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Numerical prediction of crack front shape during fatigue propagation considering plasticity-induced crack closure

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ABSTRACT

This paper deals with the numerical study of the plasticity-induced crack closure of through-thickness plane cracks, in CT specimens made of 304L austenitic stainless steel. The initial crack front is straight. Constant amplitude of the stress intensity factor is applied in order to limit the loading history influence. Crack propagation is achieved through automatic remeshing, with elastic and plastic parallel calculations. The local effective stress intensity factor range is calculated along the crack front, and considered as the propagation driving force. A comparison with experimental crack front shape allows the validation of the employed method, although some discrepancies remain near the specimen edges.

1. Introduction

The long-term structural integrity requires a careful description of the propagation characteristics of fatigue cracks. It is of vital importance to be able to give an accurate estimation of the fatigue lives of key components in many structures. The propagation of long and short cracks has been extensively studied, experimentally and mainly using finite element approaches (XFEM, FEM, BEM, ...) for prediction [1,2].

One field of prediction is concerned by the crack front shape development throughout the applied cycles, as crack front curvature is often observed in most experimental crack propagation tests [3,4]. Classical linear elastic fracture mechanics generally considers bidimensional crack geometries: the three dimensional effects of crack propagation are not considered.

The adaptive remeshing techniques [5] have been demonstrated as reliable and efficient bidimensional or three-dimensional methods in many case of loadings (tension [6,7], bending [8], torsion [9], multiaxial [10–12], thermomechanical [13,14], in or out-of-plane [11,15], ...), for geometries of bodies ranging from simple specimens [7,16] to real structures [15,17,18], with one or several cracks [19] of different initial positions and shapes. Branco et al. [5] have recently published an exhaustive review concerning these aspects.

In these studies, the crack shape can be predefined (generally semi-elliptical), with a two-degree-of-freedom model [5] or a three one [20], or it may remain without any shape constraint through multiple-degree-of-freedom representations.

Moreover, during crack propagation, the role of crack closure, as initially pointed out by Elber [21], has been widely confirmed [22]. The plasticity-induced crack closure (PICC) is due to residual plastic strains along the crack flanks, called plastic wake. It is influencing the level of premature contact between crack faces, thus implying lower values of the effective factor range $\Delta K_{eff} = K_{\max} - K_{op}$ and consequently reducing the crack growth rates.

It has been demonstrated that the effective stress intensity factor range allows rationalizing the effect of loading ratio [23], yield strength [24], texture [25] and grain size [26]. Although it cannot explain the influence of ageing [27] and environment [28], ΔK_{eff} seems to appear as a driving force for crack propagation.

Few numerical results have been reported so far related to this topic. Looking back to some reviews of the literature, the remarkable initial work of Newman [29,30] 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. A further attempt to understand the problem was undertaken by McClung et al. [31] 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 that crack opening and closing is a continuous unzipping process for both regimes. Sehitoglu and Sun [32] addressed the plane strain problem by introducing the crack tip tensile load

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Nomenclature

a	edge crack length
B	thickness of the CT-specimen
da_c	crack propagation in the center of the CT-specimen
da_e	crack propagation on the edge of the CT-specimen
da/dN	crack growth rate
G	energy release rate
K	stress intensity factor (SIF)
$P_{\max}$ ($K_{\max}$)	maximum applied load (stress intensity factor) (superscript ℓ: local) (underscript i: at node i)
$P_{\min}$ ($K_{\min}$)	minimum applied load (stress intensity factor) (superscript ℓ: local) (underscript i: at node i)
P_{op} (K_{op})	opening applied load (stress intensity factor) (superscript ℓ: local) (underscript i: at node i)
PICC	plasticity-induced crack closure
R	stress ratio
R_p	forward plastic zone
SIF	stress intensity factor
U_y	displacement perpendicular to the crack plane
W	specimen width
α	angle between the crack front and the free surfaces
Δa	local crack advance on one node between two steps
ΔK	stress intensity factor (SIF) range (=$K_{\max} - K_{\min}$)
ΔK_{eff}	effective SIF range (=$K_{\max} - K_{op}$) (superscript ℓ: local) (underscript i: at node i)
σ_0	initial yield stress

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 that 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. Different methodologies, using or not a contact definition have been compared in [33] in the presence of residual stress fields. More recently, Wei and James [34] 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 in contrast with those of McClung et al. [31]. Zhao et al. [35] modeled a CT specimen under plane stress and plane strain states. They did not observe plasticity-induced crack closure under plane strain state during steady state crack growth under cyclic tension, while they found significant levels of closure under plane stress state. 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 [36].

Despite all these valuable findings which were carried out in a bidimensional approach [37,38], either under plane strain or plane stress conditions, rare realistic simulations have been investigated in three-dimensions, probably due to large problem size caused by material non-linearity, number of elements, large number of cycles, ... De Matos and Nowell [39,40], by a comparison of two and three-dimensional analyses, concluded that it may be difficult to use two-dimensional problems to describe accurately three-dimensional situation, without empirical correction factors. Recently, Sevcik et al. [3] have studied the evolution of the crack shape during propagation, without considering closure. Some authors [9,41] 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.

Concerning the study of plasticity-induced crack closure, 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 [42] was the first author who developed a 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 [43–47]. Many of the studies have considered straight crack fronts [48–51] and have allowed studying different parameters (size of elements in the propagation zone, number of cycles between node releasing, ...). Branco et al. [52], as well as Camas et al. [49], have particularly investigated the influence of the initial crack shape and of the thickness on PICC in middle-tension specimens.

Only few authors have considered simultaneously plasticity-induced crack closure and crack shape changes during propagation. In this frame, Yu and Guo [41,53] have used a remeshing method to investigate the crack shape change, with elasto-plastic calculations, and considering closure through an analytical relationship, the equivalent thickness conception. Hou [54,55] has proposed another approach of the propagation of surface semi-elliptical cracks with a free-front technique. Two calculations have been combined: an elastic one and an elastic perfectly plastic one. The first one allows the calculation of the stress intensity factor the crack front, while the second one gives information on closure.

To substantiate the concept of ΔK_{eff} range acting locally as the driving force, recent numerical simulations of the plasticity-induced closure for planar through cracks, grown in 304L stainless steel with a straight crack front [56,57], have been performed. But they do not lead to the conclusion of a constant local ΔK_{eff} range all along the crack front. Based on experimental observations of the real crack front in the same alloy loaded under a constant value of ΔK, numerical simulations with pre-defined arc of circle crack fronts and with different histories of propagation, have demonstrated that ΔK_{eff} is the driving force [58]. Nevertheless, the difficulty to describe accurately the crack curvature near the specimen edge, as well as the lack of knowledge of the crack shape history led to remaining fluctuations of ΔK_{eff} near the edge.

The present paper aims at introducing a numerical automatic remeshing procedure allowing the prediction of the evolution of the crack shape during fatigue propagation considering plasticity-induced crack closure. Both parabolic and part of elliptical crack shapes will be considered, and the ultimate crack shape will be compared to an experimental one obtained in similar conditions.

2. Material and experimental conditions

2.1. 304L stainless steel

This work considers the enhanced plastic deformation of 304L stainless steel, and the important influence of plasticity-induced

Table 1
Chemical composition of the 304L austenitic stainless steel.

C	Mn	Si	S	P	Ni	Cr	Mo	Cu	N_2
0.029	1.86	0.37	0.004	0.029	10	18	0.04	0.02	0.056