Influence of crack micro-roughness on the plasticity-induced fatigue propagation in high strength steel

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ABSTRACT. This article deals with the locally multiaxial fatigue behaviour of high strength steel. To this end, the influence of the cracking path deflections (at the micro level) on the plasticity-induced fatigue crack growth is analyzed. With regard to this, a modelling by means of the finite element method was performed for a given stress intensity factor in the Paris regime, considering the existence of micro-roughness in the crack path (local micro-deflections with distinct micro-angles as a function of the microstructure of the material). The numerical results allow one to obtain the fatigue crack propagation rate and compare it with that for the same material in the absence of micro-roughness (with no micro-crack deflections, i.e., uniaxial fatigue behaviour).

KEYWORDS. Crack tip; Micro-roughness; Crack deflection; Plasticity-induced fatigue crack propagation; Finite element method.

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INTRODUCTION

Fatigue cracks exhibit surface micro-roughness caused by material microstructure, e.g., pearlitic steel shows continuous deflections in the fatigue crack path [1]. The non-linear crack configuration should be taken into account in the matter of crack-morphological aspects in fracture mechanics [2], since variations in crack deflection features influence considerably the fatigue crack propagation rates and threshold stress intensity factor range [3]. Elastic-plastic finite element simulations of growing fatigue cracks are used to study the plastic crack advance and the so-called crack closure phenomenon. With regard to *plastic crack advance*, the Laird-Smith mechanism of propagation by cyclic blunting and re-sharpening, which transfers material from the crack tip towards its flanks, is visualized in [4]. With this sort of modeling procedure, the rate per cycle reproduced common trends of the fatigue cracking dependence on loading range and overload [5]. Paris-like equations obtained from the numerical modeling of plastic crack advance showed good agreement with experimental results [6]. In the matter of *plasticity-induced fatigue crack closure*, a strong controversy still does exist, with researchers raising doubts about its mere existence [4,5], and others obtaining it as a numerical result [7], although the total length of closed crack at minimum load in plane strain is shown to be a small fraction of the total crack length [8].

NUMERICAL PROCEDURE

For the study of fatigue propagation by plastic crack advance, a numerical simulation by the finite element method (FEM) under small scale yielding (SSY) was performed using the MSC.Marc software (nonlinear finite element code). Material was characterized as elastic–perfectly-plastic and the von Mises yield criterion was employed to define the plastic zone in the vicinity of the crack tip. Large strains and large geometry changes were used with an updated lagrangian formulation. Material properties (Young's modulus E=200GPa, yield strength σ_Y=600MPa and Poisson coefficient ν=0.3) were those associated with a typical high-strength steel.

The geometry used in the computations is a symmetric double-edge-cracked panel under remote tension fatigue (Fig. 1). The undeformed crack was a parallel-flanks slot, where the kink length l_0 (representing 0.0012 times the total crack length) is deflected an angle α_0 (Fig. 2) and exhibits a semicircular shape (smooth blunting [9]) with b_0=5μm, i.e., 0.055l_0. Four-node isoparametric quadrilateral elements (for plane strain applications) were used. Finally, a convergence study was performed to determine the optimal finite element mesh size and the most adequate number of steps required in the computations.

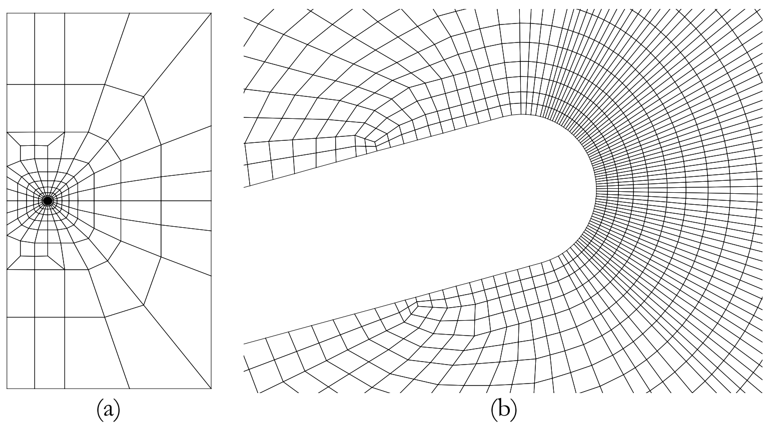

Figure 1: Finite element mesh: (a) general view; (b) crack tip.

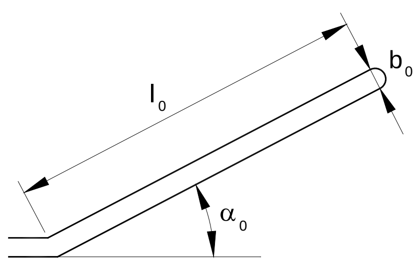

Figure 2: Scheme and dimensions of the deflected crack kink.

The key variable analyzed in this research work is the deflection angle of the kink in relation to the main crack. The four values α_0=0, 15, 30 and 45° were used. The stress intensity factor (SIF) range used in the numerical procedure was ΔK=25MPam$^{1/2}$ (associated with the Paris regime of fatigue crack propagation).

NUMERICAL RESULTS

Fig. 3 shows the cumulative equivalent plastic strain in the deformed geometry of the cracked solid with the deflected crack kink after the main crack. The initial geometry of the solid before loading (*initial crack profile*) is also shown. Results are obtained after applying 20 loading cycles (fatigue) with ΔK=25MPam$^{1/2}$.

It is observed how the crack, independently of the deflection angle, tends to propagate in mode I when subjected to remote mode I (opening) tensile loading. In addition, the distribution of cumulative equivalent plastic strain becomes more non-symmetric and exhibits more elevated values as the kink deflection angle increases.

The crack deflection provokes a retardation effect in fatigue crack growth in global mode I, this effect being more pronounced for elevated deflection angle, as shown in Fig. 4.

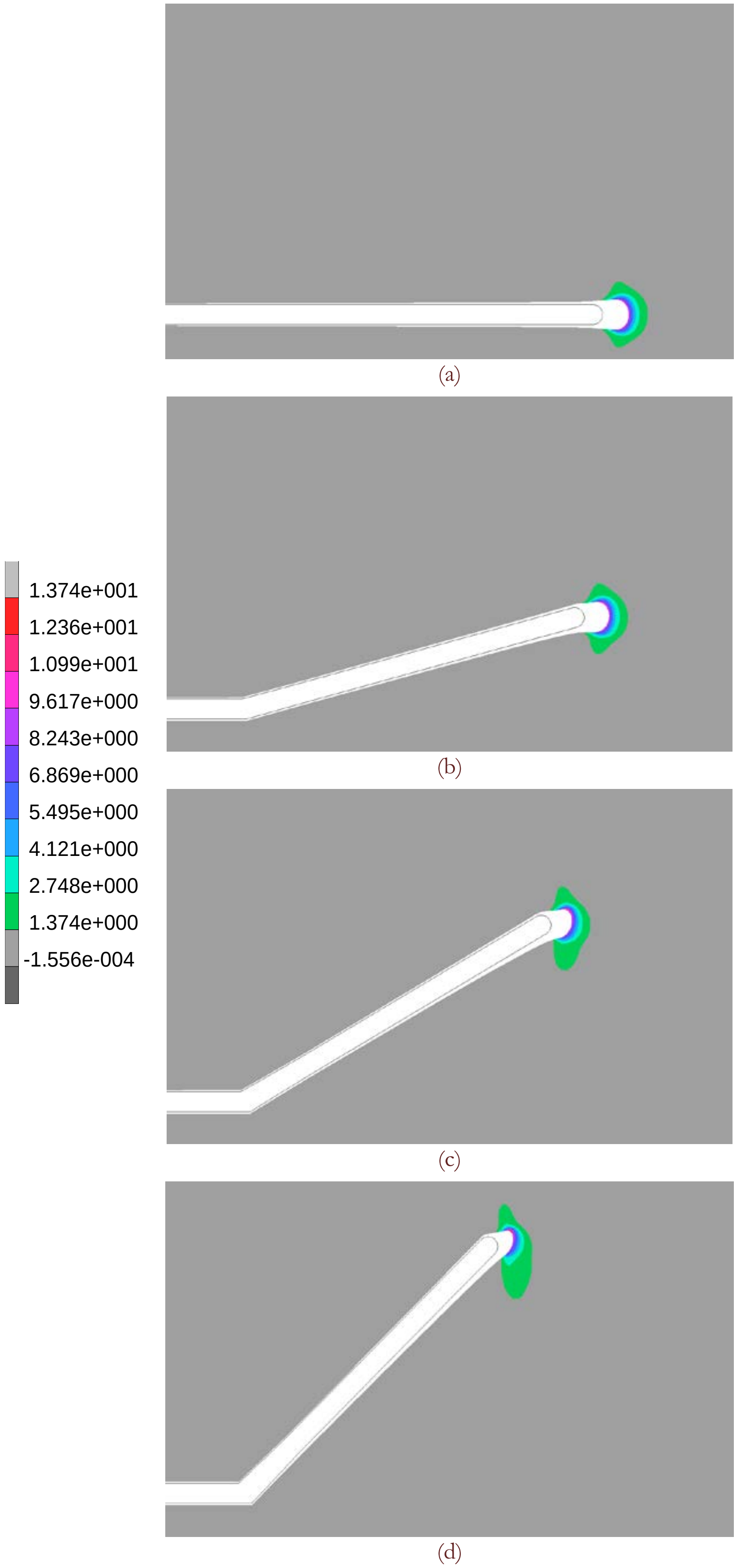

Figure 3: Cumulative equivalent plastic strain for ΔK=25MPam$^{1/2}$: (a) α_0=0º; (b) α_0=15º; (c) α_0=30º; (d) α_0=45º.

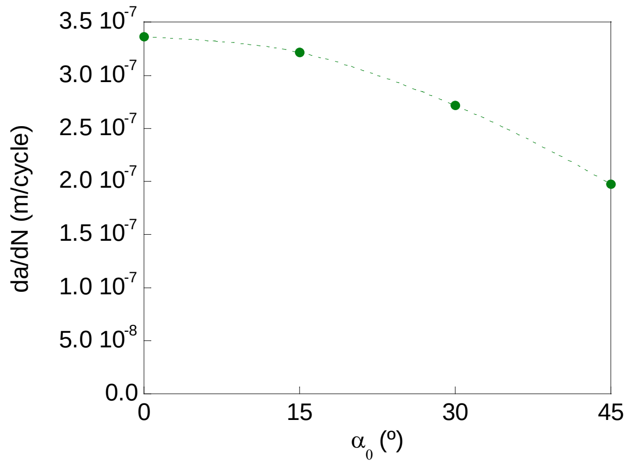

Figure 4: Fatigue crack growth rate as a function of the deflection angle of the kink.

CONCLUSIONS

Cracks with a deflected kink in a plate subjected to remote tensile loading exhibit plastic crack advance in mode I with retarded fatigue crack growth when compared with a fully straight crack (with no kink). The increment of the crack deflection angle increases the retardation effect.

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