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Damage induced anisotropy of polycrystals under complex cyclic loadings

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ABSTRACT

Motivated by a low-cyclic fatigue micromechanical model proposed recently [1], qualitative and quantitative studies are performed emphasizing the concept of damage induced anisotropy. In this model, the plastic strain and local damage variables are examined at the crystallographic slip system scale for FCC metallic polycrystals. Determined at the macroscopic scale, the elastic behavior is initially assumed to be compressible and isotropic. The anisotropic damaged behavior, caused by activation/deactivation concept, is adopted using a fourth-order damage tensor at the overall scale. Accordingly, the overall behavior, notably the deactivation phase due to the microcracks closure under complex cyclic loadings, is of particular interest in the study.

A host of plastic damaged behaviors of metallic polycrystals is predicted underlining the damage activation/deactivation effects on the multiaxial low-cyclic fatigue (LCF) behavior. Actually, the model is tested under strain- and stress-controlled conditions describing the effects of the loading complexity and the mean stress on the polycrystal LCF behavior. Finally, the model can successfully describe the LCF behavior of the Waspaloy at room temperature.

1. Introduction

Currently, the elasto-inelastic behavior of metals shows an increasing maturity especially in the engineering theory of plasticity. Taking into account the damage mechanics notably under cyclic loading with the self consistent modeling is a hard task especially, due to the non-linearity of materials response. Some attempts have been made to describe the damaged-elasto-inelastic behavior of the material under different loading paths (e.g., [2–6]). Various damage categories have been described in the literature, such as creep damage, low cycle fatigue, high cycle fatigue and brittle damage [7–11], and many others.

The nonlinearity of material behavior is generally induced by plasticity and damage mechanics. Ductile polycrystalline materials usually fail as a result of nucleation, growth and coalescence of microdamages. Experimental observations show that the accumulation of microdamages has a tendency to form a localized damage, due to plastic strain localization up to the final structure failure. In fact, in several metallic materials, the kinematic strengthening is related to the creation of slip bands. The setting of these bands in the material induces undoubtedly an internal back stress in grains leading accordingly to an anisotropic behavior. Besides, TEM observations reveal strain localized in slip bands during cycling leading to an important dislocations density in these bands [12]. Microstructural observations related to specimen outer surfaces show that crack initiation occurs in some slip bands as in Waspaloy [13]. Thus, these slip bands together with microcracks seem to be important factors leading to an anisotropic behavior concerning the elastic and plastic strains.

Modeling of the spatial localization of the cyclic fatigue damage on a given structure is not a trivial task. In fact, modeling the fatigue damage localization within the specimen free surface via the finite elements methodology can be suitably performed in the framework of the non-local mechanics [14–17]. Note that localization analyses using a classic continuum model without incorporating the internal length concept is not adequate for modeling the intrinsic failure process. To remedy the problem of mesh dependency, different approaches have been developed; among these, the non-local models (e.g., [18–21]) are largely used. From a computational viewpoint, the non-local models appear to be straightforward to implement. Until now, the non-local formulation is separately used either in brittle damage models or in ductile plastic damage models [17].

An induced-oriented anisotropy phenomenon can experimentally be observed, in fatigue. In fact, microcracks may open or close depending on the applied loading direction. Thus, different responses can experimentally be observed for compression and tension loads, which lead to damage deactivation behavior as in [22] for an aluminum alloy. Theoretically, many approaches have been proposed since the last decade (e.g., [23–34]). Recently, a micromechanical model of damaged-elasto-inelastic behavior

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