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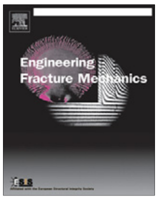

Wake length and loading history effects on crack closure of through-thickness long and short cracks in 304L: Part II – 3D numerical simulation

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ABSTRACT

The plasticity-induced crack closure shielding effect for long and short through-thickness cracks is studied in a 304L steel. A main objective is to uncouple the effect of the wake length from that of the wake history. The experimental results are presented in a first part of this contribution. In the present second part, a 3D finite elements analysis (ABAQUS) for 2D cracks with a straight crack front is proposed. Globally, a remarkable consistence is obtained between simulation and experiments. The effective stress intensity factor range is confirmed as the driving force when the LEFM concepts are applicable.

1. Introduction

More than 30 years ago, Elber [1] was the first to detect the phenomenon of fatigue crack closure. After this pioneer discovery, many researchers attempted extensively to characterize this effect experimentally, analytically, as well as numerically. The essential findings have shown that the fatigue crack closure phenomenon is an intrinsic aspect of the mechanics of growing cracks [2–4] where the main sources of the so-called fatigue crack closure came from the material plasticity. As a consequence, the crack faces of a growing crack contact each other, implying lower values of the effective stress intensity factor range ΔK_{eff} at the crack tip and thus reducing the crack growth rate da/dN. Schematically, this phenomenon, called plasticity-induced crack closure (PICC), arises due to residual plastically deformed material which is left along the crack faces called plastic wake whose size and length are the key factors affecting the level of the premature contact of the crack face and thus the level of crack closure [5–7]. A short crack, by definition, has a limited plastic wake length, and thus, crack closure effects are less pronounced for a short flaw propagating in a smooth specimen or ahead of a notch tip. A large number of experimental results [8–12] showed that the PICC level increases with increasing plastic wake length left on the crack flanks and reaches a steady state level at a critical crack length da_{cr}.

However, few numerical results have been reported so far related to this topic. Looking back to some reviews of the literature, we should note that the remarkable initial work of Newman [13–15] on this topic was a 2D simulation based on plane strain and plane stress assumptions. He found that PICC level was different and showed to be higher in plane stress.

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Nomenclature

da (da_{cr})	(critical) residual plastic wake length and short crack length on the crack flanks
da/dN	crack growth rate
B	specimen thickness
COD	crack opening displacement
CTOD	crack tip opening displacement
$P_{\max}$ ($p_{\max}$) ($K_{\max}$)	maximum applied load (pressure) (stress intensity factor)
$P_{\min}$ ($p_{\min}$) ($K_{\min}$)	minimum applied load (pressure) (stress intensity factor)
P_{op} (p_{op}) (K_{op})	opening applied load (pressure) (stress intensity factor)
PICC	plasticity-induced crack closure
R	stress ratio
R_p	forward plastic zone
SIF	stress intensity factor
U	opening ratio ($=\Delta K_{eff}/\Delta K$)
α	compliance of the fully opened crack
δ	displacement perpendicular to the crack plane
ΔK	stress intensity factor (SIF) range ($=K_{\max} - K_{\min}$)
ΔK_{eff}	effective SIF range ($=K_{\max} - K_{op}$)
σ_0	initial yield stress

This work was followed, under plane strain conditions, by that of Fleck and Newman [2] who predicted that the nature of the closure process changes from continuous to discontinuous after a sufficient increment of crack growth. Discontinuous closure is the phenomenon whereby the crack faces first contact at a remote location behind the crack tip. According to his work, the source of discontinuous closure appears to be a residual wedge of material on the crack flanks, located just ahead of the initial position of the crack tip. He suggested that closure involves only a few elements relatively distant from the current crack tip and that the closure decays steadily as the crack grows beyond its initial length. In the limit, closure would not occur at all. A further attempt to understand the problem was undertaken by McClung et al. [16] who stated that steady state closure level does occur under plane strain. They found that crack opening levels are significantly lower in plane strain than in plane stress and crack opening and closing is a continuous unzipping process for both regimes. This observed behavior is in strong contrast with the analysis of Fleck [17]. Sehitoglu and Sun [18] addressed the plane strain problem by introducing the crack tip tensile load parameter, which characterizes the stress level at which the stresses at the crack tip node change from compressive to tensile. They stated that crack advance is a strong function of tensile stresses in front of the crack tip and crack growth into a wholly compressive zone is highly unlikely. They further observed that a crack blunting mechanism in plane strain competes with the closure mechanism. More recently, Wei and James [19] reported that, after growing of a plane strain fatigue crack for a few cycles, there is no contact in the region immediately behind the crack tip and that the contact pressure along the crack faces is discontinuous. These findings are once again in contrast to those of McClung et al. [16]. Zhao et al. [20] modeled a CT specimen under plane stress and plane strain. They did not observe plasticity-induced crack closure under plane strain during steady state crack growth under cyclic tension, although they found significant levels of closure under plane stress. The influence of biaxiality on PICC has also been investigated under plane strain conditions: the transient behavior of crack closure strongly depends on the sign of the T-stress [21].

Despite all these valuable findings which were carried out in a bidimensional approach, either under plane strain or plane stress, rare realistic simulations have been involved in three-dimensions probably due to large problem size caused by material non-linearity, number of elements, large number of cycle loading, etc. Alizadeh et al. [22], by comparison of two and three-dimensional analyses, concluded that it may be difficult to use two-dimensional problems to accurately describe three-dimensional situation, without empirical correction factors.

Some authors invested in the development of 3D approaches, by simplifying some features in order to limit the problem size. It is noted that Chermahini [23] was the first author who developed the 3D PICC simulation by meshing four elements through thickness. However, these 3D simulations were still too simplified, since only one cycle was applied for each crack growth step, and in most of the cases, only very simplified material models were employed [24–28]. Recently, Sevcik et al. [29] have studied the evolution of the crack shape during propagation, without considering closure. Some authors [30,31] have used remeshing techniques in a 3D numerical study of fatigue crack growth, but PICC has not been considered by using a contact definition on the crack faces. Different methodologies, using or not a contact definition, have been compared in [32] in the presence of residual stress fields. Branco et al. [33] have particularly investigated the influence of the initial crack shape and of the thickness on PICC in middle-tension specimens. Hou [34] has considered a free-front technique with a simultaneous characterization of the closure level.

The present paper developed a 3D model to simulate PICC under different constant ΔK configurations with a stress ratio $R = 0.1$, in order to take into account the effect of the plastic wake length and size of through-thickness cracks in Compact Tension specimens of 304L stainless steel. The growth of these cracks is simulated from an initial stage of short crack of 0.1 mm (as artificially obtained for experiments) to the critical length da_{cr} ranging between 0.8 mm and 1.5 mm, crack longer