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Simulation of irreversible damage accumulation in the very high cycle fatigue (VHCF) regime using the boundary element method

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ABSTRACT

Many components have to withstand a very high number of loading cycles due to high frequency or long product life. In this regime, the period of fatigue crack initiation and thus the localization of plastic deformation play an important role. Metastable austenitic stainless steel (AISI304) that is investigated in this study shows localization of plastic deformation in bands of intense slip. In order to provide a physically-based understanding of the relevant damage mechanisms under VHCF condition, simulation of irreversible damage accumulation in slip bands is performed. For this purpose, a microstructural simulation model is proposed which accounts for the damage mechanisms in slip bands documented by experimental results. The model describes the damage accumulation through formation of slip bands, sliding and multiplication of dislocations and the amount of irreversibility of such mechanisms in case of VHCF relevant loading conditions. The implementation of the simulation model into a numerical method allows the investigation of the damage accumulation in a real microstructure simulated on the basis of metallographic analysis. The numerical method used in this study is the two-dimensional (2-D) boundary element method which is based on two integral equations: the displacement and the stress boundary integral equation. Fundamental solutions within these integral equations represent anisotropic elastic behavior. By using this method, a 2-D microstructure can be reproduced that considers orientations as well as individual anisotropic elastic properties in each grain. Contours of shear stresses along most critical slip systems are compared with images of slip band formation at the surface of fatigued specimens provided by scanning electron microscopy (SEM). Results show that simulation of slip bands is in good agreement with experimental observations and that plastic deformation in slip bands has a high impact on shear stresses at grain boundaries acting as possible crack origin in the fully austenitic material condition. In contrast to most other publications in the field of fatigue simulation the present paper tackles the problem of modeling cyclic slip irreversibility and gives an insight into its effect on the microstructural damage evolution.

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1. Introduction

Design and dimensioning of cyclically loaded components is usually based on the classical fatigue limit below which the component should not fail for any number of cycles. Mostly the classical fatigue limit is based on fatigue tests up to 10 million cycles. But observations in the regime of VHCF beyond 10 million cycles reveal that failure arises even at stress amplitudes below the conventional high cycle fatigue limit (as discussed in the series of VHCF conferences since 1998, e.g. Ref. [1]). For that reason the exploration of fatigue mechanisms in that regime and the characterization of fatigue life become more and more important. In the VHCF regime the period of fatigue crack initiation consumes the majority of the total fatigue life and cyclic plastic deformation is heterogeneously distributed due to low stress amplitudes. In this context, sites of stress concentration get a dominant life controlling meaning. The localization of cyclic plastic deformation in the metastable austenitic stainless steel considered in this study is conducted by motion of dislocations arranged in slip bands. Slip bands are accepted as very important feature of cyclic straining in crystalline materials and represent the first sign of fatigue damage [2]. As the cyclic strain becomes localized in slip bands, a rough surface relief with extrusions and intrusions develops at the traces of emerging slip bands, which are believed to be critical precursors to the nucleation of fatigue cracks. These slip bands are affected by cyclic slip irreversibility, which even in VHCF regime leads to a sizeable irreversible accumulated plastic slip deformation and

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finally leads to significant microstructural changes up to crack initiation [3].

The prediction of fatigue life under VHCF condition requires the knowledge and understanding of the basic microstructural fatigue damage processes. For this purpose the present study focuses on the investigation of slip bands, which—as mentioned before—primarily sustain the localization of cyclic plastic deformation. In Ref. [4] several slip band modeling approaches are summarized, which describe the formation of surface roughening due to slip bands, e.g. the well-known model by Essmann et al. [5] or the model by Tanaka and Mura [6]. The slip band model adopted in this study combines some ideas of the models proposed in Ref. [4]. The model is applied on a mesoscopic scale and accounts for the mechanisms of slip band formation, motion and multiplication of dislocations, its cyclic irreversibility and—as an effect of the mechanisms mentioned before—cyclic hardening. In the following the motion and multiplication of dislocations is expressed with the term sliding and the mechanisms of sliding, irreversibility and hardening are related to the slip band as a whole.

To investigate the effect of the suggested slip band model on damage relevant parameters such as shear stresses or sliding deformation it is adapted to real simulated microstructures. Because of the high geometrical complexity of real microstructures and a variety of possibly occurring slip bands, the computation of damage relevant parameters can hardly be done analytically. It is advisable to use a numerical method. Several studies in the field of microstructural modeling and simulation of fatigue damage use the finite-element method (FEM) in conjunction with crystal plasticity models. Zhang et al. [7] explicitly model multiple slip bands within individual grains of a polycrystalline material by using a shear-enhanced crystal plasticity model implemented in the FEM. Simulated slip bands are in qualitative agreement with SEM observations. Although the FE-method combined with crystal plasticity models has been devoted to a wide range of applications the implementation of the newly proposed slip band model of this study would present some difficulties: formation of new slip bands would require a remeshing algorithm and computation of sliding displacement in slip bands would necessitate special finite elements like cohesive-zone elements. Furthermore, various models (e.g. Ref. [7]) adopted by the FE-method presently do not reflect the mechanism of irreversibility nor do they employ any predictive means to account for it, particularly models based on crystal plasticity [8].

In this study a two dimensional boundary element method (BEM) is applied, in which the proposed slip band model can be implemented very effectively. The most outstanding feature of this method is that it uses displacement differences or sliding displacements directly as unknowns on slip band layers. The proposed BEM can simulate slip bands in a two dimensional microstructure consisting of grains with individual anisotropic elastic properties.

In the following paragraphs at first the simulation model with its slip band mechanisms is presented and then the numerical method is specified. The irreversible damage accumulation in slip bands is investigated in a model representing the morphology of a real microstructure characterized by means of SEM in combination with the electron backscattered diffraction (EBSD)-technique and the orientation imaging microscopy (OIM) analysis.

2. Simulation model

In the previous section, it was introduced that by means of a BEM a 2D microstructure consisting of grains with individual anisotropic elastic properties can be simulated. Plastic material behavior by localization of cyclic plastic deformation in slip bands will be considered by mechanisms which define the properties of formation, sliding, irreversibility and hardening of a slip band as follows. Although the metastable austenitic stainless steel implies further microstructural inhomogeneities such as deformation induced martensite or inclusions, in this study the focus is on slip band evolution as it is the predominant process in the fully austenitic condition.

Formation of a slip band is assumed to occur at sites of shear stress concentration [9,10]. Once a critical resolved shear stress in the most critical slip system is exceeded, a slip band is generated at the critical position and propagates along the intersection line of the corresponding slip system and the surface plane of the two dimensional microstructure. The critical resolved shear stress is defined as $\tau^0_{crit} = 80$ MPa, which corresponds to the threshold for slip band formation observed in Ref. [11].

Fig. 1 shows a transmission electron microscopy (TEM) micrograph of the dislocation arrangement in metastable austenitic stainless steel in the fully austenitic condition fatigued under VHCF condition. The micrograph indicates that dislocations are arranged in pile-ups at grain boundaries. Therefore, the model used in this study is based on the theory of dislocation pile-ups at grain boundaries [12], in order to determine the sliding distribution along the slip band. Due to the equilibrium of forces produced by external loading and repulsive forces between dislocations a characteristic dislocation distribution occurs. Taking into account the distortion of a dislocation, which is defined by the magnitude of the Burgers vector, a sliding distribution $\Delta u(\xi)$ can be determined

$$\Delta u(\xi) = \frac{2(1-\nu)}{G}\sqrt{(l/2)^2 - \xi^2}(\tau - \tau_{crit}), \tag{1}$$

where ν and G are Poisson's ratio and shear modulus in the slip plane, respectively (Table 1). l is the length of slip band and ξ is the coordinate along the slip band starting at the dislocation source. τ and τ_{crit} represent the shear stress existing in the dislocation source and the critical resolved shear stress. In order to account for mutual influences between slip bands, the sliding distribution in Eq. (1) is converted into a qualitative shape function. In this way, the quantitative sliding values of the slip bands result from the simulation by predefining the critical resolved shear stresses in the dislocation sources. The sliding distribution model assumes that dislocations perform planar slip. This assumption appears

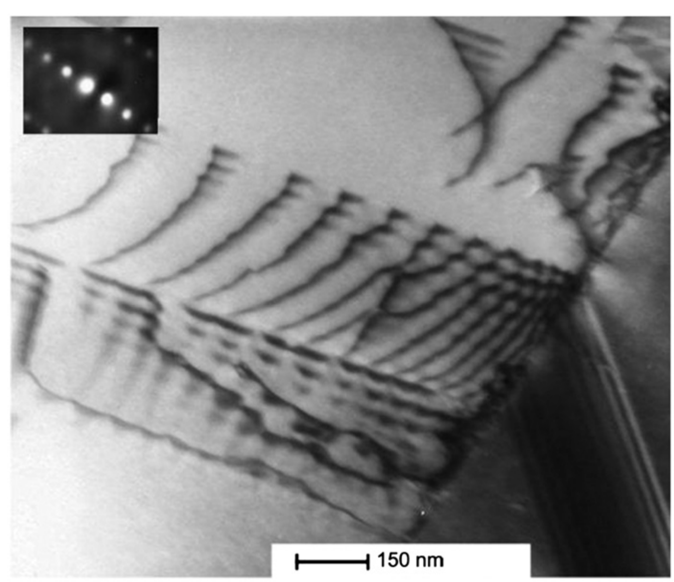

Fig. 1. TEM micrograph of dislocation pile-ups at a grain boundary in metastable austenitic stainless steel fatigued under VHCF condition (loading amplitude: 240 MPa, number of cycles: 10^7).

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