Probabilistic Engineering Mechanics 50 (2017) 45–52

Contents lists available at ScienceDirect

Probabilistic Engineering Mechanics

journal homepage: www.elsevier.com/locate/probengmech

Modeling transgranular crack growth in random 3D grain structures under cyclic loading

Carla Beckmann *, Jörg Hohe

Fraunhofer-Institut für Werkstoffmechanik IWM, Wöhlerstr. 11, 79108 Freiburg, Germany

ARTICLE INFO

Keywords:
Probabilistic method
Crack formation
Fatigue
Polycrystalline metals

ABSTRACT

A probabilistic method to predict the crack formation in polycrystalline materials with a random microstructure under cyclic loading is developed. In particular, transgranular crack growth in 3D grain structures generated randomly by the Voronoï process is considered. The potential crack extension planes in the individual grains are dependent on the different grain orientations and the crystal structure of the considered material. Under cyclic loading fatigue cracks initiate and propagate along the slip planes of the crystal structure. For this reason, an energy-based criterion is used in order to describe the successive material damage under cyclic loading which is completely projected into the crack extension planes and finally causes the crack propagation. Subsequently, the computation of the crack path in a number of randomly generated grain structure models provides a raw data base in order to determine probability distributions of the number of cycles up to a pre-defined crack depth. As an input for many fracture mechanics evaluation concepts which are based on an assumed incipient crack depth, the number of cycles and the corresponding scatter band width up to a postulated incipient crack depth is of great interest.

1. Introduction

Many materials in structural components in operating state are subject to cyclic loading. Since even deformations in the elastic range cause material fatigue, there is a great interest for development of methods for accurate lifetime prediction starting from crack initiation to final fracture. Due to their different damage behaviors, it is necessary to distinguish between short and long crack growth. The linear elastic fracture mechanics evaluation concepts can only be applied to long cracks because the microstructural influence which is very important for short crack initiation and propagation cannot be taken into account. For description of the incipient cracking, methods are required reproducing the microstructural mechanisms, as the movement of dislocations along slip planes in consideration of the crystal structure (Lankford [1], McEvily [2], Hussain [3]).

In Christ et al. [4] three different groups of models to predict short crack growth are identified. Beside models based on an empirical approach to consider grain boundary effects (Hobson [5], Brown [6]) resp. based on discrete dislocations (Doquet [7], Wilkinson [8]), particularly mechanism-based models considering plastic deformation at the crack tip are important for the present study. Based on models of Bilby et al. [9] and Navarro and de los Rios [10], Schick et al. [11] developed a slip band crack model in order to predict short crack propagation and its scatter in a random grain structure. Further 2D probabilistic methods for short crack propagation in polycrystalline materials are described by Bolotin and Belousov [12], Kraft and Molinari [13] and Meyer et al. [14].

With the increase of computing power the generation and using of much more complex 3D models to predict the degradation and failure in polycrystalline materials is possible. A two-scale approach of Benedetti and Aliabadi [15] shows how the implementation of microstructural submodels improve the component assessment on the macroscopic level. The special feature in the method of Rimoli and Ortiz [16] is the explicitly resolved crack propagation path by the computational mesh. Simonovski and Cizelj [17] show that using a cohesive-type contact instead of cohesive elements for modeling the grain boundaries in a polycrystalline structure yield to a significant higher numerical stability. With a 3D phase-field model Abdollahi and Arias [18] represent a different approach with the advantage that the interaction of several microstructural mechanisms can be considered.

Complex crystal plasticity approaches are implemented in the 3D models of Lin et al. [19], Proudhon et al. [20] and Wan et al. [21], but the extremely high computation times prohibit an efficient lifetime

* Corresponding author.
E-mail address: carla.beckmann@iwm.fraunhofer.de (C. Beckmann).

https://doi.org/10.1016/j.probengmech.2017.10.005
Received 12 January 2017; Received in revised form 8 August 2017; Accepted 18 October 2017
Available online 27 October 2017
0266-8920/

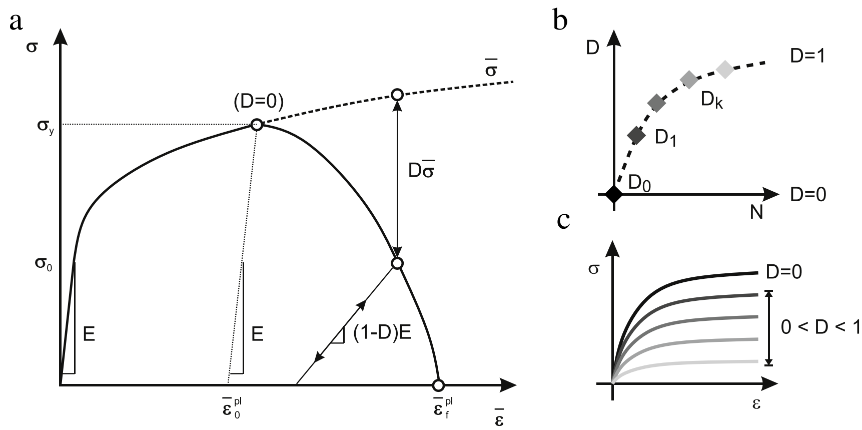

Fig. 1. Damage degradation (a), damage parameter (b) and yield curve (c).

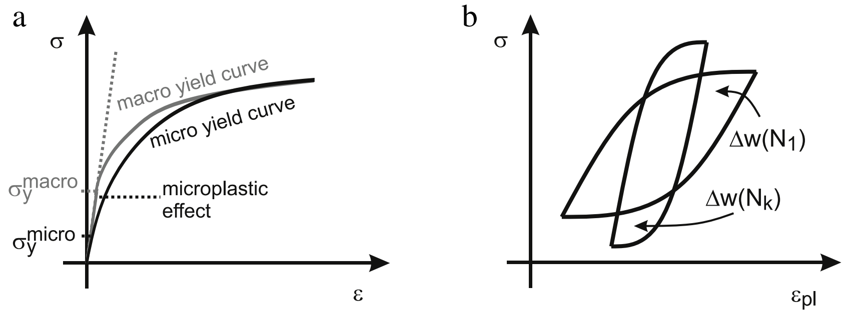

Fig. 2. Microplastic yield (a) and dissipated hysteresis energy per cycle (b).

prediction in the application of component assessments. For this reason, Gulizzi et al. [22] represent a method to reduce extensively the computational cost of polycrystalline micro simulations. The same objective pursue Benedetti et al. [23] by a reduction of the degree of freedoms in their polycrystalline models using a 3D grain-boundary formulation for small strains crystal plasticity.

In the present study, as an extension of Schick et al. [11], a stochastic finite element method based on microstructural characteristics, as grain size distributions and crack growth along slip planes, is developed in order to predict not only the number of cycles up to an incipient crack depth but also to identify the corresponding scatter band width with a numerically efficient approach. This model is a benefit as an input for fracture mechanics concepts for fatigue assessment, using a postulated incipient crack, because the initial crack depth to be used as a starting point for these concepts as well as the lifetime up to this starting point can be integrated much more accurately.

2. Fatigue and damage definition

Material damage due to fatigue caused by cyclic mechanical loading is a typical damage mechanism for metallic materials. In particular, for components in operating state it is crucial that material fatigue may arise out of cyclic loading far below the macroscopic material yield strength. On the microstructural level, the clash of grains with different orientations and the presence of inhomogeneities, such as inclusions, lead to stress concentrations. Consequently, material fatigue due to microplastic yield caused by movement of dislocations along activated slip planes under cyclic loading occurs. In this relation, the grain boundaries constitute a barrier so that crack nucleation arises due to an irreversible accumulation of dislocations. By further cyclic loading the crack growth is induced at the most severe pile-up to the completely material failure.

Based on this damage mechanism Tanaka and Mura [24] developed a model of damage accumulation considering that in particular slip band cracks are expected for high shear stress values. In the case of uniaxial stress the maximum shear stress occurs if the normal of the slip plane and the slip direction are inclined at 45° to the stress axis.

In the present study the failure on material level is described by the continuum damage equation

$$\boldsymbol{\sigma} = (1 - D)\bar{\boldsymbol{\sigma}} \tag{1}$$

with the scalar damage parameter D, the stress tensor $\boldsymbol{\sigma}$ and the effective undamaged stress tensor $\bar{\boldsymbol{\sigma}}$. A schematic representation of the damage degradation referred to Eq. (1) is pictured in Fig. 1(a) with the elasticity modulus E, the yield stress $\boldsymbol{\sigma}$ and the equivalent plastic strain $\bar{\varepsilon}_0^{pl}$ at the onset of damage and at failure $\bar{\varepsilon}_f^{pl}$ resp. As plotted in Fig. 1(b), the value of the damage parameter is $D = 0$ for the undamaged state and achieves its maximum $D = 1$ for complete material failure. The influence of an increasing damage parameter on the material yield curve is sketched in Fig. 1(c).

For the additional field variable D, an additional field equation is required. This equation is provided in terms of the damage evolution equation. Using a load-cycle based approach, the damage degradation per cycle

$$\frac{\partial D}{\partial N} = \frac{k_1}{L}\Delta w^{k_2} \tag{2}$$

is defined by an energy-based criterion (Abaqus [25]) with the dissipated microplastic energy Δw per load cycle N, the model-dependent characteristic length L and the material constants k_1 and k_2. In this context, the term microplasticity refers to a plastic deformation occurring below the static yield limit due to cyclic dislocation movements with plastic strains far below their elastic counterparts.

In Fig. 2(a) the microplastic effect is sketched in an exaggerated manner in order to show that for modeling a micro yield curve is