Fatigue Crack Growth Behavior of Aluminum 7075-T6 Tubes with a Transverse Hole under Axial and Torsion Loadings

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ABSTRACT. *Experimental results were obtained from fatigue tests of thin-walled 7075-T6 aluminium tube specimens with a circular transverse hole. The loading conditions included pure axial, pure torsion, and combined in-phase and out-of-phase tests. Tests were also conducted under axial loading with intermittent torsion cycles. Macro-cracks grew along the maximum principal plane direction (i.e. mode I crack growth). In out-of-phase tests crack branching occurred with a torturous crack path, resulting in a lower crack growth rate compared to in-phase loading, attributed to repeated bifurcation at the crack tip. Intermittent torsion cycles decreased fatigue life and accelerated axial crack growth rate, with the effect increasing with increased number of applied torsion cycles.*

INTRODUCTION

Notches are present in many mechanical components and fatigue cracks often nucleate and grow from notches. In addition, the state of stress at a notch is typically multiaxial due to the stress concentration effect of the notch, and/or due to loading in different directions, either simultaneously or in a sequential manner. Therefore, study of notched fatigue behaviour under multiaxial stress states presents an important area of much practical significance.

Under multiaxial stresses, once a crack is nucleated, it can grow in a mixed-mode manner. Many parameters can influence mixed-mode crack growth behaviour, including load magnitude, material strength, load R-ratio, load non-proportionality, overloads and crack closure [1]. For mixed-mode loading, both crack growth direction and crack growth rate are important considerations and several prediction models or correlation parameters for each exist. For example, the maximum tangential stress criterion [2] has been found to give close predictions of the experimentally observed crack growth path or direction [3], and equivalent stress intensity factor parameters, such as that proposed by Tanaka [4] can satisfactorily correlate the experimental data [3].

Although there are a number of studies for smooth specimen fatigue behaviour under multiaxial stresses, for example in [5], the number such studies for notched specimens is relatively small. Sakane at al. [6] studied multiaxial low-cycle fatigue behaviour of circumferentially round notched bars with three types of groove under uniaxial, in-phase, and out-of-phase loadings. They reported that crack initiation life in torsion of notched specimens is shorter that in tension which may result from no constraint of strain in shear loading.

Jen and Wang [7] investigated crack initiation life for solid cylinders with transverse circular holes under in-phase and out-of-phase multiaxial loading. The crack initiation life of notched specimens under out-of-phase loading was found to be shorter than that under in-phase loading. Thomson and Sheppard [8] performed a series of experimental studies under uniaxial and torsion cyclic loading for smooth and fillet notched cylindrical solid specimens. They found higher crack growth rate for torsional cases in comparison with uniaxial loading.

Tanaka et al. [9] carried out fatigue crack propagation tests using thin-walled tubular specimens with a circular notch under axial and torsional loading. They found that crack growth rates for torsion and combined axial-torsion loadings are higher than under axial loading. They attributed this to the excessive plasticity ahead of the fatigue crack tip.

The objective of this study was investigating fatigue crack growth behaviour of 7075-T6 aluminum under axial, torsion and combined axial-torsion (simultaneously or sequentially) loadings using thin-walled tubes with a circular transverse hole. In this paper, first the experimental program is described, followed by a presentation and discussion of the observed behaviour.

EXPERIMENTAL PROGRAM

Thin-walled tubes made of aluminum 7075-T6 with outside diameter of 70 mm, thickness of 2.41 mm, and length of about 300 mm were used for the experiments. A 6.35 mm diameter through-thickness circular hole was made in the middle of the tube, transverse to the tube axis. The stress concentration factor in tension loading is 3.19, while this value for torsion loading is 3.87. To avoid machining marks and sharp edges, a special rimming tool was used in finishing the hole.

All tests were performed using a servo-hydraulic axial-torsion testing load frame with a load capacity of ±100 kN and torque capacity of ±1000 N.m. A high resolution microscope camera was used to capture cracking images and to measure crack length during each test. Crack images were taken during short pauses in cyclic loading and while the tube was under a static tensile load, the magnitude of which did not exceed that used during the cyclic loading part of the test.

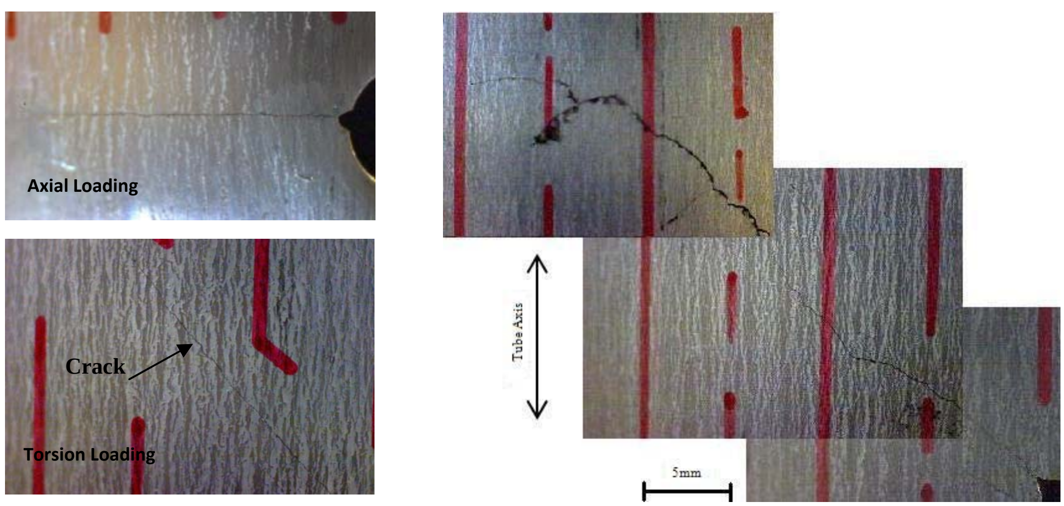
Since the tubes did not have a reduced gage section, several initial tests failed due to fretting fatigue failure at the intersection of the gripping collet and the tube outside diameter. It was, therefore, to introduce a sharp notch at the perimeter of the hole at the hole edge for axial loading cases and at 45° to the specimen axis for the torsion loading cases. These locations correspond to the maximum stress location and, therefore, the natural crack location. To produce the notch, a special Jeweler's filing tool was used to make a notch of about 1 mm depth.

EXPERIMENTAL RESULTS AND OBSERVATIONS

Crack length was measured along the crack growth direction in all tests, which was along the maximum principal stress direction, as all the cracks grew as mode I cracks. The seven-point polynomial technique [10] was used for data reduction, resulting in very good fits. For stress intensity factor calculations the solution for a circular through crack in a cylinder from the AFGROW DTD handbook [11] was used, given by:

$$\Delta K = F_0 \sigma_a \sqrt{\pi a} \tag{1}$$

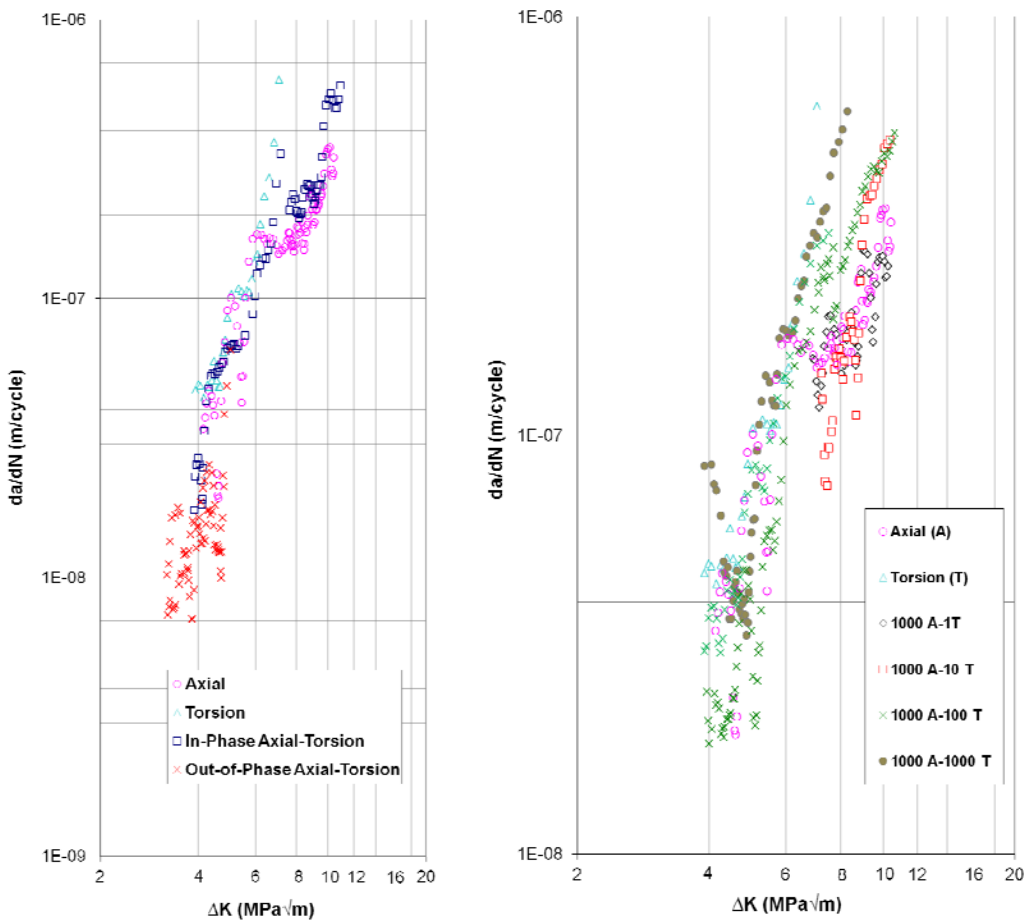
where F_0 is the geometry factor, σ_a is nominal stress amplitude, and a is crack length. The crack length used consisted of the sum of the hole diameter, the notch length, and the measured crack length from the end of the notch to the crack tip. The stress intensity factor solution for the cracked cylinder was nearly identical to the solution for the simple case of a center-cracked flat plate. As mentioned earlier, cracks under axial loading grew perpendicular to the tube axis, while under torsion they grew at 45° to the tube axis, as shown in Fig. 1(a). These planes correspond to the maximum principal stress plane.



(a) (b)

Figure 1. (a) Orientation of crack path for axial and torsion loadings and, (b) rough crack path and crack branching for out-of-phase axial-torsion tests.

Crack growth rates obtained from fully-reversed pure axial and pure torsion tests are shown in Fig. 2(a), which shows somewhat higher rates in torsion, as compared to axial loading. To evaluate the effect of static torsion on axial crack growth behaviour, a fully-reversed axial test with a mean torque was also performed. Although there was no effect of mean torsion on axial crack growth rate, a rougher crack path compared to axial tests was observed.

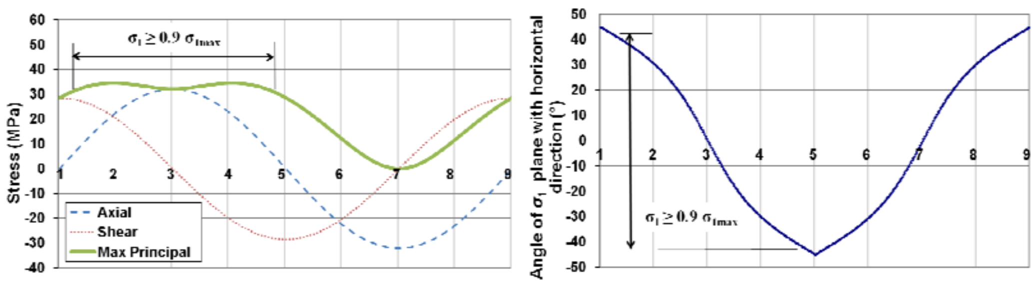


(a) (b)

Figure 2. Superimposed crack growth rate behaviours for (a) axial, torsion, in-phase, and out-of-phase tests and, (b) axial, torsion, and axial tests with various numbers of intermittent torsion cycles.

In fully-reversed in-phase tests cracks also grew along the maximum principal stress direction (mode I), which was at 60° to the tube axis. In out-of-phase tests, the observed crack was at 50° to the tube axis (or 40° to the horizontal axis), as can be seen from Fig. 1(b) for one of the out-of-phase tests. For this case, although two planes at ±59° to the tube axis (or ±31° to the horizontal axis) are subjected to the maximum principal stress amplitude, all planes in the range of ±42° to the horizontal axis are subjected to more than 90% of the maximum principal stress amplitude. This is illustrated in Fig. 3. Crack growth rates from in-phase and out-of-phase tests are also shown in Fig. 2(a).

In out-of-phase tests crack branching occurred and crack growth path exhibited a torturous crack path, as shown in Fig. 1(b). This behaviour was not observed for the in-phase tests. The torturous crack path in the out-of-phase tests resulted in periods of decreased crack growth rate or retardation, as well as increased crack growth rate data scatter, as can be observed from Fig. 2(a). This figure also shows somewhat lower crack growth rate in out-of-phase loading, as compared to the in-phase loading.



(a) (b)

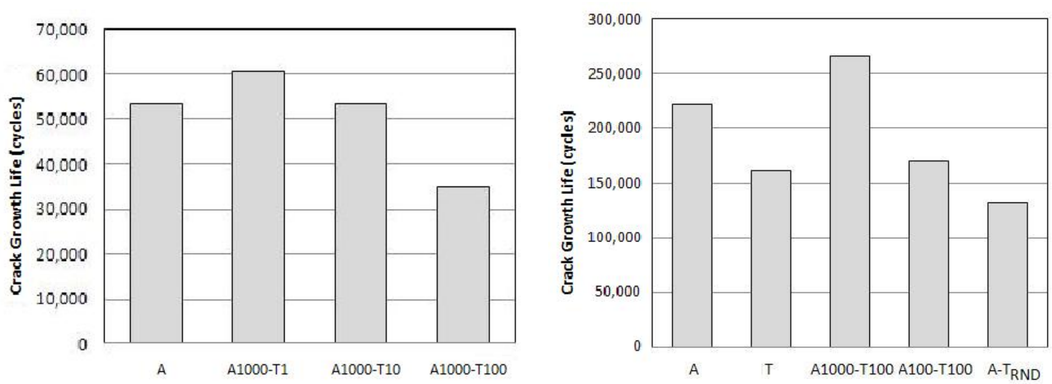
Figure 3. Variation of maximum principal stress (a) and its plane orientation (b) in a loading cycle for out-of-phase axial-torsion tests.

To evaluate the effect of intermittent torsion cycles on crack growth behaviour under axial loading, block load tests were conducted with each block consisting of 1000 fully-reversed axial cycles followed by 1, 10, or 100 fully-reversed torsion cycles in each block. In addition, a test with 100 fully-reversed axial cycles followed by 100 fully-reversed torsion cycles in a load block was also conducted. In all such tests, the stress levels for the axial and torsion were similar, resulting in nearly the same maximum principal stress amplitudes.

Superimposed crack growth rate behaviours for pure axial, pure torsion, and axial tests with various numbers of intermittent torsion cycles are shown in Fig. 2(b). For all experiments of this type, where there were a relatively small number of torsion cycles compared to axial cycles, the cracks grew on the maximum principal stress plane for axial loading (i.e. perpendicular to the tube axis). It should be noted that the torsion cycles in these tests do not induce a normal stress on the maximum principal stress plane for the axial cycles. However, for the test with equal number of axial and torsion cycles in each block the crack grew in the maximum principal stress direction corresponding to torsion loading (i.e. at 45° to the tube axis). For this case, the axial cycles result in a normal stress on the maximum principal stress plane which is half of the normal stress resulting from the torsion cycles.

The crack growth rate somewhat increased with an increase in the number of torsion cycles, as can be seen from Fig. 2(b), resulting in a shorter crack growth life, as can be observed from Fig. 4. This figure presents fatigue life from a crack length of 2 mm to 15 mm from the hole edge for these loadings. The effect is not significant, however.

To evaluate the effect of random normal torque distribution on crack growth rate, a fully-reversed axial test with random torsion cycles with a normal distribution was also conducted. In this test, the axial cycles had a constant stress amplitude of 34.5 MPa, while the torsion cycles had fully-reversed variable amplitude cycles with shear stress amplitude smaller than 13.8 MPa. The crack in this test also grew on the maximum principal stress amplitude plane (i.e. perpendicular to the tube axis). A faster crack growth rate and, therefore, a shorter life was observed, as compared to the pure axial test at the same axial stress level. This test is identified as A-T_{RAND} in Fig. 4(b). A detailed analysis of effects such as plasticity and/or roughness induced closure is necessary to explain the observed behaviour in this test, as well as in axial tests (i.e. mode I growth) with intermittent torsion cycles (i.e. intermittent mode II cycles).



(a) (b)

Figure 4. Fatigue crack growth life from a crack length of 2 mm to a crack length of 15 mm form the hole edge for different loading conditions at (a) 62 MPa stress level and, (b) 34.5 MPa stress amplitude level.

Comparison of crack growth rates at a stress intensity factor range of $\Delta K = 5$ MPa$\sqrt{m}$ for all loading conditions is shown in Fig. 5. As can be seen from this figure, crack growth rate is higher in torsion (T) than in axial (A) loading, as explained earlier. Crack growth rate is slower for out-of-phase loading, as compared to in-phase loading, due to the rough crack path in out-of-phase loading. It can also be seen that the out-of-phase loading has the slowest crack growth rate amongst all the loading conditions considered. This is due to the fact that a wide range of planes are subjected to a high percentage of the maximum principal stress, in contrast to the other loading conditions considered, resulting in repeated bifurcation at the crack tip.

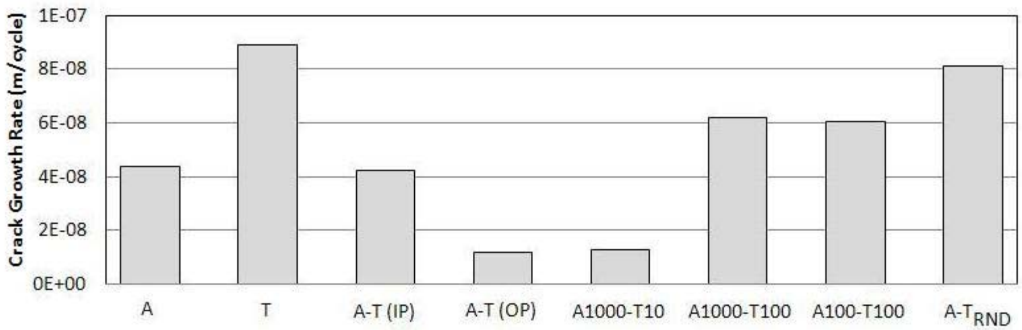


Figure 5. Comparison of crack growth rates at ΔK = 5 MPa√m for all loading conditions.

CONCLUSIONS

Based on the experimental results and analysis presented, the following conclusions can be made:

1. For all the loading conditions used, crack(s) grew on or near the maximum principal stress amplitude plane, corresponding to mode I macro-crack growth.
2. A higher crack growth rate was observed in torsion, as compared to axial loading. A mean or static torque did not influence axial crack growth rate.
3. In out-of-phase axial-torsion tests fatigue life was longer than in in-phase tests, and with a lower crack growth rate. This is believed to be due to crack branching and a torturous crack path resulting in periods of decreased crack growth rate or retardation from repeated bifurcation at the crack tip.
4. Intermittent torsion cycles decreased fatigue life and accelerated axial crack growth rate. Where there were a relatively small number of torsion cycles compared to axial cycles at the same stress level, the cracks grew in mode I corresponding to axial loading. However, for the test with equal number of axial and torsion cycles in each block the crack grew in mode I corresponding to torsion loading.
5. Random torsion cycles in constant amplitude axial test reduced axial fatigue life and increased crack growth rate. However, the crack grew in mode I corresponding to axial loading. Detailed analysis of effects such as plasticity and/or roughness induced closure is necessary to explain the observed behaviour of axial tests with intermittent mode II cycles.

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