

Fatigue Damage Prediction in Metallic Materials Based on Multiscale Modeling

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This paper addresses the problem of predicting fatigue damage accumulation in metallic materials accounting for local crystal orientation effects using a multiscale model. Single crystal plasticity is introduced to describe crystalline material behavior. At the mesoscale level, different material properties and crystal orientations are assigned to individual grains in a finite element model. Finally, an average method is used to compute the material properties at the mesoscale, which are then applied to a macroscale representative test structure. To predict fatigue damage evolution, a comprehensive fatigue damage criterion is modified to account for single crystal plasticity.

I. Introduction

HIGH-CYCLE fatigue (HCF) is one of the leading causes of structural failure in aerospace vehicles. Although significant attention has been devoted to this area for many years, prediction of the failure modes associated with HCF still remains a challenging area of research [1]. Unfortunately, traditional life prediction methods are commonly based on the macroscopic response of the material, and the failure laws mostly depend on experimental observations. Because of current industrial and military demands for materials to approach the limit of their capabilities, the use of traditional life prediction methods implies a large amount of data and experiments to support the safe life approach. The rise in costs has prompted the search for more efficient methods to predict fatigue life. From a physical point of view, the repeated variations of elastic stresses in metals induce microinternal stresses above the local yield stress, with dissipation of energy via microplastic strains, which leads to local crystallographic slip due to dislocations glide. Then, there is formation of permanent microslip bands and decohesions, often at the surface of the material, typically linked to the presence of surface roughness in the form of intrusions and extrusions. After this first stage located inside the grains, where the microcracks typically follow the planes of maximum shear strain, there is a second stage in which the microcracks cross the crystal boundaries to grow more or less perpendicular to the direction of the maximum principal stress up to coalescence to produce a mesocrack [2].

The need to predict the evolution of fatigue damage from crack nucleation to long crack propagation requires a physics-based multiscale model for HCF. In this paper, a micro–meso multiscale model that accounts for grain orientation effects is developed to capture the damage initiation and progression due to HCF. To

implement the multiscale model into the application for HCF, a corresponding modified fatigue damage criterion is also used.

II. Multiscale Modeling

A. Microscale Model

Single crystal plasticity theory is used to capture crystallographic orientation effects that are not considered by classical isotropic models of metal plasticity. The kinematic theory for single crystal deformation presented here follows the pioneering work of Taylor [3] and its precise mathematical theory by Hill [4], Rice [5], Hill and Rice [6], Asaro and Rice [7], and Asaro [8,9]. Using the standard multiplicative decomposition assumption, the deformation gradient $\mathbf{F} = \partial \mathbf{x} / \partial \mathbf{X}$ can be decomposed into elastic and plastic components as shown in Fig. 1.

$$\mathbf{F} = \mathbf{F}^e \cdot \mathbf{F}^p \quad (1)$$

Here, \mathbf{F}^p denotes plastic deformation of the material in an intermediate configuration in which lattice orientation and spacing remain the same as in the reference configuration. \mathbf{F}^e denotes the elastic component of the deformation gradient, which includes stretching and rotation of the lattice. The velocity gradient, $\mathbf{L} = \partial \mathbf{v} / \partial \mathbf{x}$, in the current configuration is related to the deformation gradient by:

$$\mathbf{L} = \dot{\mathbf{F}}\mathbf{F}^{-1} = \mathbf{L}^e + \mathbf{L}^p \quad (2)$$

where $\mathbf{L}^e = \dot{\mathbf{F}}^e \mathbf{F}^{e-1}$ and $\mathbf{L}^p = \mathbf{F}^e \dot{\mathbf{F}}^p \mathbf{F}^{p-1} \mathbf{F}^{e-1}$ represent the elastic and plastic components of the velocity gradient, respectively.

Assuming that the inelastic deformation of a single crystal arises solely from crystalline slip, the plastic velocity gradient can be rewritten in terms of the resolved slip rate $\dot{\gamma}^{(\alpha)}$, the slip direction $\mathbf{s}^{(\alpha)}$, and the normal $\mathbf{m}^{(\alpha)}$ to the slip plane as follows:

$$\mathbf{L}^p = \sum_{\alpha} \dot{\gamma}^{(\alpha)} \mathbf{s}^{(\alpha)} \otimes \mathbf{m}^{(\alpha)} \quad (3)$$

where α denotes the α th slip system.

The resolved shear stress, which plays a vital role in promoting slip, has been derived from the Cauchy stress tensor by the standard relationship.

$$\tau^{(\alpha)} = \boldsymbol{\sigma} : (\mathbf{s}^{(\alpha)} \otimes \mathbf{m}^{(\alpha)})_{\text{sym}} \quad (4)$$

It is important to note that the slip direction and the vector normal to the slip plane used in the previous equation are defined for the deformed configuration, not the reference configuration. The slip direction and normal vector for the deformed configuration can be expressed in terms of the reference configuration as follows:

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