Extreme Mechanics Letters 6 (2016) 45–51

Contents lists available at ScienceDirect

Extreme Mechanics Letters

journal homepage: www.elsevier.com/locate/eml

Deformation fields near a steady fatigue crack with anisotropic plasticity

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ARTICLE INFO

Article history:
Received 22 October 2015
Received in revised form 24 November 2015
Accepted 28 November 2015
Available online 30 November 2015

Keywords:
Fatigue
Cohesive interface simulations
Anisotropic plasticity

ABSTRACT

In this work, from finite element simulations based on an irreversible, hysteretic cohesive interface model, a steady fatigue crack can be realized if the crack extension exceeds about twice the plastic zone size, and both the crack increment per loading cycle and the crack bridging zone size are smaller than the plastic zone size. The corresponding deformation fields develop a plastic wake behind the crack tip and a compressive residual stress field ahead of the crack tip. In addition, the Hill's plasticity model is used to study the role of plastic anisotropy on the retardation of fatigue crack growth and the elastic strain fields. It is found that for Mode-I cyclic loading, an enhanced yield stress in directions that are inclined from the crack plane will lead to slower crack growth rate, but this retardation is insignificant for typical degrees of plastic anisotropy. These results provide key inputs for future comparisons to neutron and synchrotron diffraction measurements that provide full-field lattice strain mapping near fracture and fatigue crack tips, especially in textured materials such as wrought or rolled Mg alloys.

Essential concepts in fracture mechanics include the characterization of the relationship between the loading parameter (e.g., stress intensity factor, K) to the crack extension ($a - a_0$ or Δa), and the design of material microstructures to tune the process zones and thus the toughness [1,2]. The stress fields in an annular zone near the crack tip can be described by the product of the applied stress intensity factor, K_{appl}, the inverse square root singularity, $1/\sqrt{2\pi r}$ (with r being the radial coordinate), and a set of characteristic fields that only depend on the polar angle, θ. The lower bound of this K-annulus is set by the crack tip process zone, and the upper bound by the geometric boundaries. Examples of crack growth retardation or stress singularity shielding include plastic deformation, crack branching, fiber pull-out as a bridging mechanism, and phase transformation in the vicinity of the crack tip. The plastic process zone is "clean" since the rigorous mechanistic analysis can be conducted, while there exists a "messy" process zone at the crack tip and inside the plastic process zone where complicated damage mechanisms are still difficult to quantify. In the top-down approach by Hutchinson et al. [1,2], the "messy" process zone is represented by a cohesive interface model that relates the traction to the interface separation, so that the role of plastic deformation on fracture resistance can be quantitatively investigated. This approach naturally separates the scales dominated by K-field, "clean" plasticity-induced process zone, and "messy" damage-related process zone, respectively. It also enables the development of a field projection approach from which the cohesive interface properties can be obtained from the far-field deformation measurements [3,4].

The corresponding analysis of deformation fields near a fatigue crack tip is far more complicated because the

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http://dx.doi.org/10.1016/j.eml.2015.11.006
2352-4316/

process zone obviously traverses from the front to the hind of the crack tip. During the cyclic loading, the increase of the applied stress intensity factor to $K_{\max}$ leads to a plastic deformation region ahead of the fatigue crack tip, and the unloading from $K_{\max}$ and $K_{\min}$ leads to a reverse yield in a smaller zone, thus leading to a compressive residual stress in front of the crack [5,6]. Deformation behind the crack (i.e., the plastic wake) does not, however, permit such a simple analysis. In principle, one can adopt the top-down approach in [1,2] to study the role played by the clean plastic process zone during fatigue loading, by assuming a set of cohesive interface constitutive laws for the messy damage process zone. The primary difficulty along this line lies on how to develop a phenomenological cohesive interface model that allows the simulation to numerically develop a steady fatigue crack. If successful, then the magnitude, distribution, and history of the deformation fields in the "intermediate" vicinity of the crack tip can be quantitatively related to the surrounding plasticity and the history of the applied stress intensity factors. On the other hand, the intrinsic fatigue mechanisms in the messy process zone involve cumulative damages and nucleation of flaws due to the large cyclic plastic deformation, which require quantitative analysis on the inter- and intra-granular scales [7]. Thus, the simulated deformation fields in the "immediate" vicinity of the fatigue crack tip will deviate from reality; if this deviation can be quantitatively measured, a mechanistic model of the cohesive interface behavior may become feasible. In the above, "intermediate" and "immediate" correspond to the clean and messy process zones, respectively.

The understanding of the fatigue crack growth behavior has been significantly enriched due to recent development of in situ, full-field, non-destructive measurements on microstructural lengths scales using neutron and synchrotron X-ray diffraction techniques [8–10]. Deformation fields on the grain scales are inhomogeneous. The shift of the diffraction peaks will give rise to the lattice strain, which relies on the intergranular interactions and the inhomogeneous deformation fields on the grain scale (or called Type-II field). The peak broadening is related to the inhomogeneous deformation inside the grains, or called Type-III field. These measurements will help build the connection between the stress analysis from the top-down point of view and the failure mechanisms on the inter-and intra-granular scales from the bottom-up point of view. In synergy with the simulated deformation fields by the cohesive interface model, we can identify the regimes in which the simulations fail to reproduce the measured deformation field. This comparison can be used to determine whether the phenomenological cohesive interface model can actually produce a steady fatigue crack with the correctly modeled plastic process zone, and also help develop a mechanism-based cohesive interface model. Simulation results in this paper will provide such benchmark inputs for future comparisons.

Another important motivation of this work arises from textured alloys that are commonly used in engineering applications, e.g., metal forming and spring-back studies in textured steels, and fatigue and fracture studies in wrought or rolled Mg alloys. The plastic deformation is anisotropic, due to the initial texture, or polar nature of deformation twins, or pressure sensitivity that leads to yield asymmetry. Consequently, it is anticipated that the fatigue crack growth rate might vary with respect to the crack direction. It is thus of great technical importance to determine the deformation fields near a fatigue crack for these anisotropic plastic materials.

This work aims to develop a simulated steady fatigue crack, and to study the stress/strain distributions near the crack tip for Mises and anisotropic plastic solids. A cohesive interface is introduced along the crack path while the surrounding medium is elastic–plastic. The interface constitutive laws specify the relationship between the interface traction and the interface separation. Using such a top-down approach, a number of cohesive models have been proposed for the fatigue crack simulations [11–19]. Nguyen et al. [13] has demonstrated that the introduction of an irreversible cohesive law with unloading–reloading hysteresis is the simplest phenomenological way to model the accumulated crack tip damage and thus to realize a steady crack growth. In our cohesive interface model in [9] that is based on Nguyen et al. [13], we first specify the relationship between the normal traction T_n and the normal separation Δ_n by

$$\frac{T_n}{\sigma_{\max}} = \frac{\Delta_n}{\delta_n} \exp\left(1 - \frac{\Delta_n}{\delta_n}\right), \tag{1}$$

for the fully reversible behavior, and then introduce the unloading–reloading hysteresis by considering the unloading stiffness, K^-, and the reloading stiffness, K^+, separately,

$$\dot{T}_n = \begin{cases} K^- \dot{\Delta}_n, & \dot{\Delta}_n < 0 \\ K^+ \dot{\Delta}_n, & \dot{\Delta}_n > 0 \end{cases} \tag{2}$$

$$K^- = \frac{T_n^{unload}}{\Delta_n^{unload}}, \tag{3}$$

$$\dot{K}^+ = \begin{cases} \left(K^+ - K^-\right) \dot{\Delta}_n/\delta_a, & \dot{\Delta}_n < 0 \\ -K^+ \dot{\Delta}_n/\delta_f, & \dot{\Delta}_n > 0. \end{cases} \tag{4}$$

In the above equations, $\sigma_{\max}$ is the interface strength, δ_n is a characteristic length scale, δ_a and δ_f are length parameters that are used to tune the damage rate, and T_n^{unload} and Δ_n^{unload} are the normal traction and separation when the unloading step starts. Since only Mode-I crack is considered in this work, the tangential response of the cohesive interface model is not specified.

The interface model in Eqs. (1)–(4) has been implemented as a user-defined element (UEL) subroutine in the commercial finite element software, ABAQUS [8,9,20]. A standard compact-tension (CT) specimen is used in our finite element simulations, with geometry specified in Fig. 1, which has a pre-notch in the middle and two loading pin holes for fatigue loading. Only half of the specimen is meshed due to symmetry with quadrilateral elements in the bulk and cohesive interface elements along the crack plane. Following the experiments on 316 stainless steel in [8], the specimen is assumed to be elastic and perfectly plastic with the Young's modulus $E = 210$ GPa, Poisson's ratio $\nu = 0.3$, and yield stress $\sigma_Y = 288$ MPa. The interface