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Procedia Engineering 74 (2014) 57 – 63
Procedia Engineering
www.elsevier.com/locate/procedia

XVII International Colloquium on Mechanical Fatigue of Metals (ICMFM17)

A micro-mechanical model for multiaxial high cycle fatigue at small scales

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Abstract

The grain microstructure and damage mechanisms at the grain level are the key factors that influence fatigue of metals in small dimensions. This is addressed by establishing a micro-mechanical model for the prediction of multiaxial high cycle fatigue (HCF) at a length scale of about 100 µm, which is typical for micro-electro-mechanical systems (MEMS). The HCF model considers elasto-plastic behavior of metals at grain level and microstructural parameters, i.e. grain size and grain orientation. While for individual grains a deterministic failure prediction is obtained, the model serves as a failure criterion in probabilistic studies on aggregates of grains. For this, it is assumed that a fatigue crack initiates in a grain, if the accumulated plastic shear strain in the grain exceeds a critical limit. For model validation, the grain size and grain orientation on the surface of nickel micro-samples were measured with Electron Backscatter Diffraction (EBSD) analysis after fatigue testing. The overall predictive power of the HCF model - which grains will be damaged by fatigue- is validated. Nevertheless, some misclassifications occur as some grains are damaged, which were predicted to be safe. For some cases, post-fatigue investigations on individual grains reveal reasons for those misclassifications.

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Keywords: High Cycle Fatigue (HCF); Grain Size; Grain Orientation; Small Scale; Micro Electro Mechanical Systems (MEMS)

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doi:10.1016/j.proeng.2014.06.224

1. Introduction

Fatigue is one of the main failure modes in engineering components during their life time. It is still a topic of current researches to understand fatigue mechanisms and establish prediction criteria for fatigue life and endurance limit. In our 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 (10^6 - 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]. Initial classical fatigue criteria and related experiment 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 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 next 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.

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