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A numerical analysis of the mechanisms behind plasticity induced crack closure: Application to variable amplitude loadings

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ABSTRACT

The effect of loading parameters on fatigue crack growth has been explained using the concept of crack closure. Plasticity induced crack closure (PICC) is linked to the crack tip plastic deformation, which becomes residual with crack propagation. The objective here is to identify the main mechanisms behind PICC, and for that different loading cases were considered namely overloads and load blocks. An analytical model was used to isolate the effect of residual plastic deformation on PICC, however significant differences were obtained relatively to finite element results. A second mechanism, which is crack tip blunting, was used to explain the transient behaviour observed after overloads and load blocks. For overloads and low–high load sequences there is a sudden increase of crack tip blunting with load increase which explains the sudden decrease of crack opening level. For high–low load sequences there is a sudden decrease of crack tip blunting which enhances the effect of residual plastic wake. Finally, the partial closure concept was tested looking to non-linear crack tip parameters but no evidences of Donald's effect were found for the material studied.

1. Introduction

Different mechanism have been proposed to explain the effect of load pattern on fatigue crack growth rate (FCGR), namely crack branching, crack deflexion, crack tip blunting, strain hardening or crack closure. Korda et al. [1] performed constant amplitude (CA) tests on ferrite–perlite microstructures. They reported that small deflexions on the crack path, as well as microbranching, altered the da/dN behaviour. Suresh [2] suggested that a bifurcated crack tip profile is subjected to a lower effective ΔK than a straight crack of the same projected length subjected to an identical value of far-field ΔK. Furthermore he stated that for aluminium alloys under LEFM conditions a reduction in effective ΔK of approximately 25% can be realised in the post-overload regime solely from the crack deflexion process. Another consequence of the misfit developed between the surfaces of branched cracks is the development of contact friction. Crack blunting is another mechanism which reduces the stress intensity factor, K, and hence causes crack growth retardation. An overload blunts the crack tip and a number of cycles is required to reinitiate and propagate the crack from this notch. Crack closure is however the most widely used mechanism to explain da/dN variations associated with the variation of physical parameters. The load history effect is usually taken into account in the modelling of da/dN through the variations of the crack opening stress intensity factor [3]. When the extent of crack closure is restricted, such as at high load ratios, with small flaws or cracks at notches, there is an increase in near-tip crack driving force [4].

However, the mechanisms behind crack closure are not fully understood. In a previous study of the authors [5] the residual plastic deformation was modelled as a set of vertical plastic wedges. The effect of each plastic wedge on plasticity induced crack closure was found to increase with its plastic elongation and to decrease exponentially with distance to crack tip. A second mechanism was however found necessary to explain the effect of finite element mesh size on the predictions of crack closure level [6]. In fact, the mesh refinement was found to increase the residual plastic elongation. This increase would produce a continuous increase of crack opening level with mesh refinement. Nevertheless, the opposite trend was observed by Solanki et al. [7], Jiang et al. [8] and González-Herrera and Zapatero [9]. Therefore, a second effect of mesh refinement must exist, which can explain this apparent contradiction. This second mechanism was identified as crack tip blunting. Nevertheless, so far, the study of crack tip blunting with focus on numerical simulation of the crack opening level has not been addressed in the literature. It has however been studied in other contexts. Crack tip blunting under maximum load and

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Nomenclature

a	crack length	$M(T)$	middle-tension (specimen)
a_0	initial crack length	NLP	non-linear parameters
CA	constant amplitude loading	OL	overload
CTOD	crack tip opening displacement	PICC	plasticity induced crack closure
d	distance from crack tip	R_{eff}	effective stress ratio (=K_{open}/K_{max})
F_{maxBL}	maximum baseline load	t	specimen's thickness
F_{minBL}	minimum baseline load	W	specimen's width
FEM	finite element method	Y	geometric factor for K calculation
FCGR	fatigue crack growth rate	σ	remote stress
HL	high–low load sequence (load blocks)	σ_{ys}	yield stress
K	stress intensity factor	Δa	crack propagation increment
LH	low–high load sequence (load blocks)	Δy_p	elongation of residual plastic wedges
LEFM	linear elastic fracture mechanics	ΔK	stress intensity factor range ($K_{max} - K_{min}$)

re-sharpening of the crack-tip under minimum load is widely used to explain fatigue crack growth under cyclic loading [10]. It was also shown by various authors that there is a relationship between the striation spacing (related to the amplitude of crack tip blunting over a full fatigue cycle) and the crack growth rate [11,12]. Tvergaard [13], Hunnell and Kujawski [14] and Toribio and Kharin [15] numerically modelled crack tip blunting and re-sharpening in order to predict FCGR. Pommier and Risbet [3] studied the plastic blunting in order to predict da/dN. The rate of plastic blunting, $d\rho/dt$, was used to characterize the crack tip plasticity, which was one of the mechanisms considered for energy dissipation. The blunting was considered a global state variable which characterized specifically the development of crack tip plasticity.

The objective here is therefore to study the main mechanisms associated with crack closure, which are expected to be the formation of residual plastic wake and the crack tip blunting. A numerical study was developed considering different load patterns, namely overloads and load blocks. The validity of partial closure concept was also tested by calculating non-linear crack tip parameters.

2. Numerical model

A Middle-Tension specimen was studied, having $W = 60$ mm and a small thickness ($t = 0.2$ mm) in order to obtain a plane stress state (Fig. 1a). A straight crack was modelled, with an initial size, a_o, of 5 mm ($a_o/W = 0.083$). The specimen is symmetric about three orthogonal planes and therefore only 1/8 was simulated considering proper boundary conditions (Fig. 1b and d). Pure plane strain state was also modelled constraining out-of-plane deformation (Fig. 1c). The material considered in this research was the 6016-T4 aluminium alloy ($\sigma_{ys} = 124$ MPa). Since plasticity induced crack closure (PICC) is a plastic deformation based phenomenon, the hardening behaviour of the material was carefully modelled. Three types of mechanical tests were performed to model the hardening behaviour: uniaxial tensile tests, and monotonic and Bauschinger shear tests [16]. From the experimental data and curve fitting results, for different constitutive models, it was determined that the mechanical behaviour of this alloy is better represented using an isotropic hardening model described by a Voce type equation:

$$Y = Y_0 + R_{sat}(1 - e^{-n_v \bar{\varepsilon}^p}) \tag{1}$$

combined with a non-linear kinematic hardening model described by a saturation law:

$$\dot{X} = C_x \left[X_{sat} \frac{(\sigma' - X)}{\bar{\sigma}} - X \right] \dot{\bar{\varepsilon}}^p \tag{2}$$

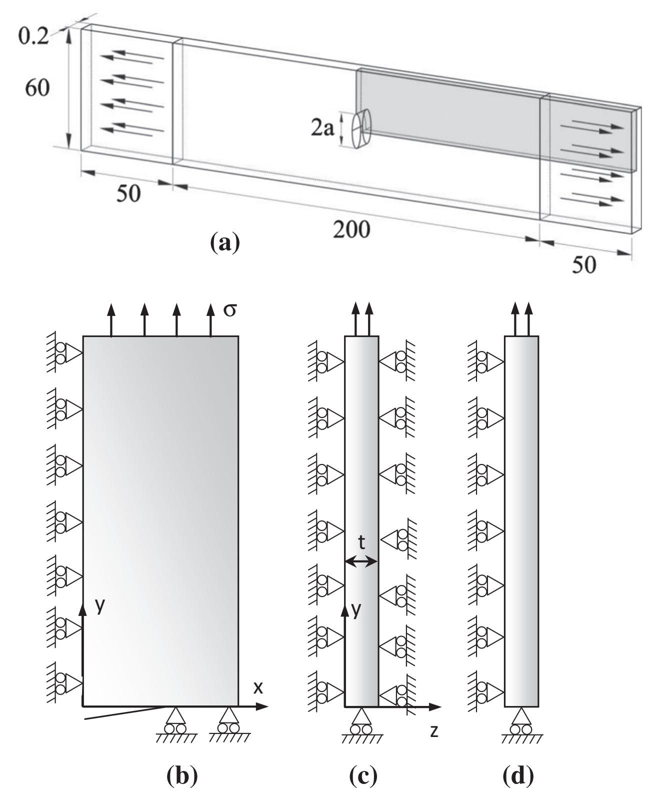

Fig. 1. (a) Middle-tension, $M(T)$, specimen. (b) Frontal view. (c) Plane strain state. (d) Plane stress state.

In previous equations Y is the equivalent flow stress, $\bar{\varepsilon}^p$ is the equivalent plastic strain, Y_0 is the initial yield stress, R_{sat} is the saturation stress, n_v, C_x and X_{sat} are material constants, $\boldsymbol{\sigma}'$ is the deviatoric stress tensor, X is the back stress tensor and $\dot{\bar{\varepsilon}}^p$ is the variation rate of equivalent plastic strain rate. The material constants determined for the batch of material in study, that were used in the numerical simulations, were: $Y_0 = 124$ MPa, $R_{sat} = 291$ MPa, $n_v = 9.5$, $C_x = 146.5$ and $X_{sat} = 34.90$ MPa [16]. An anisotropic yield criterion was considered, which is expressed by the quadratic function:

$$F(\sigma_{yy} - \sigma_{zz})^2 + G(\sigma_{zz} - \sigma_{xx})^2 + H(\sigma_{xx} - \sigma_{yy})^2 + 2L\tau_{yz}^2 + 2M\tau_{zx}^2 + 2N\tau_{xy}^2 = 1 \tag{3}$$