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# Numerical simulation of fatigue plasticity-induced crack closure for through cracks with curved fronts

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The plasticity-induced crack closure of through-thickness cracks, in CT specimens of 304L austenitic stainless steel, is numerically simulated using finite elements. Crack propagation is achieved through node releasing, by applying constant $\Delta K$ amplitude, so as to limit the loading history influence. The calculation of the effective stress intensity factor range, $\Delta K_{eff}$, along different shapes of crack fronts close to real crack fronts, are compared to calculation previously performed for through-thickness straight cracks. The results for the curved crack fronts support that $\Delta K_{eff}$ is the driving force of the propagating crack.


## 1. Introduction

The design of many critical structural components needs a careful description of the propagation characteristics of fatigue cracks. The propagation of long and short cracks has been extensively studied, and the role of crack closure, as initially pointed out by Elber [1], has been widely confirmed [2].

The phenomenon of crack closure under fatigue loading is mainly due to the material plasticity, for materials that exhibit strong plasticity in medium $\Delta K$ range [2–4]. This plasticity-induced crack closure (PICC) is a consequence of plastic residual strains along the crack faces, called plastic wake. Its size and length will then influence the level of the premature contact of the opposite crack faces [5–7]. Following Elber [1], such contact then leads to a decrease of the stress intensity factor range, and then of the effective stress intensity factor range $\Delta K_{eff} = K_{\max} - K_{op}$.

In particular, it has been demonstrated that the effective stress intensity factor allows a rationalization of the loading ratio in 7075-T6 alloy [8], of the yield strength on AISI 1018 in duplex and normalized conditions [9], of the effect of texture in thin sheet (1.6 mm) and thick plates (12.7 mm) of Al-Li 2090 T8X [10], or of grain size on threshold in Armco iron [11].

The major concept supporting that $\Delta K_{eff}$ can be considered as the driving force for crack propagation has emerged from numerous studies [12–20]. However, crack closure cannot rationalize the effect of ageing in Ti alloy forged bars [21] or of environment and microstructure in Al alloys [22]. Moreover, most of these studies are related to long cracks and the role of crack closure for short cracks is still discussed especially for microstructural cracks. But results for 2D physically short through cracks tend to support the validity of the $\Delta K_{eff}$ rationalization concept [23].

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**Nomenclature**

| | |
|---|---|
| $da_e$ | edge crack propagation |
| $B$ | specimen thickness |
| $P_{\max}$ ($K_{\max}$) | maximum applied load (stress intensity factor) (superscript $\ell$: local) |
| $P_{\min}$ ($K_{\min}$) | minimum applied load (stress intensity factor) (superscript $\ell$: local) |
| $P_{op}$ ($K_{op}$) | opening applied load (stress intensity factor) (superscript $\ell$: local) |
| PICC | plasticity-induced crack closure |
| $R$ | stress ratio |
| SIF | stress intensity factor |
| $U_y$ | displacement perpendicular to the crack plane |
| $W$ | specimen width |
| $\Delta K$ | stress intensity factor (SIF) range (=$K_{\max} - K_{\min}$) |
| $\Delta K_{eff}$ | effective SIF range (superscript $\ell$: local) |
| $\sigma_0$ | initial yield stress |

Newman [24,25] was the precursor on this subject, by a 2D approach with plane stress and plane strain considerations. He demonstrated that PICC is favoured under plane stress state. McClung et al. [26] agreed with that.

More recently, a CT specimen has been modelled under both plane strain and plane stress assumptions [27]. High levels of PICC were observed under plane stress, during crack growth under cyclic tension, while no closure was obtained under plane strain state. Moreover, Lugo and Daniewicz [28] investigated the influence of the T-stress on PICC under plane strain conditions. Additionally, Alizadeh et al. [29] have compared bi-dimensional and three-dimensional calculations and concluded that empirical correction factors have to be used to be able to describe accurately 3D situation by a bidimensional approach. They concluded on the need of more accurate experimental and modeling work for 3D natural cracks.

Le Minh et al. [30] compared an extension of the steady-state method to the classical node release one to study fatigue 3D propagation and PICC, for a 3D approach. Nevertheless, their study has been restricted to straight-through cracks in SEN coupons.

As closure is mainly observed near the specimen free edge, a curvature of the crack tends to develop, with slower propagation near the edge. De Matos and Nowell have first studied only straight crack fronts [14], and they have then modified the crack shape only near the edge [31]. They have done 2D (plane strain and plane stress) and 3D calculations of PICC. 3D simulations raise the problem of numerical size, as the plasticity of the material has to be considered, with small elements to represent the high stress and strain gradient near the crack front, for several cycle numbers. So, some features have been simplified by the authors who investigated 3D approaches of this problem in order to reduce the calculation time [32–36].

Moreover, several studies have investigated the influence of corner point and free edges singularities on the crack shape as they are raising stress singularity problems.

In particular, it is argued that there is a critical intersection angle at the edge [37–41]. Nevertheless, it must be pointed out that De Matos and Nowell [31] supported, by modifying the crack shape only near the edges, that these singularities do not seem to have a great influence on PICC of 3D fatigue cracks. Moreover, Pook [40] concluded that corner point singularities normally don't have to be considered under mode I, although they can affect SIF calculation during 3D analyses.

The first three-dimensional study of PICC was carried out by Chermahini [42]. Nevertheless, with only 4 elements in the coupon thickness, and one load cycle for each step of crack propagation, the simulation was too simplified.

The influence of the crack front curvature appears to be evidence through experiments, but is commonly ignored in classical linear elastic fracture mechanics. In a majority of the studies [15,43–47], a simple crack geometry is considered, with ideally straight crack fronts throughout propagation. The aim of these papers was to investigate the influence of several parameters on PICC: mesh size around the crack tip, type of elements, value of the load corresponding to node releasing... The change in the crack front curvature during fatigue propagation has been studied by node releasing or remeshing [20,41,48], but unfortunately without considering PICC or using a semi-empirical constraint factor for semi-elliptical crack fronts [49]. Different methodologies, using or not a contact definition have been compared in [50] in the presence of residual stress fields. The combined influences of PICC and crack front shape have been studied by few authors [16,20,44,51–54]. It appears that the yielded zone at the specimen edge increases when the local radius of curvature decreases, whereas in the mid plane the yielded area only depends on applied load and specimen thickness [55]. The effective stress intensity factor range $\Delta K_{eff}$ is studied by Hou [16,53] as the driving force during propagation, considering that, whatever the initial crack front shape is, the steady state shape should correspond to a constant value of $\Delta K_{eff}$ along the crack front. Wu [54] have proposed an iterative crack shape, based on a prior definition of a function giving the distribution of the stress intensity factor.

To substantiate this concept, recent 3D numerical simulations of the plasticity-induced closure for planar through-thickness cracks, grown in 304L stainless steel with a straight crack front [46,47], have been performed. But they do not lead to the conclusion of a constant local $\Delta K_{eff}$ range all along the crack front. Moreover, Branco et al. [51] showed that the evolution of $K_{\max}$ (and consequently of $\Delta K_{eff}$ range) along the specimen thickness is greatly influenced by the crack shape [51].