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Numerical analysis of plasticity effects on fatigue growth of a short crack in a bainitic high strength bearing steel

B. Alfredsson *, I. Linares Arregui, S. Hazar

Royal Institute of Technology (KTH), Department of Solid Mechanics, Stockholm, Sweden

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ABSTRACT

Plasticity effects on fatigue growth were simulated for a physically short crack. The material description comprised the Drucker-Prager yield surface, non-associated flow rule and non-linear combined hardening. The simulated development of the growth limiting parameter agreed with the experimental crack behaviour with early rapid propagation followed by a transition to slow R-controlled growth. The crack was open to the tip without any crack face closure throughout all load cycles. Instead compressive residual stresses developed at the unloaded tip which supplied an explanation to the slow rate of the propagated short crack in this bainitic high strength bearing steel. The material's strength differential effect was the key difference explaining why compressive residual stresses instead of crack face closure was responsible for the short crack effect in this material.

1. Introduction

Short cracks are known to propagate faster at fatigue with low load ratio R than equally loaded long cracks, which for instance Suresh and Ritchie [1] describe already in 1984. Furthermore, the conventional threshold ΔK_{th} determined at low R-values with load shedding is not necessarily the lower limit for fatigue growth of short cracks. Suresh and Ritchie [1] summarize plasticity and micro-structure reasons for the different growth behaviour of short cracks. Microstructural discontinuities such as grain boundaries may reduce the growth rate or even impede continued growth of the short crack, which is visualized by for instance Schaef et al. [2]. The microstructure may also deflect the crack path to follow a differently oriented slip system in the next grain [3].

Elber [4] made experiments on sheets of soft aluminium with long centre cracks and found that material yielding and plastic deformation at the crack tip resulted in crack face closure in the wake behind the crack tip. Tensile plastic deformation at the tip made the crack faces incompatible, limited the SIF range and the fatigue growth rate by crack face closure at low load. Suresh and Ritchie [1] note that "Since short cracks – by definition – possess a limited wake, it is to be expected that in general such cracks will be subjected to less closure". Following this argument the short crack would grow by the full nominal load range without closure. At increasing length, build-up of plastic strains in the wake would gradually reduce the effective load range and therefore also the growth rate. This phenomenon has been extensively investigated by numerous researchers; see for instance James and Knott [5] or the review by Zerbst et al. [6]. It appears that the differences in growth behaviour between long and short cracks are primarily related to either microstructure or plastic deformation at the advancing crack tip with plasticity induced closure absent for the short crack. The relative importance of crack tip plasticity and microstructure is controlled by the size of the plastic zone and the material grains.

Plasticity induced fatigue crack closure has been studied numerically using FEM by a large number of researchers; see the reviews by Solanki et al. [7], McClung [8], Newman [9] and Ljustell [10]. Plasticity induced crack closure was studied as a continuum phenomenon related to material and loading. Although focus was placed on long cracks, the results may still be of relevance when studying continuum effects on short cracks. For each load cycle there is an asymmetry in plastic straining between loading and unloading. At loading, large tensile plastic strains develop at the crack tip, which are not fully reversed during the subsequent unloading. The result is a plastic wake behind the advancing crack tip with potential closure of crack faces. When such closure appears it reduces the effective SIF range ΔK_{eff} and the fatigue propagation rate.

Plastic straining in tension near the crack tip at $K_{\max}$ may also result in residual compressive stresses at the tip for $K_{\min}$. Schijve [11] made fatigue experiments with overloads on aluminium

* Corresponding author.
E-mail address: alfred@kth.se (B. Alfredsson).
URL: http://www.kth.se (B. Alfredsson).

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Nomenclature

a crack length, sub-scripts *mech*, *micro* and *phys* refer to short crack limits in ASTM E-467
a_{DP} pressure dependent parameter
a_0, a_{PC} short crack start and pre-cracking halt crack length, respectively
$\dot{a}$, $\dot{a}_0$ crack growth rate (da/dN), reference crack growth rate 1 nm/cycle
b speed of stabilization value of the drag stress
C^m coefficients for the deviatoric plastic strain rate of the back-stress tensor
D_{ijkl} elastic stiffness tensor
$\dot{e}_{ij}^{pl}$ deviatoric plastic strain rate
E Young's modulus
f yield surface
g plastic flow potential
G shear modulus
I_1 first stress invariant
K bulk modulus
K_I, K_{min}, K_{max} mode I stress intensity factor (SIF) with minimum and maximum values
K_0 closure free Paris' law material parameter
K_{op}, K_{cl}, K_{lim} opening, closing and limiting SIF for ΔK_{eff}, respectively
P, P_{lim} force on specimen, force at K_{lim}
Q asymptotic value of the drag stress
r_{pl}, $r_{pl,cycl}$ monotonic- and cyclic plastic zone size, respectively
R load ratio P_{min}/P_{max} or K_{min}/K_{max}
R_{iso} the drag stress
s_{ij} deviatoric stress tensor
t specimen thickness
u_y opening displacements of crack surface
α_{ij} back-stress tensor
β closure free exponent in Paris' law
δ_{ij} Kronecker delta
ΔK_{nom}, ΔK_{eff} nominal and effective SIF range, respectively
γ^m memory coefficients of the back-stress tensor
ε model response of true strain in uniaxial experiment
ϵ_{ij}^{el}, ϵ_{ij}^{pl} elastic strain tensor and plastic strain tensor, respectively
ϵ_{eq}^{pl} equivalent plastic strain
$\dot{\lambda}$ plastic multiplier
ν Poisson's ratio
σ model response of true stress in uniaxial experiment
σ_{eq} equivalent or effective stress
σ_{ij}, σ_{yy} stress tensor and stress component in y-direction, respectively
σ_{Y0}, $\sigma_{Y0,cycl}$ monotonic and cyclic yield stress at zero hydrostatic stress, respectively
x, y, z moving coordinates system with origin at the crack tip node
X, Y, Z fixed coordinates system with origin at the notch root

Acronyms
DP Drucker-Prager
EDM electro discharge machining
FEM finite element method
LEFM linear elastic fracture mechanics
NL non-linear
PC pre-cracking
PD potential drop
RT room temperature
SDE strength differential effect
SIF stress intensity factor

sheets and found a rate reducing effect from residual compressive stresses at the crack tip even though crack face closure was avoided by a tensile mean load. The concept of compressive residual stresses as an alternative growth limiting mechanism was confirmed by Sehitoglu and Sun [12] through numerical simulations. They found residual compressive stresses at the crack tip after the tensile part of a load cycle although the crack was fully opened. When present, compressive residual stresses at the tip can reduce the fatigue crack propagation rate. At low R-values the rate limiting effects of crack face closure and residual compressive stresses may be difficult to separate from each other. Both may have significant influence on the crack driving force and the relative importance dependents on material and load level. Further evidence of multiple rate reducing mechanisms are presented by for instance Hertzberg et al. [13] and Lang [14].

When studying plasticity induced fatigue crack closure numerically, there exist some technical modelling concerns which may artificially influence the results. These are typically related to crack advancement modelling or how the results are captured. Solanki et al. [7] point out mesh refinement, node release timing and the evaluation technique for crack opening as three such questions. The node release timing has two aspects. One is the instance during load cycle when the node is released, e.g. at maximum or minimum load. The other aspect is the number of cycles between node releases [15,16]. Jiang et al. [17] include the simulated crack advance length and Cochran et al. [18] add crack advance velocity to the list of important modelling questions.

Results presented in the literature illustrate the importance of constitutive models on the simulated crack closure. There appears to be a dividing line between elastic perfectly-plastic and elastic plastic with low linear hardening on one side and primarily elastic plastic with non-linear hardening or moderate to high linear hardening on the other. The first group is typically used for studying the FEM modelling issues. In such analyses, it is preferred to have a well-defined and established material description with a limited number of parameters. However, in combination with kinematic hardening these material descriptions may result in ratcheting and non-converging closure results with respect to mesh refinement [19,17], crack advancement cycling [15] and crack advancement distance [17]. The group of material descriptions with non-linear hardening are typically designed to follow real materials and include multiple parameters which may make unequivocal conclusions on FEM modelling questions harder to establish. For this group of material descriptions some report convergence with mesh refinement, e.g. [17,20]. On the other hand, Cochran et al. [18] report absence of closure convergence for a relatively soft non-linear hardening material at user controlled crack advancement. Pommier and Bompard [21] investigated the relative importance of kinematic vs isotropic hardening for modelling crack closure. The material with prevailing kinematic hardening displayed cyclic plasticity at the tip and less crack tip closure than material with isotropic hardening.

Increased computation speed has recently opened for simulating crack growth in three-dimensions with sufficient resolution to quantify and compare crack closure at the surface with that in the interior. A three-dimensional model includes out of plane effects and realistic assessment of the plane stress conditions for the specimen outer surface; see for instance [22–24]. Closure