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Micromechanical study of the loading path effect in high cycle fatigue

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ABSTRACT

In this work, an analysis of both the mechanical response at the grain scale and high cycle multiaxial fatigue criteria is undertaken using finite element (FE) simulations of polycrystalline aggregates. The metallic material chosen for investigation, a pure copper, has a Face Centred Cubic (FCC) crystalline structure. Two-dimensional polycrystalline aggregates, which are composed of 300 randomly orientated equiaxed grains, are loaded at the median fatigue strength defined at 10^7 cycles. In order to analyse the effect of the loading path on the local mechanical response, combined tension–torsion and biaxial tension loading cases, in-phase and out-of-phase, with different biaxiality ratios, are applied to each polycrystalline aggregate. Three different material constitutive models assigned to the grains are investigated: isotropic elasticity, cubic elasticity and crystal plasticity in addition to the cubic elasticity. First, some aspects of the mechanical response of the grains are highlighted, namely the scatter and the multiaxiality of the mesoscopic responses with respect to an uniaxial macroscopic response. Then, the distributions of relevant mechanical quantities classically used in fatigue criteria are analysed for some loading cases and the role of each source of anisotropy on the mechanical response is evaluated and compared to the isotropic elastic case. In particular, the significant influence of the elastic anisotropy on the mesoscopic mechanical response is highlighted. Finally, an analysis of three different fatigue criteria is conducted, using mechanical quantities computed at the grain scale. More precisely, the predictions provided by these criteria, for each constitutive model studied, are compared with the experimental trends observed in metallic materials for such loading conditions.

1. Introduction

Fatigue crack initiation in metallic materials is a local phenomenon intimately related to the plastic activity at the grain scale. Indeed, in High Cycle Fatigue (HCF), it has been observed that the plastic deformation localises heterogeneously in some favourably-oriented grains leading to slip bands formation and to fatigue cracks initiation mainly at the interface between these bands and the surrounding matrix. In this context, it seems relevant to try to evaluate the mesoscopic mechanical quantities (i.e. the average values per grain) in order to study the HCF strength. Unfortunately, due to complex anisotropic elasto-plastic behaviour of the crystals constituting a metal, no simple method exists to precisely estimate these quantities.

Homogenisation schemes are a common way to relate the mechanical response of each grain to the macroscopic loading applied to a polycrystal. This approach has been successfully used in the development of HCF criteria. The first attempt of multiscale approach in fatigue was proposed by Dang Van [1]. The work of Papadopoulos [2], a continuation of the one of Dang Van, has allowed improvements such as a better consideration of the effect of phase shift on the fatigue strength of metals under combined tension and torsion. Monchiet et al. [3] have developed a criterion based, like the one proposed by Dang Van, on the elastic shakedown concept but in which the damage is coupled to plasticity in order to explain the mean stress effect in HCF. Morel and Huyen [4], starting from the definition of the fatigue crack initiation criterion at the grain scale proposed by Papadopoulos, has constructed a criterion in a probabilistic framework allowing to take into account the variability of the fatigue crack initiation threshold and providing satisfactory predictions for biaxial loading cases (combined tension and torsion, biaxial tension) [5]. Despite the qualities of these criteria (ease of application, fairly accurate predictions), simplifying assumptions are made in their development. The influence of these hypotheses (for instance, the consideration that the elastic behaviour is the same at the grain scale and at the macroscopic scale) on the predictions is not necessarily quantified. Moreover neighbouring and free surface effects can hardly be taken into account.

A promising approach, consisting in computing, by FE method, the mechanical response of explicitly modelled polycrystalline aggregates, allows to take into account microstructural details

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Nomenclature

γ_s:	plastic slip on the slip system s	$\underline{\tau}$:	mesoscopic shear stress vector (Fig. 1b)
v_s:	accumulated plastic slip on the slip system s	τ_a:	mesoscopic shear stress amplitude (Fig. 1b)
τ_s:	resolved shear stress on the slip system s	τ_m:	mesoscopic mean shear stress (Fig. 1b)
r_s:	isotropic hardening variable on the slip system s	$T_{s,a}$:	macroscopic resolved shear stress amplitude on the slip system s
x_s:	kinematic hardening variable on the slip system s	$\tau_{s,a}$:	mesoscopic resolved shear stress amplitude on the slip system s (Fig. 1b)
$\boldsymbol{\sigma}$:	stress tensor	Σ_n:	macroscopic normal stress acting on the plane $\underline{n}$
ε^p:	plastic strain tensor	σ_n:	mesoscopic normal stress acting on the plane $\underline{n}$ (Fig. 1b)
$\underline{n}_s$:	unit vector normal to the slip plane (Fig. 1)	$\sigma_{n,a}$:	mesoscopic normal stress amplitude acting on the plane $\underline{n}$
$\underline{l}_s$:	unit vector in the slip direction (Fig. 1a)	$\sigma_{n,m}$:	mesoscopic mean normal stress acting on the plane $\underline{n}$
$\boldsymbol{m}_s$:	orientation tensor of the slip system s	σ_h:	mesoscopic hydrostatic stress
$\langle\bullet\rangle_a$:	volume-weighted average over the aggregate	P_{Fn}:	failure probability of a slip plane
$\langle\bullet\rangle_g$:	volume-weighted average over the grain g	P_{Fg}:	failure probability of a grain
$\boldsymbol{\Sigma} = \langle\boldsymbol{\sigma}\rangle_a$:	macroscopic stress tensor	P_{Fa}:	failure probability of an aggregate
$\langle\boldsymbol{\sigma}\rangle_g$:	mesoscopic stress tensor		
$\underline{\sigma}(\underline{n})$:	mesoscopic stress vector across the plane of unit normal vector $\underline{n}$ (Fig. 1b)		

generally neglected in the homogenisation schemes and to deepen the analysis of the mesoscopic mechanical responses of metals under cyclic multiaxial loading. In recent years, several works have involved this kind of numerical simulations to contribute to the study of the HCF behaviour. For instance, Benett and McDowell [6] have analysed the distribution of fatigue crack initiation parameters inspired from well-known HCF criteria. This study was enriched by the work of Guilhem et al. [7] in which the mechanical response of the grains is studied according to their position in the aggregate (for instance at the free surface or in the core), their orientation and the one of the neighbouring grains. Moreover, a study of Robert et al. [8] has highlighted the important role played by the cubic elasticity in the mesoscopic responses of polycrystalline copper. At last, others factors affecting fatigue strength, such as surface roughness or pre-hardening, began to be investigated [9,10].

The present study falls within this framework and is divided into two parts:

- The first part consists in an investigation of the role of each source of anisotropy (i.e. elastic and plastic) on the mesoscopic mechanical responses of a polycrystalline copper cyclically loaded, at levels corresponding to the median fatigue limit at 10^7 cycles, in various biaxial loading conditions.
- The second part is dedicated to the evaluation of the predictions of three fatigue criteria, inspired by those proposed by Dang Van [1], Papadopoulos [2] and Morel and Huyen [4], using the results of the FE simulations in the cases of combined tension-shear and biaxial tension and a comparison of these predicted fatigue limits with experimental trends.

2. Modelling approach

2.1. Constitutive material models at the grain scale

The anisotropic behaviour of the grains is due, on the one hand, to the elastic behaviour and, on the other hand, to the crystallographic nature of the plastic slip. In FCC structure, as for pure copper, the elastic behaviour is cubic and the plastic slip occurs along the {1 1 1} planes in the ⟨1 1 0⟩ directions which correspond respectively to the closed-packed planes and directions of this crystal structure. In order to dissociate the effect of each sources of anisotropy on the mesoscopic mechanical responses, three constitutive models, assigned to the grains, are investigated:

- Linear isotropic elasticity.
- Linear cubic elasticity.
- Linear cubic elasticity with crystal plasticity.

In each case, a Hooke's law is used to describe the elastic behaviour. In the first case, an isotropic elastic behaviour is considered and is defined by the Young's Modulus E and the Poisson's ratio ν. In the second and third cases, cubic elasticity is considered and completely characterised by three coefficients defined in the crystal coordinate system: C_{1111}, C_{1122} and C_{1212}.

Finally, crystal plasticity is described by a single crystal visco-plastic model proposed by Méric et al. [11]. In this constitutive model, the plastic slip rate $\dot{\gamma}_s$ on a slip system s is governed by a Norton-type flow rule (Eq. (1)) involving the resolved shear stress τ_s acting on s and the isotropic and kinematic hardening variables, resp. r_s and x_s, associated to s.

$$\dot{\gamma}_s = \left\langle \frac{|\ \tau_s - x_s\ | - r_0 - r_s}{K} \right\rangle_+^n sgn(\tau_s - x_s) = \dot{v}_s sgn(\tau_s - x_s) \quad (1)$$

where K and n are the parameters defining the viscosity and r_0 corresponds to the critical resolved shear stress. The resolved shear stress τ_s acting on s is computed from the stress tensor $\boldsymbol{\sigma}$ by means of the orientation tensor $\boldsymbol{m}_s$ (Eqs. (2) and (3)). This tensor allows also to compute the plastic strain rate tensor $\dot{\varepsilon}^p$ knowing the plastic slip rate $\dot{\gamma}_s$ occurring on each slip system s (Eq. (4)).

$$\tau_s = \boldsymbol{m_s} : \boldsymbol{\sigma} \quad (2)$$

$$\boldsymbol{m}_s = \frac{(\underline{n}_s \otimes \underline{l}_s + \underline{l}_s \otimes \underline{n}_s)}{2} \quad (3)$$

$$\dot{\varepsilon}^p = \sum_s \dot{\gamma}_s \boldsymbol{m}_s \quad (4)$$

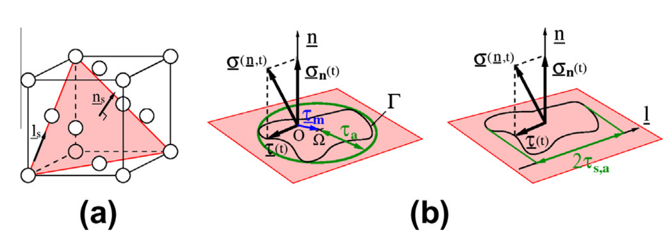

Fig. 1. Representation of some mechanical quantities and vectors in (a) a FCC unit cell and (b) a slip plane.