PLASTICITY-INDUCED FATIGUE CRACK CLOSURE IN HIGH-STRENGTH STEELS: REALITY OR ARTIFACT?

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ABSTRACT

Finite-deformation elastoplastic analyses of cracks subjected to mode I cyclic loadings at various load ranges and ratios, as well as with an overload, are presented focusing the evolutions of the near tip deformations. The results manifest the ambiguity of common justifications concerning fatigue crack closure (FCC) as the universal and intrinsic governing factor of fatigue crack growth. The Laird-Smith conceptual mechanism of cyclic crack advance by means of material transfer from the crack tip towards its flanks is visualised, but no crack closure is detected, and its supposed origin in the filling-in a crack with material stretched out of crack plane behind the tip is discarded. Nevertheless, the rate of cyclic crack growth (numerically computed) reproduces the key experimental trends of fatigue cracking concerning the roles of ΔK and overload. In addition, calculated compliance curves always manifest nonlinearity, also despite of the absence of closure, which raises serious doubts about their reliability as a method to detect and evaluate crack closure.

RESUMEN

Se presenta un análisis elastoplástico en grandes deformaciones de fisuras bajo solicitación cíclica en modo I a distintas amplitudes y asimetrías de carga, y también con una sobrecarga, con énfasis en las deformaciones en torno al extremo de la fisura. Los resultados manifiestan la ambigüedad de las justificaciones comunes del cierre de fisura por fatiga (CFF) como el factor intrínseco y universal que gobierna el crecimiento de fisuras por fatiga. Se visualiza el mecanismo conceptual de Laird-Smith de avance cíclico de la fisura mediante traslado de material desde su punta hacia sus caras laterales, sin detectar indicios de cierre de la misma, y descartando el relleno de material deformado situado fuera del plano de la misma como supuesto origen de dicho cierre. Sin embargo, la velocidad de crecimiento cíclico de la fisura (calculada numéricamente) reproduce las tendencias experimentales clave de la fisuración por fatiga en cuanto a los efectos de ΔK y de la sobrecarga. Además, las curvas de flexibilidad calculadas siempre manifiestan no-linealidad, también a pesar de la ausencia de cierre de fisura, lo que hace aflorar serias dudas en cuanto a su fiabilidad como método para detectar y evaluar el cierre de fisura.

KEYWORDS: Fatigue, Crack blunting—re-sharpening, Crack closure, Large strains.

1. INTRODUCTION

Plasticity-induced fatigue crack closure (PIFCC) is believed by many to be an intrinsic feature of the fatigue crack growth (FCG) [1], although not everybody involved in fatigue analyses shares this conviction [2-4]. Despite crack closure has been focused for over 35 years of investigations using a range of approaches, since its raising by Elber, neither agreement between measurements by different methods nor consensus of opinions on the relevance, and even the very existence, of the PIFCC in the course of FCG do exist, cf. [1-5].

With the idea of the stress intensity range ΔK as the driving force for FCG, fatigue crack closure (FCC) is usually considered as the physical mechanism directly responsible for the dependence of FCG on K_{max} or load ratio $R = K_{min}/K_{max}$, as well as on over- or underload, forming thus a framework to interpret many FCG effects. The crack closure due to various possible sources (incidental ones, such as in-crack debris, oxides or other chemical in-crack depositions and crack surface roughness, or ubiquitous such as crack-tip plasticity) is apparently out of doubts as a phenomenon potentially accompanying FCG under certain conditions. However, specifically PIFCC still is quite dubious as a universal intrinsic mechanism responsible for a variety of aspects of fatigue. A great deal of uncertainty owes here to the difficulties of direct detection of closure, which is evaluated subtly either making deductions from the FCG data (i.e., postulating *a priori* the role of supposed closure in the process) or interpreting the compliance curves obtained with clip gauges, strain gauges or other load-deformation measurements [1,5]. This way, the very identification of PIFCC lacks of convincing proofs, and its responsibilities in FCG remain debatable.

With regard to this, analysis of fine peculiarities of the crack tip displacement, stress and strain fields is essential for unveiling the really relevant factors of

FCG, as well as for understanding the behaviour of cracks through linking pertinent mechanical fields with the mechanisms of local damage and crack advance. Since *in situ* measurements of the mechanical variables of interest are hardly feasible near the crack tip, computational simulation is the right way to determine them. With regard to this, accounting for both physical (inelasticity) and geometrical (large deformations) nonlinearities is essential for realistic implications for fracture. Up to date, among available analyses of cracks, some, including comprehensive ones [6,7], have not accounted for large deformations, whereas others [8-11], although fulfilling this deficiency, have been confined to monotonic loading or presented partial data concerning cyclic one.

This paper offers the results of numerical modelling of the evolution of deformations at the crack tip subjected to mode I cyclic loading under plane strain and small-scale yielding (SSY) with the aim to clarify some aspects relevant to crack behaviour in metals and alloys in fatigue. Thus it is intended to contribute to "purify the responsibilities" and advance towards resolution of some long-standing controversies, such as, about the crack blunting—re-sharpening behaviour at load cycling, the crack closure or the sources of the overload effect in FCG.

A typical medium-high strength steel was taken as a model material in the computations. However, using normalisation techniques, the generated elastoplastic solutions are applicable not only to a particular material but to a similitude class of situations fixed by the magnitudes of pertinent dimensionless parameters, such as the ratio of Young modulus E to the yield stress σ_Y, Poisson coefficient ν, and so on.

2. MODELLING

At large strains, material hardening approaches saturation, so that elastic—perfectly-plastic constitutive model can be an acceptable approximation, provided the value of its key parameter σ_Y corresponds not to the initial yield point in a tension test, but to some saturation stress level (the "effective" yield stress as modified by strain-hardening). The model of ideal elastoplastic solid having E = 200 GPa, ν = 0.3 and σ_Y = 600 MPa with von Mises yield criterion and associated flow rule was chosen. Neither damage accumulation (apart from plasticity) nor crack growth by bond breaking (decohesion) was involved.

The model of undeformed crack was a parallel-flanks slot of the width b_0 = 5 μm and semicircular tip, as substantiated elsewhere [9]. Analysed test-pieces — edge- and centre-cracked plates— and loadings were mainly such as justified and used in previous studies [9,11] with special care to ensure the SSY and employment of the stress intensity factor K as the reasonable controlling parameter of the near tip situation (K-dominated crack tip autonomy).

The simulations were performed for constant amplitude loading patterns at different load ranges ΔK and ratios R, and the effect of a single overload was considered, too. The simulated load cases consisted of up to ten loading-unloading cycles along the patterns as follows:

(I) $\Delta K = K_0$, $R = 0$;

(II) $\Delta K = 2K_0$, $R = 0$;

(III) $\Delta K = K_0$, $R = 0.5$;

(IV) $\Delta K = K_0$, $R = 0$, with an overload to $K_{ov} = 2K_0$ in the sixth cycle,

with the reference value K_0 = 30 MPa√m, which renders the loading regimes when fatigue cracking usually goes on in steels [2,12].

Large-deformation elastoplastic solutions were obtained using a nonlinear finite element code with updated lagrangian formulation as described elsewhere [9]. The mesh design followed the guidelines from the previous studies of large near-tip deformation under monotonic and cyclic loadings [8,9], and the optimum one was formed by bi-linear quadrilateral elements with the size of the smallest near tip ones $0.02b_0$.

3. RESULTS

For all test-pieces and load cases, displacements near the crack tip evolved similar to what is shown in Fig. 1, where cyclic crack blunting and re-sharpening is obvious, as well as crack growth Δa_p is seen as a movement of the tip apex A_0 with respect to its initial location, which goes on by plastic deformation without bond breaking.

Although the crack upon unloading acquires here a keyhole shape shrinking in a wake behind the tip (Fig. 1d), deformed crack width b_t never and nowhere returns to the initial value b_0. That is, plastic crack growth does go on, but no crack closure takes place. This contradicts the results of small-displacement simulations [6] in which, however, bond breaking was involved.

Fig. 2 displays this plastic crack advance Δa_p in terms of a time-like parameter t (it was taken for convenience to render sine-waveform applied load paths shown there, too). The inferior straight-line envelopes for the $\Delta a_p(t)$-patterns mark there resulting crack advancement. Their slopes render corresponding magnitudes of the rate of plastic crack growth $(da/dN)_p$. Along constant-amplitude loading periods this rate appears to be a function of ΔK, whereas the role of R (or K_{max}) is indiscernible. Calculated $(da/dN)_p$ values are of the order of 10^{-6} m/cycle, which is proper for the Paris regime in steels [2,12]. The Paris-like equation

$$\left(\frac{da}{dN}\right)_p = const \cdot \ddot{A}K^m \qquad (1)$$

may be fitted with generated numerical results at m = 2.15, which is reasonable for many alloys [12].

It is worth emphasising that this deformation-only mode of crack extension is sensible to an overload, which halts simulated crack advance (Fig. 2d).

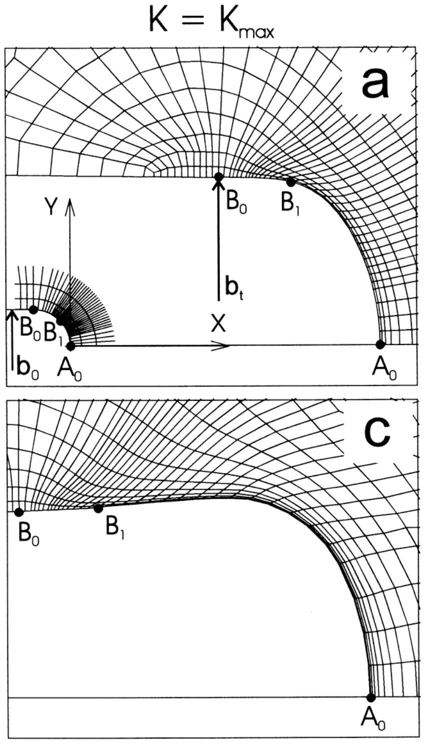

Fig. 1. Crack tip deformations in the double-edge-cracked panel at $K_{\max}$ and $K_{\min}$ (unloading) of the first (a,b) and the fifth (c,d) cycle of the loading route II. Undeformed tip contour is seen in the bottom-left corners in (a,b,d), and the undeformed mesh fragment is shown in (a).

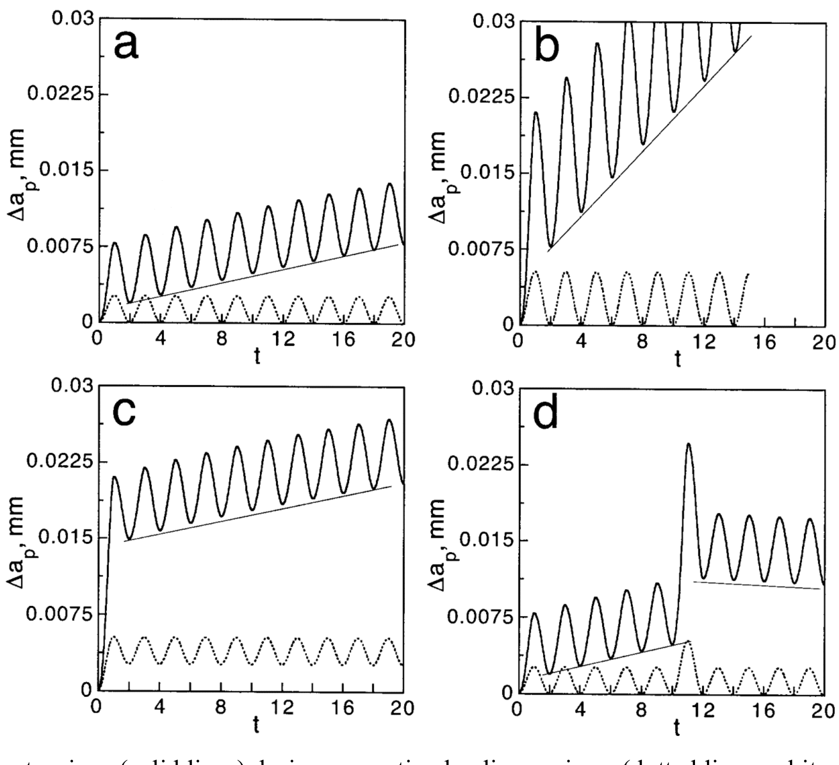

Fig. 2. Plastic crack extensions (solid lines) during respective loading regimes (dotted lines, arbitrary units).

4. DISCUSSION

Performed simulations evidence cyclic plastic crack growth. As a matter of fact, Fig. 1 visualises the Laird-Smith conceptual scheme of FCG in ductile materials by blunting and re-sharpening [12, p.198], whereas Fig. 2 represents the effects of ΔK and overload, which are consistent with experimental trends of FCG [2,12]. No signs of PIFCC have ever been detected, so, it must be neither a necessary requisite nor a decisive factor for such FCG trends.

Despite agreement between modelling and experimental trends, we are far from claiming that the Laird-Smith plastic advancement is the whole mechanism of FCG, since this inevitably involves material damage and breaking driven by the stress-strain evolution in the process zone, so that FCG proceeds by mechanisms of deformation and damage which go on simultaneously. However, this can convert the "measurements" of PIFCC from FCG behaviour into an *artifact,* since plastic advancement, being the clearly ubiquitous contributor to FCG (although with greater or less share), behaves itself in agreement with known experimental FCG trends with no aid of PIFCC.

Moreover, deformed meshes in Fig. 1 reveal the way of FCG by means of material transfer from the crack front onto lateral faces of the crack, as is seen in a neighbourhood of the material point B_1. There material "bricks" initially situated a little bit aside the top A_0 of the arc $B_0B_1A_0$, which shapes undeformed tip, move sideways forming crack flank increments. These are also enlarged by stretching in the in-plane of the crack direction with large strain $\varepsilon_{XX} > 0$ (Fig. 3).

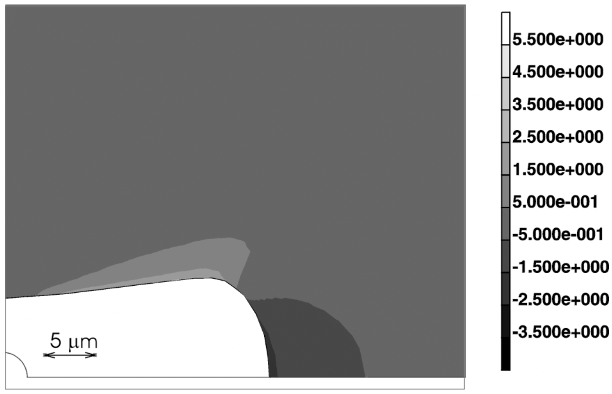

Fig. 3. Distribution of plastic strain ε_{XX}^{p} at the end of the sixth cycle of the route II in deformed solid configuration (original tip is in the bottom-left corner).

Computed displacement and strain fields (Figs. 1 and 3) not only reveal the way of crack extension but also discard the mechanism of PIFCC suggested from small-strain modelling [6], that stretching of material elements in the direction normal to the crack plane behind the tip can fill-in the crack with deformed material, and this way produce PIFCC at unloading. This comes out from the data (see scheme in Fig. 4a) that out-of-plane elongation of material elements under plane strain incompressible plasticity left on the crack faces behind the tip at unloading $\varepsilon_{yy}^{p} > 0$ and $\varepsilon_{xx}^{p} \approx -\varepsilon_{yy}^{p} < 0$. However, these results contradict to Figs. 1 and 3, which manifest that this mechanism turns out to be not operative when large displacements, and rotations in particular, of material elements are taken into account.

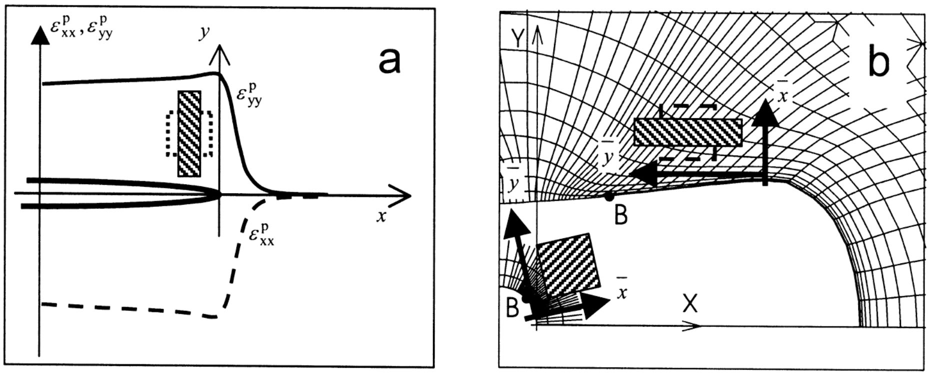

Fig. 4. Schematics of the small-deformation analysis results [6, Fig. 8] to rationalise the mechanism of PIFCC showing where from material supposedly comes to fill-in the crack, in (a), *vs.* the large-deformation simulation results showing where to material goes to make the crack growing ahead, in (b).

Indeed, the results of small- and large-deformation analyses concerning the near tip strains are not so contradictory one to another in terms of deformations of material elements near the tip contour with respect to local frames $(\bar{x}, \bar{y})$, which are formed by material points and move together with the material elements, as shown in Fig. 4b. Considering there near-tip material "bricks" having their local coordinates $(\bar{x}, \bar{y})$ in the undeformed configuration nearly collinear with the global spatial coordinates (X,Y), these local material frames at large deformations rotate together with their material carriers to about 90º. That is, in local material frames $(\bar{x}, \bar{y})$ the strains on the crack faces behind the tip evidently are $\varepsilon^{p}_{\bar{y}\bar{y}} > 0$ and $\varepsilon^{p}_{\bar{x}\bar{x}} < 0$, i.e., they behave similarly to what was obtained in small-deformation modelling [6], where, however, the local material and global spatial coordinates remain always the same. In large deformation analysis they are not, and so, the strain $\varepsilon^{p}_{\bar{x}\bar{x}} < 0$ in local material coordinates transforms into $\varepsilon^{p}_{XX} \approx \varepsilon^{p}_{\bar{y}\bar{y}} > 0$ in global spatial ones for certain material elements near the crack tip (Figs. 3 and 4b). This way, large displacements and rotations in the crack tip vicinity transfer material not to fill-in the crack behind the tip and render PIFCC, but to form extending increments of flanks, i.e., plastic crack advance. This provides the reason to consider an *artifact* the suggested origin of PIFCC.

Generated results bring also doubts concerning the approach based on variation of specimen compliance as an indicator of the very existence and the measure of crack closure [1,5,12], which roots in the idea of the effective crack-length dependence of the specimen elastic compliance. Closure loads are there identified by deviation from linearity in compliance curves "load—deformation (displacement or strain)" as it is schematised in Fig. 5. To this end, all load-displacement and load-strain data from the simulations presented herein displayed compliance variability. The points in Fig. 5 give one example of them calculated for centre-cracked panel, where strain values represent the ε_{YY} results averaged over the area of virtual strain gauge of the size about 0.1x0.2 mm placed 0.2 mm ahead of the tip. Processing in conformity with the slope variation method used in "measurements" of PIFCC (Fig. 5), these simulated compliance curves can render certain values of supposed crack closure, which, however, has never occurred in the simulations, but cyclic crack extension did take place, as it has been already pointed out. Therefore, compliance-based "evidences" of crack closure can become *artifacts*, in particular, with regard to PIFCC.

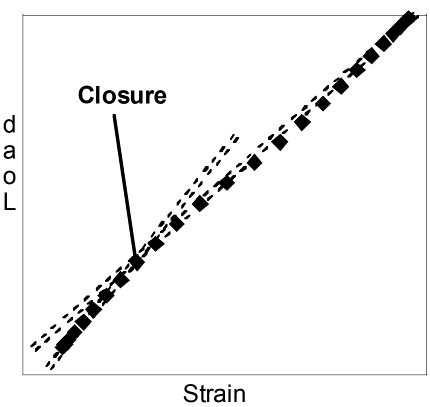

Fig. 5. Simulated local compliance curve (points) and its processing according to the slope variation approach to identify the event of supposed crack closure.

As a final remark about the idea of closure as the intrinsic factor and key rationale for FCG trends concerning the roles of ΔK and K_{max}, variable load amplitude, over- or under-load peaks, etc. [1,12], stress-strain data from previous elastoplastic simulations [11] evidenced that both ΔK and K_{max} affect substantially the near tip stresses and plastic strains, whose evolutions manifest affinities with experimental trends of fatigue cracking as to the role of ΔK, K_{max} and the overload. This brings a support to the idea [2-4] that FCG must be governed by stress and strain fields ahead of the tip, apparently via their control over the really intrinsic process constituents — damage accumulation and rupture (bond-breaking) under definite stress-strain fields, so that the resulting FCG process becomes a *two-parameter* one in terms of fracture mechanics variables ΔK and K_{max}. This way, cyclic stress and strain states ahead of the tip acquire the importance of the intrinsic factors of FCG, whereas crack closure of various origins turns out to be an extrinsic factor [2], which may sometimes be an accompanying, but neither ubiquitous nor decisive one.

5. CONCLUSIONS

High-resolution elastoplastic simulations of plane-strain tensile crack in medium-high strength steels under cyclic loading were performed addressing the effects of the load range, ratio and overload on the crack tip deformations.

Generated results visualised plastic crack growth by means of material transfer from the crack tip towards its flanks, but no signs of plasticity-induced fatigue crack closure (PIFCC) were detected. However, this calculated plastic crack growth itself reproduced the key features of fatigue cracking concerning the role of ΔK and the arrest by overload. This raises reasonable doubts concerning the exclusive responsibility of closure for the mentioned effects, as well as this questions the deductions about hypothetical crack closure derived from the crack growth data.

Moreover, simulations discarded the supposed mechanism of crack closure due to out-of-plane stretching of material elements filling-in the crack and coming in contact at unloading, which was justified earlier by small-deformation simulations. It was shown that this elongation of material elements, accompanied with large displacements and rotations, contributes to the enlargement of crack, but not to its closure. This mode of crack growth during cyclic loading merely by plastic deformation without bond breaking provides visualisation of the Laird-Smith physical concept of fatigue cracking by blunting—re-sharpening.

All simulated specimen compliance curves, both local and global ones, turned out to be nonlinear merely because of crack tip plasticity without any hypothetical contribution of crack closure, which clears off the reasons for the detections and evaluations of crack closure from the compliance changes registered in experiments, bringing them a great deal of uncertainty.

This way, generated results manifest the ambiguity of main justifications about the crack closure as the governing factor of key importance for fatigue crack growth.

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