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A numerical study of plasticity induced crack closure under plane strain conditions

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ABSTRACT

The level of plasticity induced crack closure (PICC) is greatly affected by stress state. Under plane strain conditions, however, the level and even the existence of PICC still are controversial. The objective here is to study the influence of the main numerical parameters on plane strain PICC, namely the total crack propagation, the number of load cycles between crack increments, the finite element mesh and the parameter used to quantify PICC. The PICC predictions were included in a parallel numerical study of crack propagation, in order to quantify the impact of plane strain values on fatigue life. The results indicate that literature may be overestimating plane strain PICC due to incorrect numerical parameters. The number of load cycles usually considered is unrealistically small, and its increase was found to vanish crack closure, particularly for kinematic hardening. This effect was linked to the ratcheting effect observed at the crack tip. The total crack increment, Δa, must be large enough to obtain stabilized PICC values, but this may imply a huge numerical effort particularly for 3D models. The size of crack tip plastic zone may be overestimated in literature, which means that the meshes used may be too large. Additionally, the crack propagation study showed that the plane strain PICC has usually a dominant effect on fatigue life, and plane stress PICC is only relevant for relatively thin geometries.

1. Introduction

The concept of fracture surface interaction leading to a decrease of stress intensity at the crack tip and to an increase of fatigue life was stated in 1963 [1]. Elber [2,3] discussed the concept in terms of fracture mechanics parameters, promoting a strong research effort into the mechanisms and phenomena associated with fatigue crack closure. Ritchie et al. [4] and Suresh and Ritchie [5,6] identified the main closure mechanisms, which are plasticity induced crack closure (PICC), oxide-induced crack closure and roughness induced crack closure. There is a huge amount of experimental, numerical and analytical work supporting the existence of crack closure and its significant influence on fatigue crack propagation, therefore the design of efficient structures submitted to cyclic loading requires the inclusion of this phenomenon.

The stress state has a major influence on the level of PICC. There is a general agreement that plane stress state has significantly larger levels of crack closure compared with plane strain loading conditions. Ewalds and Furnée [7] measured the crack closure on a centre cracked specimen of 2024-T3 aluminium alloy and then compared the obtained results after a thickness reduction by removing surface layers at both sides of the specimens. The results reported that the crack opening stress dropped significantly after the thickness reduction. Similar results were observed by Matsuoka and Tanaka [8] in a 5083 aluminium alloy. In their work, surface layers were machined away after an overload which resulted in a drastic decrease in the retardation on the fatigue crack growth. Optical interferometry was used by Ray and Grandt [9] employing transparent polymer specimens. Larger amounts of crack closure were observed at surface. Wei and James [10] studied CT specimens with thicknesses of 2 and 10 mm, and measured higher closure values for the thinner geometry. Bao and McEvily [11] studied CT specimens 0.3 and 6.35 mm thick with similar results. Lateral notches were also considered to obtain a plane strain state in a SENB4 specimen [12]. Also the numerical studies showed lower values of PICC for plane strain state compared with the plane stress state [10,13,14]. The difference between plane stress and plane strain states is also evident in 3D numerical analysis [15,16].

The level and even the existence of PICC under plane strain conditions, however, still are controversial. This controversy may explain the less attention paid to crack closure under plane strain

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compared with plane stress [10]. The main problem from the theoretical point of view is to visualise the additional volume of material necessary to explain the PICC, since under plane strain conditions the out-of plane flow is not allowed, by definition. In fact, there are researchers arguing that PICC does not exist (particularly for plain strain conditions), even suggesting that the plastic wake is responsible for crack opening and not for crack closure [17–20]. According to these researchers it is ahead of crack tip that things really happen, while the closure has no effect. The fatigue crack growth is assumed to be controlled by a two parameter driving force, which is a function of the maximum stress intensity factor and total stress intensity range [21,22]. However, Fleck [23] proposed that plane strain PICC may occur by material displacements remote to crack tip. A theoretical explanation was given by Pippan and Riemelmoser [24] by using a dislocation mechanics approach based on the concept of small angle grain boundaries. It was proposed that the dislocation strip in the wake of the crack elastically rotates the crystal below with respect to the crystal above and a missing triangle arises [24,25]. In other words, the material is transported parallel to crack flank towards the crack tip, which was validated numerically [26]. Singh et al. [27] studied an overload situation. The comparison with the undeformed mesh showed that the material had predominantly moved forward from behind the overload location (where blunting has occurred), achieving the volume conservation necessary for PICC to occur in plane strain.

In a large number of studies the existence of plane strain PICC is not being questioned and values are determined for different numerical and physical parameters as they are for plane stress state. The empirical model proposed by Newman [28], for example, included the plane strain state. In some of these studies, however, the authors found no closure in their numerical studies, namely Zhao et al. [14] in a CT specimen, Vor et al. [16] at the center of a 3D CT specimen. On the other hand, Lugo and Daniewicz [29] found closure for positive and negative T-stresses. Parry et al. [30] studied the combined effect of PICC and roughness induced crack closure and obtained $\sigma_{open}/\sigma_{max}$ in the range 0.06–0.4. Values in the region of 0.2–0.3K_{max} have been found by different authors [13,31–33]. Pokluda [34] states that under plane strain $\sigma_{open}/\sigma_{max}$ $\approx$ 0.2–0.25, assuming that the residual stretch associated with the plastic wedge might be nearly compared with crack tip opening displacement. He also says that the contact takes place at a rather close vicinity of the crack tip. Table 1 summarises some of the numerical studies of plane strain PICC, indicating the main numerical and physical parameters. A great diversity of results is evident.

In author's opinion, the numerical parameters affect significantly the numerical predictions and may explain the significant differences observed in literature for plane strain PICC. This influence has not been adequately debated in literature and deserves more attention. So, the objective here is to analyse the influence of main numerical parameters on plane strain PICC, namely the total crack propagation, the number of load cycles between crack increments, the finite element mesh and the parameter used to quantify PICC. The literature was reviewed in detail, in order to discuss and understand discrepancies. The PICC predictions were included in a parallel numerical study of crack propagation, in order to quantify the influence of plane strain values on fatigue life.

2. Numerical procedure

A Middle-Tension specimen with $W = 60$ mm and $t = 0.2$ mm was studied numerically due to the symmetry of the sample and loading conditions, only 1/8 of the $M(T)$ specimen was simulated, by using adequate boundary conditions. The opposite crack surface was simulated by assuming frictionless contact conditions over a symmetry plane placed behind the growing crack front. Pure plane strain conditions were simulated constraining out of plane deformation as Fig. 1 illustrates. A straight crack was modelled, with an initial size a_o of 5 mm ($a_o/W = 0.167$). All the simulations were performed assuming a constant amplitude cyclic loading. Table 2 indicates the load parameters defined in the five sets of constant amplitude tests considered. Sets with constant K_{min}, K_{max}, ΔK and R were studied, as can be seen.

The material considered in this research was the 6016-T4 aluminium alloy ($HV_{0.5} = 92$). Since PICC is a plastic deformation based phenomenon, the hardening behaviour of the material was carefully modelled. In present work, an anisotropic yield criterion [35] was considered, which is expressed by the quadratic function:

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

where σ_{xx}, σ_{yy}, σ_{zz}, τ_{xy}, τ_{xz} and τ_{yz} are the components of the effective stress tensor $(\sigma' - X)$ defined in the orthotropic frame and F, G, H, L, M, N, are coefficients that characterise the anisotropy of the material. In order to model the hardening behaviour of this aluminium alloy, three types of mechanical tests have been performed: uniaxial tensile tests and monotonic and Bauschinger shear tests. 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:

$$Y = Y_0 + R_{sat}(1 - e^{-n_v \bar{\varepsilon}^p}) \quad (2)$$

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

$$\dot{X} = C_x \left[X_{sat} \frac{(\sigma' - X)}{\bar{\sigma}} - X \right] \dot{\bar{\varepsilon}}^p \quad (3)$$

In these 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, σ' is the

Table 1
Literature results for plane strain state.

Ref.	Geom	Load	H	L_1 (µm)	NLC	Δa (mm)	P	$\sigma_{open}/\sigma_{max}$
Pommier [73]	DEC	$\sigma_{max}/\sigma_{ys} = 0.66$ $R = 0$; $R = -1$	Isotropic	$R_p/20$	2	40 inc.	N2	0.07 a 0.27($R = 0$) 0.15 a 0.17 ($R = -1$)
Solanki et al. [13]	CT, $M(T)$	$K_{max}/\sigma_{ys} = 1.07$ mm$^{-0.5}$ $R = 0$	EPP		1			0.15–0.25 (CT)
Zhao et al. [14]	CT	$\sigma_{max}/\sigma_{ys} = 0.25$–0.35	Chaboche, EPP	12.7	2	6	N2	No
Zapatero et al. [78]	CT	$K_{max} = 10$–30; $R = 0.1$, 0.3, 0.5	Isotropic, linear	$R_p/30$	1	>0.1R_p	tt, N1	0.2–0.9
Singh et al. [82]	$M(T)$	$\Delta K = 4.6$, $R = 0$,	Kinematiclinear	2	2	1		0.075
Vor et al. [16]	CT	$\Delta K = 12$, 15, 18	Chaboche	50	15	1.5	N1	No

P (PICC parameter): C – compliance, TT – tip tension; N1 – Node 1; N2 – Node 2; and tt – tip tension.
H (hardening model): EPP – elastic-perfectly plastic, BL – Bilinear; and K – pure kinematic hardening.