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Small fatigue crack growth under multiaxial stresses

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ABSTRACT

A significant portion of the fatigue life is typically spent in growth of small cracks. In addition, the stress state in many structures and components is multiaxial. Therefore, the study of small crack growth behaviour with regards to its growth path as well as growth rate under combined stresses can be of great importance in many applications. This study investigates small crack growth behaviour of several steels under multiaxial states of stress. Experimental observations from solid and thin-walled tubular round specimens under various multiaxial cyclic loadings including in-phase and out-of-phase, tension–torsion and tension–tension, and with or without mean stresses are used to characterise small crack growth behaviour. The steels used include 1045 and 1050 medium carbon steels, 304L stainless steel, and Inconel 718. Effects of load non-proportionality, mean stresses, and friction-induced closure on small fatigue crack growth behaviour are discussed. Critical plane analysis and an effective strain intensity factor are used to predict crack growth path as well as to correlate crack growth rates under various combined stress conditions.

1. Introduction

Stress and strain states of many industrial components and structures are multiaxial, which arises from multi-directional loading, residual stresses, or geometrical effects. Fatemi and Shamsaei [1] have recently reviewed some of the most important issues to be considered in multiaxial fatigue analysis and life estimation. One issue among these is crack growth under combined stresses, as it can constitute a significant portion of the total fatigue life.

The fatigue process includes initiation or nucleation and growth of micro-cracks. Crack initiation life consists of crack nucleation and micro-crack growth up to a length of typically about several hundred micrometers (i.e. microscopic growth), as presented in Fig. 1. At this length scale, microstructure texture and crack surface morphology can play a dominant role on crack growth behaviour.

Crack growth life typically consists of a period of small crack growth followed by long crack growth (i.e. macroscopic growth). For the small crack growth regime, the crack is typically affected by the local plasticity and does not generate its own plastic zone. In contrast, longer cracks at the macroscopic level are generally less affected by the local plasticity and they generate their own plastic zone at the crack tip. Modelling of such cracks typically requires the use of fracture mechanics analysis.

Experimental observations suggest material, load magnitude, initial crack tip condition, load ratio, and mean stress affect the crack growth mode [2]. In plate-type geometries under multiaxial stresses, cracks often form under mixed-mode loading; however, they usually turn into a mode I macro-crack soon after micro-crack growth. Thin-walled tubular specimens under torsion loading can be used to generate mode II macro-crack growth.

Mixed-mode fatigue crack growth behaviour may be affected by different factors such as overloads, crack closure, T-stress, and load non-proportionality. Crack deflection and interaction with microstructure result in roughness-induced closure which has a significant effect on threshold behaviour, especially in the presence of mixed-mode loading [3]. Small cracks under roughness-induced closure mechanism often exhibit different crack growth behaviour than long cracks under plasticity-induced closure mechanism.

Zhang and Fatemi recently studied crack closure and load ratio effects [4,5], as well as load mixity (K_{II}/K_I) effect [4] on short crack growth behaviour in plate-type specimens under four-point bending. They observed crack growth on paths with small K_{II}/K_I ratio (i.e. primarily mode I), similar to what had been observed for long crack growth of the same material under mixed-mode loading [6], and as predicted by the maximum tangential stress criterion. Crack closure was observed under all load mixity ratios in the short crack regime for load ratio ($R = P_{min}/P_{max}$) of 0.05, and the higher the initial load mixity ratio the higher the crack growth rates. They reported roughness-induced crack closure for the mixed-mode tests even at a high load ratio of 0.5 in the short crack regime.

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Nomenclature

a	surface crack length	γ_a	shear strain amplitude
E	modulus of elasticity	$\Theta_{95,\mathrm{IP}}$	range of planes experiencing 95% of fatigue damage for IP loading
G	shear modulus	$\Theta_{95,\mathrm{OP}}$	range of planes experiencing 95% of fatigue damage for OP loading
k	material constant	σ_a	axial stress amplitude
N	applied cycles	σ_m	mean axial stress
N_f	cycles to failure	$\sigma_{n,\max}$	maximum normal stress on the maximum shear strain plane
$\Delta\varepsilon_n$	maximum normal strain range on the maximum shear plane	σ_y	yield strength
$\Delta\gamma_{\max}$	maximum shear strain range		
$\Delta K_{Eff.}$	effective strain intensity factor		
ΔK_{CPA}	critical plane effective strain intensity factor		
ε_a	axial strain amplitude		
$\bar{\varepsilon}_a$	effective strain amplitude		

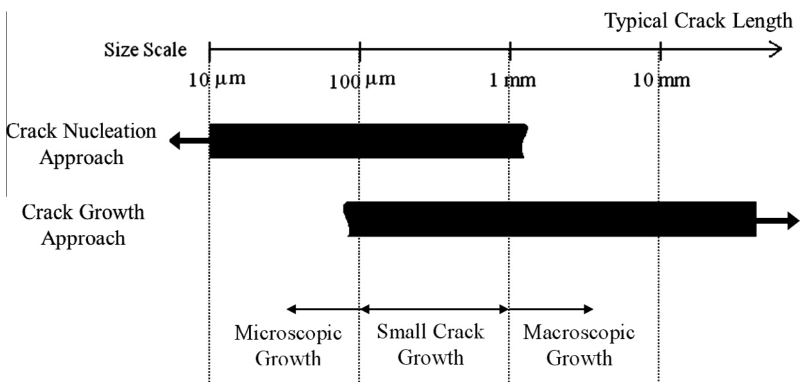

Fig. 1. Different stages of crack nucleation and growth during the fatigue process and the approach typically used for analysis.

Many studies, such as [7,8], suggest that the geometry configuration of a notch affects the crack growth behaviour which can be explained by different plastic zone fields. In the case of mixed-mode loading, modelling the crack tip cyclic plasticity is complicated. Pommier et al. [9] have recently proposed an approach to model the elastic–plastic cyclic behaviour of the crack tip under mixed-mode loading.

Since the crack changes direction during its growth under mixed-mode loading, both crack growth rate and crack growth direction need to be considered [2,3,10]. Several criteria for prediction of crack growth direction under mixed-mode loadings have been proposed over the last 50 years. Among these, the maximum tangential stress (MTS) [11] and the minimum strain energy density [12] criteria are most commonly used due to their simplicity as well as support by experimental observations [4,13]. The MTS criterion considers the direction of crack growth to correspond with the maximum tangential stress direction. The minimum strain energy density criterion predicts crack growth to be in a direction along which the strain energy density reaches its minimum. However, applications of these criteria are generally limited to the linear elastic fracture mechanics regime.

To correlate fatigue crack growth rates under mixed-mode loading, effective strain and effective stress intensity factors have been used. Crack growth life can then be calculated by integrating a Paris-type equation. Effective stress intensity factors include one proposed by Tanaka [14] and effective strain intensity factors include those proposed by Socie et al. [15] and by Reddy and Fatemi [16].

The effective stress-based intensity factor proposed by Tanaka [14] assumes fatigue crack growth occurs when the sum of the absolute values of the crack tip displacements in a plastic strip reaches a critical value. Socie et al. [15] proposed an effective strain-based intensity factor taking into account modes I and II fatigue crack growth under axial-torsion strain-controlled loading:

$$\Delta K_{Eff.} = [(E\Delta\varepsilon_n)^2 + (G\Delta\gamma_{\max})^2]^{1/2}\sqrt{\pi a} \tag{1}$$

where $\Delta\varepsilon_n$ is the maximum normal strain range on the maximum shear plane, $\Delta\gamma_{\max}$ is the maximum shear strain range, E is the Young modulus, G is the shear modulus, and a is the surface crack half-length. Hoshide and Socie [17] also extended the J-integral concept, originally proposed for correlation of crack growth rate under mode I, to mixed-mode crack growth.

The effective strain-based intensity factor proposed by Reddy and Fatemi [16] is based on the Fatemi–Socie (FS) critical plane fatigue damage parameter [18], given by:

$$\Delta K_{CPA} = G\Delta\gamma_{\max}\left(1 + k\frac{\sigma_{n,\max}}{\sigma_y}\right)\sqrt{\pi a} \tag{2}$$

where σ_y is the material monotonic yield strength, k is a material constant found by fitting fatigue data from uniaxial tests to fatigue data from torsion tests, and $\sigma_{n,\max}$ is the maximum normal stress acting on the maximum shear strain plane.

Park et al. [19] conducted fatigue tests on hourglass round specimens made from A533B steel under in-phase and 90° out-of-phase bending-torsion loading. They monitored crack growth from initial sizes in the range of 50–300 µm to final sizes of several mm. They reported good small crack growth correlation capability for their test data by using the effective strain-based intensity factor range, ΔK_{CPA}, given by Eq. (2).

Doquet and Bertolino [20] used compact-tension–shear (CTS) specimens made from Ti–6Al–4V to perform fatigue crack growth