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Computations of fatigue crack growth with strain gradient plasticity and an irreversible cohesive zone model

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Abstract

Computations of fatigue crack growth with a first-order strain gradient plasticity (SGP) model and an irreversible cohesive zone model are reported. SGP plays a significant role in the model predictions and leads to increased fatigue crack growth rates relative to predictions with classical plasticity. Increased magnitudes of tractions and material separation at the crack tip together with reduced crack closure appear as the cause for accelerated crack growth in SGP. Under plane strain conditions SGP appears as an essential feature of the development of the crack closure zone. Size effects are explored relative to changes in internal material length scale as well as to structural length scales.

Keywords: Strain gradient; Plasticity; Materials length scale; Fatigue crack propagation; Crack closure

1. Introduction

Fatigue failure predictions for crystalline elastic–plastic materials, i.e. metals, are continuing engineering challenge since a majority of engineering structures and machines experience periodic loading. Although the sizes of these structures vary from several meters (for e.g. an aircraft wing) to several micrometers (in electro-micromechanical devices) the failure mechanisms are similar: a crack initiates, propagates, finally leading to the failure of the structure.

A computational model for fatigue crack growth is required to account for several concurrent processes including the process of material separation at the crack tip, plastic deformation at the crack tip, and the processes in the wake of the crack tip.

We study fatigue crack growth by way of a cohesive zone model embedded inside a continuum model. To that end we include the full-boundary conditions at the crack tip: free in the wake of the crack tip and bonded ahead of the tip. In the present contribution, irreversible damage accumulation in the cohesive zone is used to account for crack propagation.

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The plastic deformation of the continuum surrounding the crack is described by an isotropic continuum flow theory of plasticity. Such a theory is applicable to studies of fatigue crack propagation if the size of the plastic zone at the crack tip is larger or equal to the grain size of the material considered, Suresh [5]. However, several past studies also have applied continuum theories to the analyses microstructurally small fatigue cracks where the plastic zone size is less than the grain size. In that case, the application of an isotropic continuum flow theory of plasticity provides reduced amount of insight since it ignores the local anisotropy of plastic deformation on the level of individual grains.

Special attention is paid to the presence of plastic strain gradients or equivalently – to the presence of geometrically necessary dislocations. Past studies have argued that this quantity should be considered in both the fatigue crack advance processes as well as in crack closure processes. In an investigation of fatigue crack growth based on a concept that connects crack growth rate to cyclic crack opening displacement it was argued that due to the small plastic zone size strain gradients would substantially affect crack growth and threshold conditions, Sevillano [1]. However, no specific details of the crack tip deformation field were considered. A connection between crack closure processes and plastic strain gradients was made in Pippan and Riemelmoser [2], Riemelmoser and Pippan [3]. Contact of crack surfaces in the wake of the fatigue crack tip has been identified as significant contribution to fatigue crack resistance, Elber [4]. As the crack surface get into contact, the crack driving force is reduced, Suresh [5]. The occurrence of closure is viewed to be related to the transport of material to the fatigue crack tip front. Under plane stress conditions such material transport is understood to occur from the free surface. Under three-dimensional conditions complex and constraint dependent deformation mechanisms still enable such material transport, Roychowdhury and Dodds [6]. Under plane strain conditions, the transport of material normal to the plane of consideration is not possible. Nevertheless, a series of numerical studies of fatigue crack growth in the context of strain hardening continuum plasticity models have shown that crack closure does occur even under plane strain conditions under certain loading conditions, among the many studies see e.g. Fleck and Newman [7], Tvergaard [8], Pommier [9], Alizadeh et al. [10] and the comprehensive overview on this subject in Solanki et al. [11]. While these studies report that crack closure takes place, no fundamental explanation for the mechanism of the formation of the closure zone is provided. In a discrete dislocation model, Pippan and Riemelmoser [2], Riemelmoser and Pippan [3] identified geometrically necessary dislocations as essential to material transport in crack closure under plane strain. These dislocations remain in the material once the crack tip has passed and rotate the material in the wake of the crack through a mechanism similar to that of the formation of a small angle grain boundary. This rotation mechanism transports material towards the crack tip but is constraint by material in front of the current crack tip. Consequently, material piles-up and forms a wedge just behind the crack tip. The fatigue crack growth simulations of Deshpande et al. [12] employing a discrete dislocation model also predicted crack closure but over the entire length between the initial and current crack tip. In these computations, the crack extension considered was, however, small, and no separation of the overall dislocation population into statistically stored and geometrically necessary dislocations was undertaken.

In any computation of plastic deformation in a continuum mechanics model the evaluation of plastic strain gradients is possible in addition to the commonly reported plastic strains. However, past studies of fatigue crack growth with continuum mechanics models have ignored plastic strains gradients. If geometrically necessary dislocation – corresponding to plastic strain gradients – in fact play a dominant role in a fatigue crack growth process it is necessary to employ a plasticity framework which first of all evaluates plastic strain gradients, and secondly incorporates these into the formulation of the constitutive model. Considerations of geometrically necessary dislocations are an integral component of strain gradient plasticity models. There are two types of strain gradient models, i.e. first and second-order models. Both models include length scales such that size effects under mechanical loading are captured. Observations on the deformation behavior of metals (e.g. micro-torsion, [13], micro-bending, [14], and micro-indentation, [15,16]) demonstrate that plastic strain gradients and specimen size play a vital role in the mechanical response of small-sized components and in the vicinity of stress concentrations. Second-order strain gradient plasticity models, i.e. Cosserat material models, (e.g. [17–29]) include strain gradients next to the conventional strains in the energy description. The work conjugates for strain and strain gradients are stresses and micro-moments, respectively. Higher-order boundary conditions thus need to be described to complete the problem statement. First-order strain gradient models contain only strains and stresses in the energy description, and strain gradients are included in the incremental