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Fatigue crack growth behaviour of tubular aluminium specimens with a circular hole under axial and torsion loadings

Ali Fatemi [a,*], Nicholas Gates [a], Darrell F. Socie [b], Nam Phan [c]

[a] *Mechanical, Industrial and Manufacturing Engineering Department, The University of Toledo, 2801 West Bancroft Street, Toledo, OH 43606, USA*
[b] *Mechanical Science and Engineering Department, University of Illinois at Urbana-Champaign, 1206 West Green St., MC-244, Urbana, IL 61801, USA*
[c] *Structures Division, Naval Air Systems Command (NAVAIR), Patuxent River, MD, USA*

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ABSTRACT

Experimental results were obtained from fatigue tests of thin-walled 7075-T6 and 2024-T3 aluminium tubular specimens with a circular hole. The loading conditions included axial, torsion, combined in-phase and out-of-phase axial-torsion, and axial with intermittent torsion cycles. Crack nucleation was observed on planes of maximum shear stress for both notched and smooth (un-notched) specimens. Macroscopic crack growth in notched specimens occurred along planes experiencing the maximum range of nominal principal stress (i.e. mode I crack growth) whereas smooth specimen cracks grew on maximum shear planes. This is explained in terms of different damage evolution mechanisms in smooth and notched specimens. Cracks grew faster in torsion compared to axial loading, as well as in in-phase loading compared to out-of-phase loading. This is attributed to the T-stress in torsion tests and crack branching with a torturous crack path in out-of-phase tests. Intermittent torsion cycles decreased fatigue life and accelerated axial crack growth rate. These effects and the differences in crack growth behaviour between different loadings are discussed.

1. Introduction

Notches are present in many mechanical and structural components and fatigue cracks often nucleate and grow from notches. In certain cases, the state of stress at a notch may be 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. In addition, multiaxial loading can have a significant effect on the location and magnitude of these stress concentrations. 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 growth rate data [3].

* Corresponding author. Tel./fax: +1 419 530 8213.
E-mail addresses: afatemi@eng.utoledo.edu (A. Fatemi), profsocie@gmail.com (D.F. Socie), nam.phan@navy.mil (N. Phan).

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Nomenclature

ΔK	mode I stress intensity factor range
da/dN	crack growth rate
A	crack growth rate equation coefficient
n	crack growth rate equation exponent
N	number of cycles
N_f	number of cycles to failure
σ_1	maximum principal stress
σ_{1a}	maximum principal stress amplitude
a	crack length (includes hole diameter for notched specimens)
ℓ	crack length from edge of hole
F_0	geometry factor
σ_a	axial nominal stress amplitude
τ_a	shear nominal stress amplitude
σ_m	mean axial stress
τ_m	mean shear stress
θ	crack orientation angle

Although there are a number of studies for smooth specimen fatigue behaviour under multiaxial stresses, for example in [5], the number of such studies for notched specimens is relatively small. Sakane et al. [6] studied multiaxial low-cycle fatigue behaviour of circumferentially notched round bars with three types of grooves under uniaxial, in-phase, and out-of-phase loadings. They reported that crack initiation life in torsion of notched specimens is longer than in tension with the same equivalent stress, 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 of low-carbon steel 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, under the same stress intensity range. They attributed this to the excessive plasticity ahead of the fatigue crack tip.

The objective of this study was to investigate notch effects on damage development and fatigue crack growth behaviour of two commonly used aluminium alloys under different loading conditions. The loading conditions included axial, torsion, and combined axial-torsion (simultaneously or sequentially) loadings applied to thin-walled tubular specimens with a circular transverse hole. In this paper, first the experimental program is described, followed by a comparison of the observed cracking behaviour between smooth and notched specimens. Damage development and crack growth rates of the notched specimens for the different loading conditions are then discussed. Finally, some conclusions based on the observed behaviour and analysis results are presented.

2. Experimental program

Thin-walled tubular specimens made of 7075-T6 and 2024-T3 aluminium alloys were used in this study. For the 7075-T6 alloy, uniform diameter tubes with outside diameter of 69.9 mm and thickness of 2.45 mm were used. A 6.35 mm diameter through-thickness circular hole was made in the middle of the tube, transverse to its axis. For the 2024-T3 alloy, tubular specimens with a reduced gage section with outside diameter of 29 mm, thickness of 1.8 mm, and a 3.2 mm diameter through-thickness circular hole were used. The geometries of both specimens are shown in Fig. 1. To avoid machining marks and sharp edges, a special reaming tool was used in finishing the hole in both sets of specimens.

The stress concentration factors, as obtained by using the stress concentration finder available in [10], are approximately 3.2 in tension loading and 3.9 in torsion loading for both geometries. Some smooth specimens of the 2024-T3 alloy were also tested, with identical dimensions to that shown in Fig. 1(b), except without the transverse hole. These tests allowed for a comparison of the damage mechanisms and cracking behaviour between smooth specimen (i.e. un-notched) fatigue cracks and those growing away from the influence of a notch.

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. For the few smooth