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Prediction of multiaxial high cycle fatigue at small scales based on a micro-mechanical model

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ABSTRACT

An approach for prediction of high cycle fatigue (HCF) at a length scale of 5–100 μm is established, which evaluates the accumulated plastic shear strain in slip bands of grains. Damage mechanisms initiated by dislocations and the grain microstructure are the key factors that influence the fatigue of metals in small dimensions. For this reason the HCF model considers the elasto-plastic behavior of metals at the grain level and microstructural parameters, specifically grain size and grain orientation. The HCF model can be applied either as a criterion for deterministic predictions of the failure in individual grains, or as a failure function in probabilistic studies on aggregates of grains, if the input parameters are given by specific distributions. This is addressed in a parameter study and a sensitivity analysis of the failure function with respect to different parameters. For model verification, the predicted results of the failure function are compared with the observed micro-damage in individual grains of nickel micro-samples. It is shown that the overall predictive power of the HCF model is fairly good. Nevertheless, some misclassifications occur as some grains are damaged, which were predicted to be safe. Those misclassifications are addressed in post-fatigue investigations on individual grains.

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1. Introduction

Fatigue is one of the main failure modes in engineering components during their life time. It is still a topic of current research to understand fatigue mechanisms and to establish prediction criteria for fatigue life and endurance limit. In this paper we concentrate on multiaxial high cycle fatigue (HCF) of micro-components to understand their lifetime behavior in real applications, e.g. micro electro mechanical system (MEMS). HCF is characterized by a small strain amplitude and high number of load cycles (10^5–10^8 cycles). In this regime, there are generally no irreversible plastic or viscous deformations at the macroscopic level, and the behavior of the bulk material is elastic. However, at the mesoscopic level irreversible plastic strains occur in some unfavorably oriented grains. Such plastic slip events can lead to formation of persistent slip bands and consequently initiation of micro-cracks [1,2]. Classical fatigue criteria and related experimental data were applicable mostly for uniaxial and proportional loadings. Therefore appropriate models were needed for fatigue analysis of mechanical problems undergoing multiaxial and complex loading situations [3]. Furthermore, many of the fatigue criteria considered just parameters resulting from experiments and calculations done at the macroscopic scale. However, fatigue damage initiates in grains due to the dislocations on slip systems. Hence, fatigue mechanism at mesoscopic scale, related heterogeneities, and size effects need to be considered. Interested readers will find a comparative study about some of the most important HCF criteria in [4].

To overcome the mentioned limitations of classical fatigue approaches, Dang Van derived a multiaxial HCF criterion from a model of physical processes at the grain scale based on elastic shakedown theory. According to his criterion no fatigue ruptures will occur at a point of the structure if the microscopic response at that point is described by elastic shakedown. Fatigue cracks will initiate predominantly in less resistant grains with their easy slip system aligned on the direction of the maximum shear stress [5–7]. Papadopoulos proposed a generalized criterion similar to Dang Van's theory relating meso- and macroscopic mechanical fields. According to Papadopoulos, elastic shakedown is reached if the accumulated plastic shear strain in each slip system does not exceed a critical limit [4,8,9]. The micro-mechanical HCF model that is presented in this work is based on previous work by Papadopoulos and Dang Van.

As mentioned before, HCF damage is controlled by mechanisms at the grain scale, and mesoscopic parameters are responsible for the fatigue crack initiation. Micro-components include just a few grains in each direction and fatigue cracks in one or some grains may lead to the failure of the whole component. In this case, each

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grain should be evaluated individually; microstructure and material parameters of individual grains should be considered for the fatigue criterion. The main parameters for describing the microstructure are grain size and grain orientation, which affect the fatigue strength as illustrated in the next section. Lukas and Kunz studied the grain size effect on the cyclic stress–strain response and fatigue life of polycrystalline copper in HCF [10]. They concluded that the total strain fatigue limit and the stress fatigue limit are almost grain size independent, while the plastic strain fatigue limit depends strongly on grain size [10]. Thus, the size of the grain could affect its plastic behavior and consequently influences the fatigue damage mechanism in the grain. Hence, the grain size is included in our numerical model as a main parameter of the microstructure. However, the work by Lukas and Kunz and other similar approaches [2,11,12] just address the empirical relationship between the fatigue life and the grain size but do not provide a physics-based model for it. The other main parameter for describing the microstructure is the grain orientation. There have not been many studies in which the effects of the grain orientation on the fatigue life are investigated. Most of the work verified the effect of grain orientation on dislocation patterns in grains and slip bands [2,13–17]. Therefore, current fatigue criteria do not present a numerical model applicable for individual grains considering both grain size and grain orientation. Previous results and the mentioned limitations provide the motivation to develop an appropriate HCF model for small scale that considers the influence of microstructural parameters on the fatigue strength.

2. Theoretical approach

In this section, the main equations for the description of damage mechanisms on slip systems are described, which will be applied for establishing of the HCF micro-mechanical model. The HCF model is defined as a deterministic failure criterion; nevertheless it works also as a core for definition of probabilistic model.

The fatigue processes in metal components originates in those grains, which undergo plastic deformation in slip bands. Therefore the amplitude of mesoscopic plastic strains plays a key role in initiation of fatigue cracks in grains. In this context crack initiation is understood as the failure of the most unfavorably orientated grains, which suffer plastic deformation. To describe the evolution of fatigue in such grains, the accumulated plastic shear strain in mesoscopic scale is considered as a damage variable. The rate of the plastic shear strain accumulation, denoted as $\dot{\Gamma}$, reads as:

$$\dot{\Gamma} = \sqrt{\underline{\dot{\gamma}}^p \cdot \underline{\dot{\gamma}}^p}\,, \tag{1}$$

where $\underline{\gamma}^p$ is the vector of plastic shear strain for the active slip system.

For loads with small amplitude – as the case in the HCF regime – often only one slip system is active in plastically deformed grains, and the plastic behavior of the grain can be modeled according to a combined kinematic and isotropic hardening rule. The kinematic hardening rule is written as [9]:

$$\underline{\dot{b}} = c\underline{\dot{\gamma}}^p\,, \tag{2}$$

where the vector $\underline{b}$ is the kinematic hardening parameter and c a constant with positive value.

Furthermore, the isotropic hardening rule is written as [9]:

$$\dot{\tau}_y = h\sqrt{\underline{\dot{\gamma}}^p \cdot \underline{\dot{\gamma}}^p}\,, \tag{3}$$

where τ_y is the yield limit and h the isotropic hardening coefficient.

According to the above mentioned hardening rules and plasticity criterion corresponding to Schmid's law, it can be shown that the mesoscopic plastic shear strain is directly proportional to the rate of the macroscopic resolved shear stress [9]:

$$\underline{\dot{\gamma}}^p = \frac{\underline{\dot{T}}}{(c+h+\mu)}\,, \tag{4}$$

where $\underline{T}$ is the vector of macroscopic resolved shear stress along the slip direction and μ the Lamé coefficient.

Eq. (4) provides a macro-meso link between the mesoscopic plastic shear strain and the macroscopic resolved shear stress. To reach an infinite life in the HCF regime and to avoid fatigue crack initiation in grains, the accumulated plastic shear strain in each grain after a high number of load cycles must not exceed a critical limit, denoted here as Γ_c. Consequently, each grain remains in the hardening phase and necessarily elastic shakedown occurs. So after a certain number of cycles a stabilized elastic state is reached and the tensor of the plastic strain becomes constant and independent of time. Using Eq. (4), it can be shown that for constant amplitude multiaxial loading the accumulated plastic shear strain Γ_∞ for each slip system of a grain in the endurance limit is directly proportional to the difference between the amplitude of the macroscopic resolved shear stress T_a and the initial yield stress τ_y^o as following [9]:

$$\Gamma_\infty = \frac{\left(T_a - \tau_y^o\right)}{h}\,, \tag{5}$$

where Γ_∞ is the accumulated plastic shear strain after an infinite number of load cycles, T_a the amplitude of the resolved shear stress along the slip direction of the considered slip system, and τ_y^o the initial yield stress before load cycling. For variable amplitude loading the Eq. (5) should be modified accordingly, which is out of scope of this work [18]. Considering an individual grain, Γ_∞ should be checked for all slip systems of the grain and compared with the critical limit Γ_c.

We introduce now the microstructural parameters, i.e. grain size and grain orientation, into Eq. (5). It is known that yield limit τ_y is dependent on the grain size, and different relations are used to model its grain size dependency. Here, we use a Hall–Petch-type equation, as illustrated by Weng in [19], because it is easily adopted into Eq. (5) and also due to good agreement between experimental and theoretical results:

$$\tau_y^o = \tau_y^\infty + k \cdot d^{-\frac{1}{2}}\,, \tag{6}$$

where τ_y^∞ is the yield stress of the slip system in a single crystal (with infinite size), d the grain size, and k a material parameter.

The vector of resolved shear stress $\underline{T}$ along a slip direction can be written in terms of macroscopic stresses and vectors of the related slip system. Fig. 1 illustrates a body exposed to the macroscopic stress tensor $\underline{\underline{\Sigma}}$. Considering a slip plane Δ in a point of this body, the slip direction and the normal to the slip plane can be shown with vectors $\underline{m}$ and $\underline{n}$, respectively. The macroscopic stress vector $\underline{\Sigma}_\Delta$ acting on the slip plane Δ has a shear stress component $\underline{C}$. During a load cycle, the tip of vector $\underline{C}$ follows a closed planar curve Ψ_Δ. The projection of the vector $\underline{C}$ on the slip direction gives the resolved shear stress vector $\underline{T}$, and the amplitude of the macroscopic shear stress T_a is equal to the half of the length generated by projection of the curve Ψ_Δ on the slip direction. Following equation describes the length of the resolved shear stress vector $\underline{T}$ as a function of macroscopic stress components and vectors of slip system [8]:

$$\begin{aligned} ||\underline{T}|| &= \underline{m} \cdot (\underline{\underline{\Sigma}}\,\underline{n}) \\ &= m_x n_x \Sigma_{xx} + m_y n_y \Sigma_{yy} + m_z n_z \Sigma_{zz} + (m_x n_y + m_y n_x)\Sigma_{xy} \\ &\quad + (m_x n_z + m_z n_x)\Sigma_{xz} + (m_y n_z + m_z n_y)\Sigma_{yz}\,, \end{aligned} \tag{7}$$

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