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A micromechanical explanation of the mean stress effect in high cycle fatigue

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A micro–macro approach of multiaxial fatigue in unlimited endurance is presented in this study, as an extension of a previous model recently proposed by the authors [Monchiet, V., Charkaluk, E., Kondo, D., 2006. A plasticity–damage based micromechanical modelling in high cycle fatigue. C.R. Mécanique 334 (2), 129–136]. It allows to take into account coupling between polycrystalline plasticity and damage mechanisms which occur at the scale of persistent slip bands (PSB) during cyclic deformation. The plasticity–damage coupled model is obtained by adapting the Gurson [Gurson, A.L., 1977. Continuum theory of ductile rupture by void nucleation and growth: part I – yield criteria and flow rules for porous ductile media. J. Eng. Mater. Technol. 99, 2–15] limit analysis to polycrystalline materials to take into account microvoids growth along PSBs. The macroscopic fatigue criterion corresponds to microcracks nucleation at the PSB–matrix interface. It is shown that this criterion accounts for the effect of the mean stress and of the hydrostatic pressure in high cycle fatigue. Such features of HCF are related to the damage micro-mechanisms. Finally, some illustrations concerning the particular case of cyclic affine loadings are presented and comparisons of the predictions of the fatigue criterion with experimental data show the relevance of this new approach.

1. Introduction

It is now generally admitted that fatigue failure of metallic components is the result of complex microscopic phenomena which occur at the grain scale under cyclic loadings. In particular, a major role is assigned to the microplasticity due to the dislocations motion and to the damage by microcracks growth (Dang Van, 1999; Essmann and Mughrabi, 1979). The objective of this study is to propose a high cycle fatigue (HCF) criterion founded on the physical microscopic mechanisms leading to damage and cracks nucleation.

In HCF context, many multiaxial fatigue criteria already exist. Among the first attempts dealing with purely phenomenological approach, mention can be made of Sines (1959) or Crossland (1956) macroscopic criteria. The first real studies based on microscopic observations for the expression of a macroscopic criterion are those of Orowan (1939) then of Dang Van (1973), who benefited of a lot of experimental results and observations obtained between the 30s and the 60s. This multiscale approach was thereafter enriched and formalized by Papadopoulos (1987). The theoretical framework proposed by Dang Van and Papadopoulos is based on the modeling of the plasticity at the grain scale and on the use of elastic shakedown theorems in order to establish a crack nucleation criterion. It is worth noticing that in this type of modeling, despite the clear physical reference to damage phenomena, no explicit introduction of the local damage mechanisms is done.

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In a recent work (Monchiet et al., 2006), we have proposed a multiscale approach of HCF based on the Dang Van and Papadopoulos theoretical background and on the consideration of plasticity and damage mechanisms at the scale of the grains. The damage mechanisms, which occur along highly deformed slip bands, named persistent slip bands (PSB) in the fatigue case, are assumed of two types: on the one hand, microvoids nucleation by accumulation of point defects of vacancies type, generated by annihilation of dislocations (Essmann and Mughrabi, 1979), and, on the other hand, the growth of these microvoids under the combined effect of the slip-like plastic activity and of the pressure. In the case of von Mises matrix material, this defect growth is generally described in the ductile damage framework, classically defined under monotonic loadings (Rice and Tracey, 1969; Gurson, 1977). The model proposed in Monchiet et al. (2006) was based on a simple adaptation of the Rice and Tracey's voids growth approach (Rice and Tracey, 1969) and led to the expression of a fatigue criterion exhibiting the crucial role of the hydrostatic pressure in high cycle fatigue. The essential feature of this first model is that damage and plasticity are uncoupled, which facilitates the numerical implementation of the criterion. However, it is convenient to note that with such a model the role of an alternated part of the hydrostatic pressure is not satisfactorily represented in view of available data.

In order to properly describe the growth of the microcavities along PSBs as well as the role of the alternated part of the hydrostatic pressure, it is proposed in this paper to adapt the limit analysis of Gurson (1977) which has the interest of coupling plasticity and damage in the constitutive law. An hollow sphere representing an elementary cell of the monocrystal containing microcavities is therefore considered and serves as the geometrical model for the analysis of a porous material governed by an equivalent von Mises criterion corresponding to the monocrystal.

Since an essential step in the treatment of fatigue type cyclic loadings is the consideration of plastic hardening, it is proposed to incorporate the hardening effects by following the previous study of Leblond et al. (1995), extended here to crystalline plasticity. The adopted crack initiation criterion corresponds to a critical value of damage at the PSB's scale. In order to upscale this criterion to the macroscopic scale, a micro–macro transition based on the Kröner's self-consistent scheme (Kröner, 1961) is used. This micromechanical reasoning leads to a closed form expression of the fatigue criterion in the case of affine loading paths. In order to evaluate the relevance of this approach, comparisons with available experimental data are proposed in a last part of this article.

2. Basic principle of the modeling

2.1. Plastic behavior at the grain scale

In this section, plastic micromechanisms at the grain scale, corresponding to an activation of slip systems are described. In the case of HCF, for FCC structures, a simple slip system assumption is commonly adopted (Dang Van, 1973; Papadopoulos, 1987). This assumption is mainly justified for low stress amplitudes, below the macroscopic yield stress. Let $\boldsymbol{\sigma}$ and $\boldsymbol{\varepsilon}$ be, respectively, the stress and strain tensors at the local scale, i.e. at the grain scale. An additive partition of the total strain $\boldsymbol{\varepsilon}$ in an elastic part $\boldsymbol{\varepsilon}^e$ and a plastic part $\boldsymbol{\varepsilon}^p$ is adopted: $\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p$. The plastic slip, on the activated slip system, is defined by $\gamma^p = 2\boldsymbol{\varepsilon}^p : \boldsymbol{\Delta}$, where $\boldsymbol{\Delta}$ is the orientation tensor, defined by: $\boldsymbol{\Delta} = \underline{n} \overset{s}{\otimes} \underline{m} = \frac{1}{2}(\underline{n} \otimes \underline{m} + \underline{m} \otimes \underline{n})$. The vector $\underline{n}$ is the normal to the activated slip plane while $\underline{m}$ is the slip direction. The plastic behavior of this monocrystal gives relation between the shear stress $\tau = \boldsymbol{\sigma}:\boldsymbol{\Delta}$ and the plastic slip strain γ^p; as classically, a Schmid's law is considered

$$|\tau - X| - \tau_0 - R = 0 \tag{1}$$

X and R are, respectively, the kinematic and isotropic hardening variables. A linear law is adopted for both hardenings: $X = c\gamma^p$ and $R = R_0 p$. The positive scalars c and R_0 are the hardening moduli and $p = \int_0^t |\dot{\gamma}^p| \mathrm{d}t'$ is the cumulated plastic slip.

2.2. Damage modeling

2.2.1. Voids nucleation and growth mechanisms

According to previous assumptions, the proposed multiscale modeling is based on irreversible mechanisms which deteriorate definitively the microstructure. In the case of FCC crystals and cyclic loadings, the plastic strain localization induces dislocations annihilation mechanism which is at the origin of point defects accumulation of vacancies type along PSBs. Dislocations annihilation is not an irreversible mechanism: point defects could be mutually annihilated. A phenomenological model for the production of defects by dislocations annihilation was previously proposed by Essmann and Mughrabi (1979). For low values of p, which correspond to the HCF situation (Monchiet et al., 2006), the porosity induced by this mechanism, denoted η_a, is given by

$$\eta_a(p) = A_0[k_a p - 1 + \exp(-k_a p)] \tag{2}$$

where A_0 and k_a are two parameters. This annihilation mechanism depends only on the plastic slip; as a consequence, it is not able to predict the important role of the hydrostatic pressure observed in fatigue. A possible way to overcome such limitation is to consider a second damage mechanism in addition to the annihilation's one and which may depend on the hydrostatic pressure. As microcavities nucleation is induced by vacancies production, they are supposed to grow under the combined effect of the plastic strains of the matrix and of the pressure, as underlined by Rice and Tracey (1969) under monotonic loadings. Therefore, the porosity η_g, corresponding to the microcavities growth, is introduced. The total porosity η is