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Effect of compressive loads on plasticity induced crack closure

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ABSTRACT

Compressive stresses play an important role on tension–compression fatigue which can be attributed to plasticity induced crack closure (PICC). The objective here is to study numerically the effect of compressive stresses on PICC and to discuss the applicability of PICC to explain the effect of negative stress ratios on fatigue crack growth rate. The compression produces reversed plastic deformation at the crack tip, reducing linearly the crack opening level. The incursion to negative stress ratios did not produce sudden changes in the behavior of PICC and no saturation with the decrease of minimum load was observed for ΔK_{eff}. Crack closure was able to collapse $da/dN–\Delta K$ curves with negative stress ratios, indicating the applicability of the crack closure concept to explain the effect of negative R. The analysis of crack tip plastic strain range with and without contact of crack flanks confirmed the validity of crack closure concept.

1. Introduction

In fatigue studies involving compressive loads, only the tension portion of the stress–time history is usually considered. Therefore, in a tension–compression loading, the stress intensity factor range (ΔK) is assumed to be equal to the maximum stress intensity factor (K_{max}) and the fatigue crack growth (FCG) rate is usually plotted as a function of K_{max} [1,2]. Also Kujawski [3,4] only considered the positive portion of the load cycle (ΔK^{+}) to define crack driving force parameters. In fact, under compression, the crack is supposed to be fully closed and no stress concentration occurs at the crack tip. This means that the stress intensity factor concept loses its physical meaning. However, the compressive stresses are known to play an important role on fatigue behavior.

Three typical loading patterns involving compressive stresses may be identified in literature: fully compressive cyclic loading, tension–compression cycles and compressive underloads. In compression–compression loading, cracks were found to nucleate and grow up to a certain crack length [5–7]. This was explained by a tensile residual stress field produced by the cyclic loading at the initial crack tip position. The notch profile has a great influence on this residual stress. In fact, the application of compression–compression load cycles was found to be the best way to initiate fatigue cracks in brittle materials, like hardmetals [8]. In tension–compression tests, the effect of the negative portion of the loading cycle has been widely studied [9–11]. According to Silva [1], there are materials for which the negative loads do not substantially interfere in crack propagation, such as 7175 aluminium and Ti6Al4V titanium alloys, while for others (such as ck45 steel) the compressive load substantially changes crack propagation. Carlson and Kardomateas [12] presented results for three alloys. It was clear that the crack growth rate was higher for $R = -2$ than for $R = 0.1$. Kujawski et al. [13] showed that the compressive loads decreased the fatigue life of their test specimens by about 300%. Iranpour and Taheri [14] showed that even the presence of few compressive load cycles could significantly affect the fatigue life of the material. Pommier et al. [15] observed that for a N18 superalloy there is a strong compressive loading effect on the fatigue crack propagation rate. They also pointed out that the effect of R strongly depends on material. A material displaying significant Bauschinger effect should be highly sensitive to compressive stress ratios. Tack and Beevers [16], working with three different steels and $-2.5 \leqslant R \leqslant 0.1$, observed the effect of compressive stresses on crack propagation and also that this effect may be subject to a saturation phenomenon. Zhang et al. [17] also observed a strong difference between $da/dN–\Delta K$ curves obtained for $R = 0$ and $R = -1$, but a very small difference between $R = -1$, -2 and -3. The size of reversed plastic zone accomplished this trend, i.e., only increased significantly between $R = 0$ and $R = -1$. In summary the fatigue crack growth rate (FCGR) cannot be correlated with ΔK, calculated based on the tensile stress range only.

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Nomenclature

a	crack length
a_0	initial crack length
da/dN	crack growth per load cycle
FCG	fatigue crack growth
FCGR	fatigue crack growth rate
K	stress intensity factor
K_{min}, K_{max}	minimum and maximum stress intensity factor
K_{open}	crack opening stress intensity factor
L_1	radial size of crack tip elements
$M(T)$	middle-tension specimen
PICC	plasticity induced crack closure
P_{op}	crack opening load
R	stress ratio (=K_{min}/K_{max})
RICC	roughness induced crack closure
t	specimen's thickness
U	fraction of load cycle for which the crack remains fully open
y	vertical distance to crack flank
Δa_i	extent of individual crack increment
ΔK	range of stress intensity factor
ΔK_{eff}	effective range of stress intensity factor
ΔK^+	positive range of stress intensity factor
Δy_p	vertical plastic elongation of material
$\varepsilon_{yy,p}$	vertical plastic strain
σ_{ys}	material's yield stress
σ_{tip}	crack tip stress along the loading direction
σ_{min}, σ_{max}	minimum and maximum stresses
σ_{maxcom}	maximum remote compressive stress
σ_{open}	crack opening stress

Different approaches have been proposed to account for the effect of compressive stresses on fatigue crack propagation. Based on the size of the reversed plastic zone, Zhang et al. [17–19] developed a fatigue crack propagation model under tension–compression loading as follows:

$$\frac{da}{dN} = C\left(1 - \gamma\frac{\sigma_{maxcom}}{\sigma_{ys}}\right)^{\beta} K_{max}^{2(\alpha+\beta+1)} \quad (1)$$

where C, α, β and γ are constants, σ_{maxcom} is the maximum remote compressive stress and σ_{ys} is material's yield stress. Benz and Sander [20] proposed the crack tip stress along the loading direction, σ_{tip}, as a control variable in FCG tests, instead of σ_{maxcom}. σ_{tip} is determined from elastic analysis and quantifies the compressive loading at the crack tip for arbitrary geometries and loading conditions. Models based on both ΔK and K_{max}, although not new, are gaining a new acceptance by the scientific community [21,22]. They seem to properly predict crack propagation, even when compressive loads exist [21]. However, as already mentioned, the models proposed by Kujawski [3,4] only consider the positive part of ΔK, assuming that the negative part does not contribute to crack growth. Noroozi et al. [23] pointed out that Kujawski's models are strictly empirical and cannot explain the influence of the compressive part of the load history on FCG. They studied the influence of loading parameters on FCG using an elastic–plastic crack tip stress–strain history. Their study demonstrated that the FCG was controlled by a two parameter driving force, which was a function of ΔK and K_{max}. In their investigation, the difference in the stress–strain concentration at the crack tip associated with the compressive part of the loading cycle was taken into account.

The effect of the compressive loads has been linked to roughness induced (RICC) and plasticity induced crack closure (PICC). Lower closure loads are measured for negative stress ratios, which are consistent with the higher crack growth rates observed. Negative opening loads can even be found [1,15,24,25]. Fonte et al. [2] studied a wide range of stress ratios ($-3 < R < 0.7$) and obtained a decrease of fracture surface roughness for negative stress ratios. The fracture surface is plastically deformed by the compressive load, which reduces the roughness and consequently the crack closure level increasing ΔK_{eff}. However, the compressive loading does not necessarily reduce the fracture surface roughness [14]. Therefore, the effect of compression cannot only be associated with RICC. Carlson and Kardomateas [12] and Pommier et al. [15] attributed the higher crack propagation rates to PICC. In fact, Borrego et al. [26] explained the variation of da/dN for R within 0.4 and -0.25 using plasticity induced crack closure. Schijve [27], de Koning [28], Newman [29], Lang [30] and Meggiolaro et al. [31] proposed empirical expressions for crack opening level which included negative stress ratios. However, Silva [1] stated that neither PICC nor RICC are able to explain all the variations of da/dN–ΔK observed experimentally.

In sum, there is a general agreement about the influence of the compressive portion of the load cycles on FCGR, however there is no agreement among researchers regarding the magnitude of this influence, the adequate models or the mechanisms behind the phenomenon. The objective here is to contribute to this debate, from the perspective of plasticity induced crack closure. The effect of compressive stresses on PICC and crack tip parameters is calculated, and the applicability of PICC to explain the effect of negative stress ratios on FCGR is discussed. A numerical model was developed to predict PICC which was applied for load cases with different values of minimum load. Note that a large number of numerical studies have been developed focused on PICC, however less effort has been made in the understanding of crack closure mechanisms at negative stress ratios. This may be attributed to the general agreement that the negative part of the cycle has a negligible effect of FCGR. The works of Wei and James [32] and Pommier [33] are relevant exceptions.

2. Numerical procedure

In order to study the effect of the compressive stresses on plasticity induced crack closure, a three-dimensional elastic–plastic model was developed. The geometry selected was a standard $M(T)$ specimen (see Fig. 1). Only 1/8 of this specimen was simulated considering adequate boundary conditions. A small thickness was

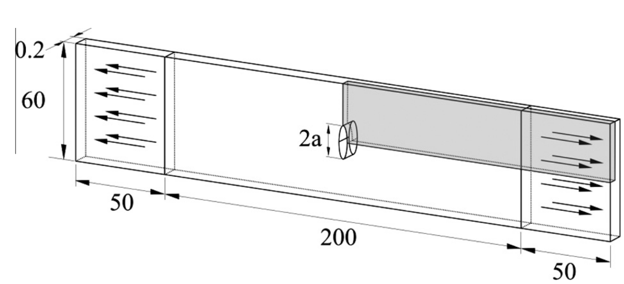

Fig. 1. Middle-tension, $M(T)$, specimen.