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Closure measurement and analysis for small cracks from natural discontinuities in an aluminium alloy

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ABSTRACT

Some materials such as 7050-T7451 and β-annealed Ti–6Al–4V exhibit very rough fatigue crack surfaces which suggests that roughness induced crack closure might be a significant issue. The present work examined a range of data for 7050-T7451 material which included experimental results under constant amplitude and variable amplitude/spectrum loading. Crack closure was either measured directly, or the effects were inferred through results from previous fractographic investigations. Analyses using an updated and improved version of the FASTRAN crack growth code combined with the experimental data were used to identify a new approach to correlate closure levels and crack growth behaviour. The new approach includes direct compliance based crack opening measurements to correlate the baseline constant amplitude properties and then using a cycle-by-cycle strip yield model with realistic constraint factors to model crack growth under spectrum loading. The new approach is consistent with fundamental differences in fatigue crack closure levels under constant and variable amplitude/spectrum loading which have been identified at the individual cycle by cycle level down to very small crack sizes. The new approach is shown to work very well for a range of cases considered here, and it provides a very useful insight into this complex behaviour.

1. Introduction

The discovery of the fatigue crack closure phenomenon by Elber [1,2] has been extremely important in understanding fatigue crack growth in high strength aircraft metallic alloys and structures. The concept of crack closure has helped to explain a number of important behaviours including mean stress effects [3], small crack effects [4,5], and spectrum load interaction (retardation and acceleration) [6]. The quantitative models are based on an approach in which residual plastic deformations remain in the wake of an advancing crack. Other mechanisms including roughness [7], oxidation and debris build-up are known to also contribute to closure in certain regimes, but they have not previously been considered in detail or quantitatively addressed.

The three main mechanisms of crack closure have been identified as follows:

a. Plasticity Induced Crack Closure (PICC). Attributed to the zone of plastically deformed material ahead of the crack tip combined with the residual plastic deformations remaining in the wake of the advancing crack [2,6].
b. Roughness Induced Crack Closure (RICC). RICC has been shown to be caused by crack face contact above the minimum load at discrete asperities [8].
c. Debris Induced Crack Closure (DICC). The formation of excess corrosion deposits such as oxide debris has been shown to promote crack closure [9].

To account for PICC effect, Newman developed the FASTRAN crack growth analysis computer code [10,11] based on the Dugdale yield zone model [12] but modified to leave plastic deformations in the wake of an advancing crack. A key feature of the code is the ability to model three-dimensional constraint effects. A constraint factor, α, is used to elevate the material's flow stress σ_o at the crack tip to account for the influence of tri-axial stress state ($\alpha\sigma_o$) on the plastic deformation ahead of crack tip. The material behavior is modelled as elastic-perfectly plastic and the flow stress σ_o is the average of the yield and ultimate stress. For plane-stress conditions $\alpha = 1.0$ (original Dugdale model), and for

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Nomenclature

a	tensile constraint factor
c	crack length, mm
C(T)	compact tension
CA	constant amplitude
DICC	debris induced crack closure
DK	stress-intensity factor range, MPa m$^{1/2}$
DK$_{eff}$	effective stress-intensity factor range, MPa m$^{1/2}$
FEA	finite element analysis
K	stress-intensity factor, MPa m$^{1/2}$
K_T	stress concentration factor
NMAX	number of cycles at which crack opening stress/load is recalculated
PICC	plasticity induced crack closure
P_{max}	maximum applied load, kN
P_{min}	minimum applied load, kN
Po	crack-opening load, kN
R	load ratio (P_{min}/P_{max})
R_a	surface roughness
RICC	roughness induced crack closure
su	ultimate tensile strength, MPa
sys	yield stress, MPa
U^P	effective stress intensity factor ratio due to plasticity only
w	specimen width, mm
γ	roughness factor
Δc^*	crack growth increment
θ	asperity angle
σ_o	flow stress
χ	mixed mode ratio

pure plane strain conditions $\alpha = 3.0$. For most realistic cracking scenarios neither pure plane-stress nor plane-strain conditions prevail, an average value is typically used. Experience with a significant number of materials and geometries have shown that α values of around 1.8–2.0 work very well, and that is consistent with theoretical [13] and 3-D elastic–plastic Finite Element Analyses (FEA) [14,15].

Limitations of the PICC only approach as used in FASTRAN have become evident when applied to materials including 7050-T7451 and β-annealed Ti–6Al–4V which exhibit very rough crack surfaces [16–21]. Newman et al. [16] applied local strain gages ahead of the crack tip in 7050-T7451 aluminium alloy compact tension (C(T)) specimens to measure crack-opening loads using Elber's reduced strain method. FASTRAN was used to successfully correlate the constant amplitude (CA) crack growth rate data, but a very low value of constraint factor $\alpha = 1.3$ was required, much less than the theoretical and numerical value of 1.8. Walker et al. [19–21] found a similar result for a coarse-grain β-annealed Ti–6Al–4V alloy which also exhibited very rough crack surfaces. The low value of α was thought to be due to the roughness closure effects not being explicitly modelled in FASTRAN.

The low α value was also reported to work well when applied to FASTRAN analysis for spectrum loading on 7050-T7451 [17] and also β-annealed Ti–6Al–4V [20,21]. Previous research efforts [20] have focused on modelling the RICC contribution explicitly, combined with plasticity induced closure modelling with α values around the expected and separately justified range of about 1.8–2.0. That approach was moderately successful for β-annealed Ti–6Al–4V material [20]. But recent improvements in FASTRAN which allow cycle-by-cycle[1] tracking of crack closure and improved accounting for sequence effects suggest that the previous apparent success may have been erroneous. Recent research at DSTO has identified significant, fundamental differences in fatigue crack path and rate at the smallest possible length scales on a cycle-by-cycle basis for CA and spectrum loading [22,23]. The differences suggest that RICC may be more significant under CA conditions, but may have far less (if any) effect under spectrum loading. Models combining the effects of plasticity-induced and roughness-induced crack closure have been reported in the literature [24], but so far their applications have been limited to constant amplitude loading.

Almost all of the data available in the literature relating to crack closure measurement pertain to CA loading, very little data exist for spectrum loading. This is especially true for small cracks which initiate from natural features. This paper details an investigation into RICC effects under CA and spectrum loading for 7050-T7451 aluminium alloy. Experimental and analytical aspects are considered and the paper addresses both small cracks originating at natural discontinuities and long cracks from starter notches.

2. Experimental details

2.1. Material

The material used throughout this study is aluminium alloy 7050-T7451. The yield strength and ultimate tensile strength of this material are 450 MPa and 520 MPa, respectively. The Young's modulus is 71 GPa and the fracture toughness was is 40 MPa $\sqrt{m}$.

Standard C(T) specimens [25] were tested under constant amplitude loading conditions [16] with low load ratio ($R = 0.1$). The reason for choosing a low-R case was that reliable compliance measurements could be obtained to determine crack opening data for comparison to the FASTRAN prediction. The specimens, measuring 50 mm wide and 6.35 mm thick, were fatigue pre-cracked under compression for 30,000 cycles with a minimum load of −4760 N and a maximum load of −445 N. The crack growth rates versus ΔK_{eff} were taken from [18] and summarized in Table 1.

2.2. Spectrum loading of low K_T hour-glass specimens with small bands of constant amplitude loading

A novel test and analysis program was recently undertaken at DSTO to investigate crack closure for small cracks from natural features in 7050-T7451 under spectrum loading [26]. A special load sequence was devised with short bands of 1000 cycles of CA at various load ratios ($R = 0.50$, 0.44, 0.38, 0.29, 0.17 and 0) inserted between bands of high R (0.8) CA and bands of spectrum. The sequence was designed to facilitate post-test Quantitative Fractography with the creation of visually identifiable bands. In this case the bands were also designed to allow the investigation of closure effects at different mean stress or stress ratio, R values.

The coupons (no starter notches) were etched to create pits from which cracks initiated naturally. The area near the centre of the coupon (i.e. the test region) was masked off and the surrounding area shot peened to ensure that the fatigue cracking initiated in the test region. Cracks typically propagated from semi-circular surface cracks 0.01–0.02 mm deep.

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[1] Cycle-by-cycle means that the calculations are performed after each cycle of load application.