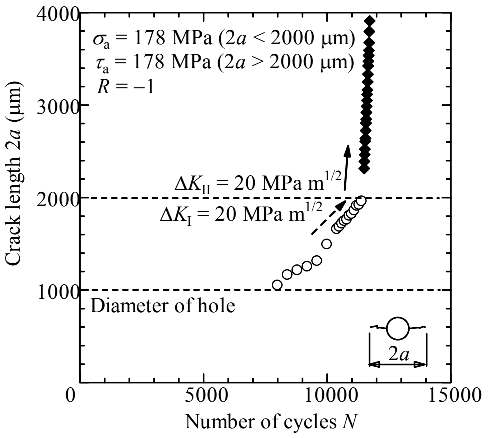
(a) (ΔK_I, $\Delta K_\mathrm{II\ single}$) = (20, 20) in MPa $\mathrm{m}^{1/2}$

(b) (ΔK_I, $\Delta K_\mathrm{II\ single}$) = (15, 25) in MPa $\mathrm{m}^{1/2}$



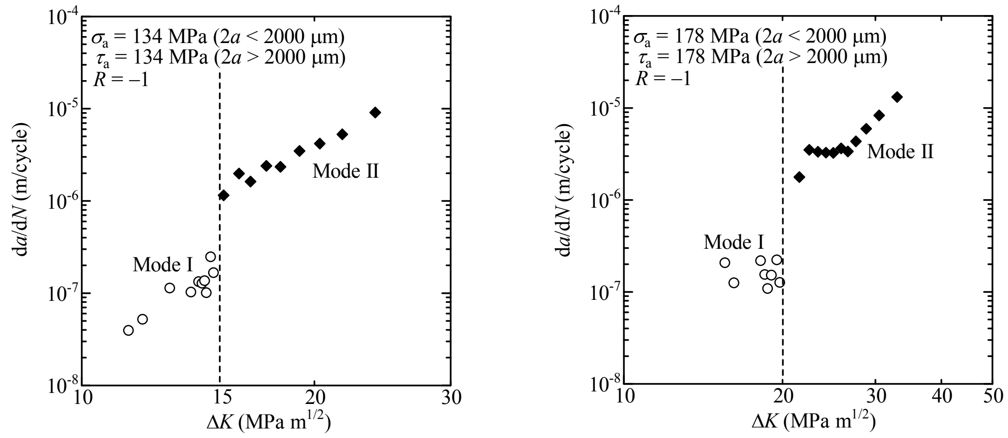
(c) (ΔK_I, $\Delta K_\mathrm{II\ single}$) = (10, 25) in MPa $\mathrm{m}^{1/2}$

Figure 5. Relationships between da/dN and ΔK_I in Sequence A.

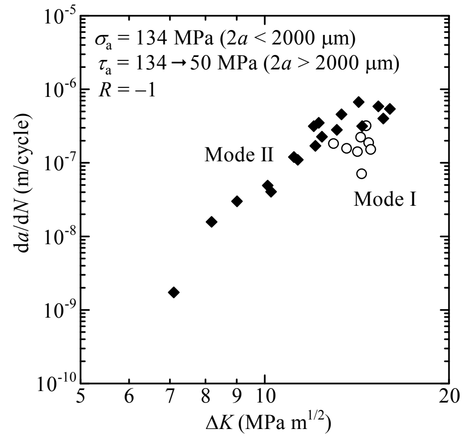


(a) (ΔK_I, ΔK_{II}) = (20, 20) in MPa m$^{1/2}$ (b) (ΔK_I, ΔK_{II}) = (15, 15→7) in MPa m$^{1/2}$

Figure 6. Relationships between da/dN and ΔK in Sequence B.

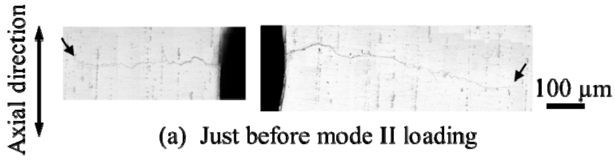


(a) (ΔK_I, ΔK_{II}) = (15, 15) in MPa m$^{1/2}$ (b) (ΔK_I, ΔK_{II}) = (20, 20) in MPa m$^{1/2}$

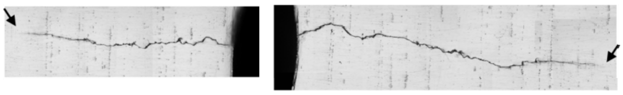


(c) (ΔK_I, ΔK_{II}) = (15, 15 → 7) in MPa m$^{1/2}$

Figure 7. Relationships between da/dN and ΔK in Sequence B.



(a) Just before mode II loading



(b) After 100-cycle mode II loading ($\Delta K_{II} = 20$ MPa m$^{1/2}$)

Figure 8. Fatigue cracks before and after 100-cycle mode II loading.

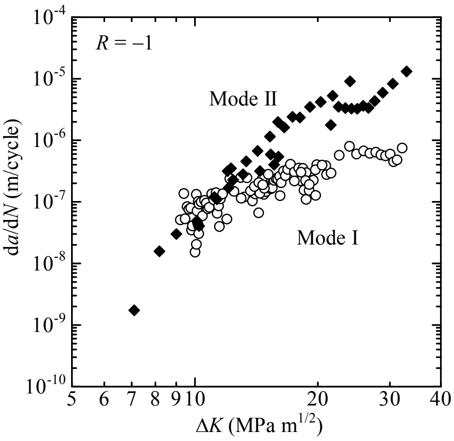


Figure 9. Summary of da/dN -ΔK relation.

Figure 9 summarizes all the da/dN data obtained in this study based on Figs. 5 and 7. At higher ΔK level (*e.g.* ΔK = 15 ~ 30 MPa·m$^{1/2}$), the mode II crack growth was an order magnitude faster than the mode I crack growth. Similar phenomenon of 7075-T6 aluminum alloy was also reported by Otsuka *et al.* [11]. The two series of da/dN data decrease gradually associated with a decrease in ΔK level, and they merged at $\Delta K \approx 10$ MPa·m$^{1/2}$. According to the present study, it is demonstrated that the mode II loading can significantly affect the crack growth in the 7075 alloy. Therefore, when the mode II loading is frequently mixed with the mode I cycles in service loading condition, the acceleration effect of mode II loading should be taken into account.

CONCLUSIONS

Effect of occasional mode II loading on subsequent mode I fatigue crack growth was investigated by using a thin-walled tube made of 7075-T6511 aluminum alloy. According to the present study, the following conclusions were obtained.

(1) Fatigue crack closure due to a single mode II loading had little influence in the subsequent mode I crack growth.
(2) Under relatively high ΔK level, the mode II growth was an order magnitude higher than the mode I growth. Therefore, to evaluate the effect of occasional shear loading on the crack growth life, it is essential to consider the mode II crack growth itself.

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