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Modeling and simulation of fatigue crack initiation in metallic joints based on crystal plasticity

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ABSTRACT
In the present study a numerical model to simulate the initiation growth of fatigue cracks in welded joints is shown. The developed model is based on a polycrystalline microstructure with potential slip bands whose directions are dependent on the grain orientations. Considering transgranular crack growth, the crack propagation direction at the grain boundaries is determined by the potential slip directions in the neighboring grain and an energy-based criterion. Subsequently, a statistic analysis of different computed crack path provides a distribution of the number of cycles up to a pre-defined crack length which is – as an incipient crack – important for many fracture mechanics evaluation concepts.
Keywords: *Fatigue Crack, Incipient Crack, Welded Joint, Polycrystalline Microstructure Model, Probabilistic Analysis.*

1. INTRODUCTION

The assessment of fatigue strength is very important for welded joints because cyclic loading of metallic materials can lead to the completely damage of the considered component. The reason is the material fatigue which is mainly caused by movement of dislocations. The accumulation of dislocations and inhomogeneity in the considered material due to pores, inclusions or other micro defects are the starting points for fatigue crack growth by sustained cyclic loading. Furthermore, the roughness of the material surface can be the reason for crack initiation.

Fatigue damage is based on extensive micromechanical processes. Nevertheless, the assessment is usually not based on detailed modelled microstructures, but e.g. Wöhler based concepts are applied [1]. Although the crack initiation is very important for the durability, in general only an approximation on a phenomenological basis is considered for length below the technical crack.

In this study a model for determination of distributions of the number of cyclesupto a pre-defined crack length in welded joints in consideration of the microstructure and the process of material separation is shown. Due to the fact that the fatigue damage initiation is mainly caused by accumulation of dislocations along slip bands, a Dugdale-Barenblatt-model [2, 3] is applied in which the plastic deformation is completely projected onto artificial crack extension. Transgranular crack propagation in a polycrystalline material is considered. The potential crack growth directions are predetermined by the grain orientations and the resultant potential slip bands. Using an energy-based criterion the crack propagation direction is determined as soon as the crack reaches the grain boundary. In doing so, step by step the crack propagation path can be determined.

The statistical analysis of a number of computed crack path finally provides a distribution of the number of cyclesupto a pre-defined crack length which is required for many macroscopic fracture mechanics methods in order to determine the fatigue strength of welded joints.

2. FATIGUE AND DAMAGE DEFINITION

In metallic materials which are subjected to cyclic mechanical loads above a critical threshold the consequence can be material damage. In homogeneity in the microstructure such as inclusions but also the elastic anisotropy caused by different grain orientations yield to stress concentrations on the microstructure level which result in locally occurring plastic slip processes. This dislocation accumulation and movement along slip bands is finally the reason for material fatigue because crack nucleation arises due to irreversible accumulation of dislocations (**Fig. 1a**). The further cyclic loading causes crack growth and with it the consequence can be the completely material failure. Based on this damage mechanism, Tanaka and Mura [4] developed a dislocation model for fatigue crack initiation.

In this study the failure of material is described by the damage equation

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

with the scalar damage parameter D, the stress tensor $\boldsymbol{\sigma}$ and the effective undamaged stress tensor $\bar{\boldsymbol{\sigma}}$.

The damage degradation is determined by an energy-based criterion in such a manner that the complete failure is achieved as soon as the accumulated dissipated plastic energy exceeds a critical value. The number of cycles for damage initiation is defined by

$$N_0 = c_1 \Delta w^{c_2} \qquad (2)$$

with the dissipated plastic energy per cycle Δw and the material constants c_1 and c_2. The damage rate is given by

$$\frac{dD}{dN} = \frac{c_3\,\Delta w^{c_4}}{L} \quad (3)$$

with the characteristic length L, which is in the considered model an artificial slip band thickness and the material constants c_3 and c_4.

Due to numerical efficiency one computed cycle N in the model represents a huge number of cycles in a real fatigue test.

A schematic representation of the progressive damage degradation is shown in **Fig. 1b** with the elasticity modulus E, the yield stress $\boldsymbol{\sigma}$, the equivalent plastic strain at the onset of damage $\bar{\boldsymbol{\varepsilon}}_0^{pl}$ and the equivalent plastic strain at failure $\bar{\boldsymbol{\varepsilon}}_f^{pl}$. The damage initiation and evolution criteria (Eq. 2 and Eq. 3) for example also applied in [5] and [6].

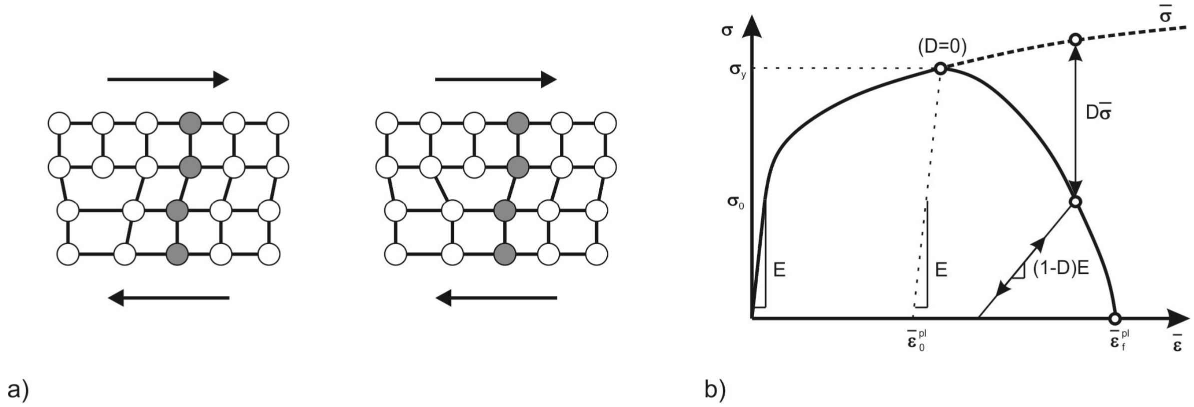

Figure 1. Movement of dislocations (a) and schematic representation of the progressive damage degradation (Abaqus [7]) (b).

3. NUMERICAL MODEL

The developed model to describe the initiation of cracks in welded joints is a crystal plasticity model in the sense of a Dugdale und Barenblatt [2, 3] type approach. Hence, the plastic deformation is projected onto a thin layer. In **Fig. 2b** a finite element model of one grain with a slip band is shown. The assumed damage mechanism by which a global loading in the elastic dimension yields to a plastic deformation along the slip band justifies this approach.

In **Fig. 2a** the model of Dugdale [3] is shown with the far field stress σ^{∞} which applied to the edges of an infinite sheet in direction perpendicular to an internal cut of the length $2c$. The plastic zone with the length R and the yield stress σ_y define the cohesive zone ahead of the physical crack tip.

In order to model the crack initiation in welded joints, models of primary periodic grain structures which are generated using the Voronoï tessellation [8] are considered (**Fig. 3**). The potential slip band directions arise from the randomly allocated grain orientations (**Fig. 3b**). In this study the crack initiation occurs at the surface but it is also possible to assume interior defects as crack initiation spots. Furthermore, tensile fatigue tests are simulated with the boundary conditions shown in **Fig. 3b**. The determination of the first slip band across which the crack will be propagated requires the computation of the favorable one. Therefore, the longest slip bands in the two potential directions per grain are identified and weighted by a Gaussian function in dependency on the deviation of the 45°-direction due to the fact that under compression and tensile loading in this direction the maximum shear stress occurs in this direction. This definition is chosen because it is well-known [9-11] that this is the preferred initial crack growth direction. Later on the crack kinks in the direction perpendicular to the loading direction [11]. As soon as all elements of the first slip band in the first grain are damaged due to cyclic loading, two new models are generated, each with one potential slip band in the neighboring grain in which all slip band elements already are damaged. In order to determine the crack growth direction, one cycle of loading is computed for both models. By means of the higher damage in the first slip band element the propagation direction of the crack in the considered grain is defined. By doing so, the further transgranular path of the crack is determined.

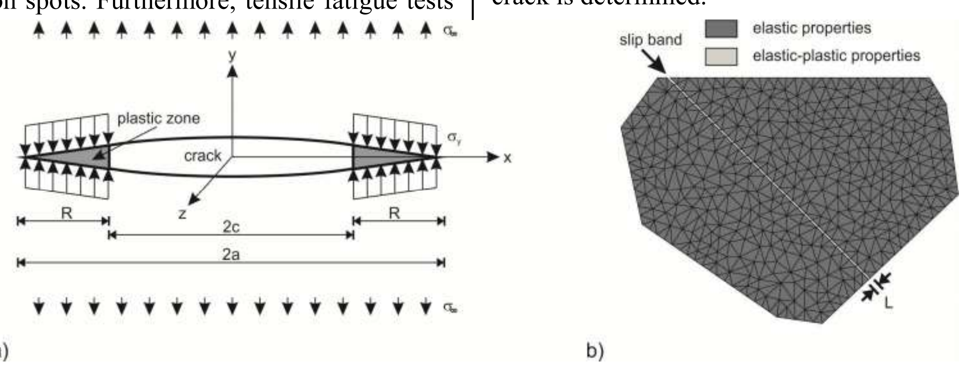

Figure 2. Dugdale plastic zone model (a) and finite element model of a grain with a slip band (b).

4. EXAMPLE

The following simple example shows how a distribution of number of cycles upto a pre-defined crack length in welded joints can be determined based on microstructure models and a damage definition. As shown in **Fig. 3**, cracks initiated on the surface in the heat affected zone of a welded joint are considered.

In a first step five microstructure models with an edge length of $L_{model} = 200\ \mu m$ are generated using the Voronoï process in order to obtain grains with a diameter of $d_{grain} = 50\ \mu m$. Elastic material properties with a Young's modulus of $E = 210\ GPa$ and a Poisson ratio of $\upsilon = 0.3$ are assumed. The slip bands have an elastic-plastic material behavior with the same elastic material parameter as the grains. In addition, a yield stress of $\sigma_y = 300\ MPa$ is estimated. Furthermore, the constants in Eq. 2 and Eq. 3 are defined by $c_1 = 0.1$, $c_2 = -0.98$, $c_3 = 0.0005$ and $c_4 = 1.0$ and one computed cycle N represents $n_{real} = 2000$ cycles in a real fatigue test. The damage is caused by a cyclic load with a strain amplitude of $\varepsilon = 0.00125$. The assumed boundary conditions are given in **Fig. 3b**. The computation of the crack propagation is cancelled as soon as the crack path has completely crossed four grains.

For the analysis the projected crack length L_{crack} perpendicular to the loading direction in dependency on the computed loading cycles $\bar{N} = n_{real} \cdot N$ is considered. The result for the first model is shown in **Fig. 4a** where in addition to the main crack the potential secondary cracks are considered. The corresponding grain microstructure with the randomly assumed grain orientations is given in **Fig. 4b**. Moreover, the potential slip bands and the crack path are plotted.

In **Fig. 4a** is clearly visible that during the crossover of the crack from the first to the second grain the energy-based criterion yields the crack propagation in the direction of the slip band in which a higher projected crack length together with a lower number of loading cycles in contrast to the other potential slip band direction is achieved.

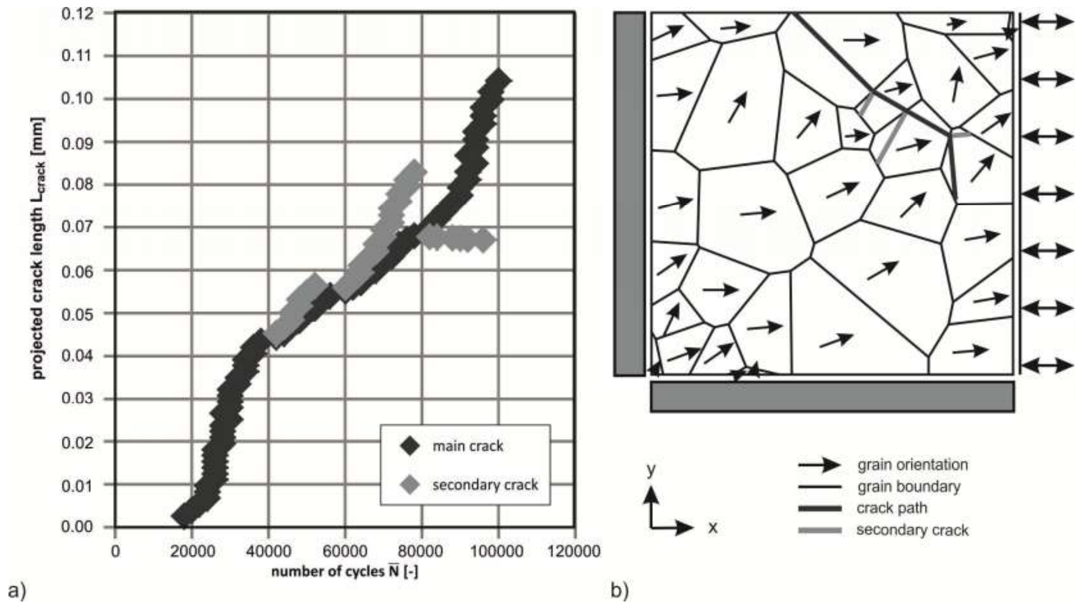

Figure 3. Crack growth (a) and polycrystalline model with crack path (b).

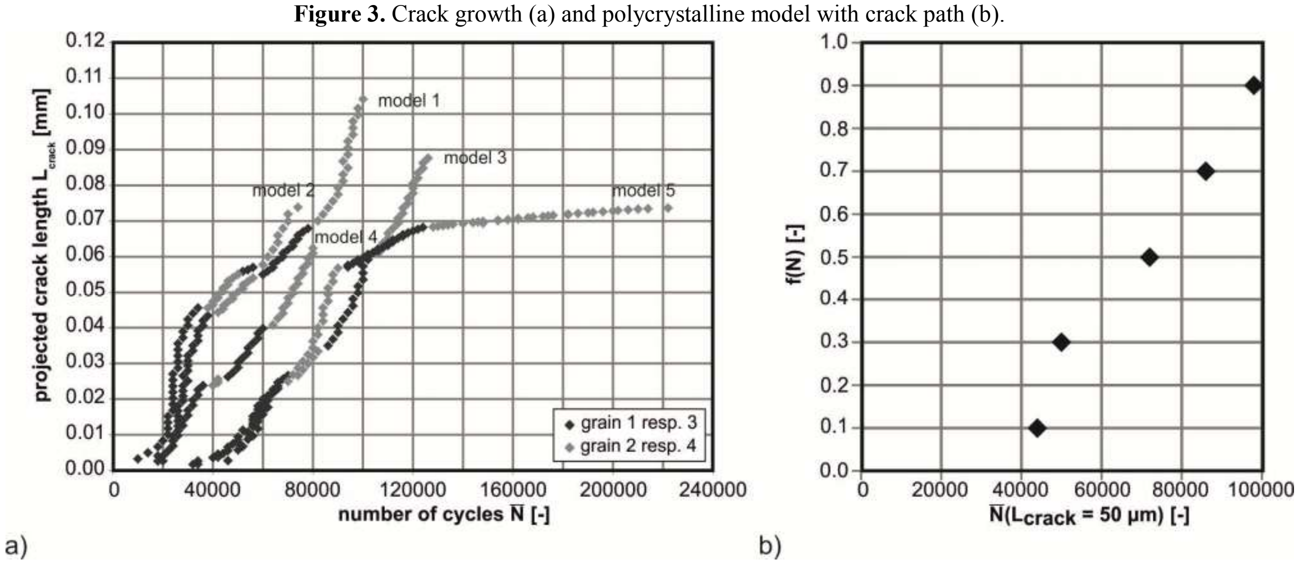

Figure 4. Crack growth (a) and distribution of the number of cyclesupto a pre-defined crack length (b).

During the transition from the third to the fourth grain the direction of the main crack is not conformed to the slip band direction which was primarily determined. Due to the fact that in spite of further cyclic loading this first determined direction is so inappropriate that the crack growth is stopped, the other slip band is chosen in order to predefine the crack propagation direction.

The projected crack length in dependency on the number of cycles for all computed models is plotted in **Fig. 5a**. The development of the crack propagation is similar but a significant spreading is observed. The peculiar deviation of the crack growth at the end of the computation for model 5 is due to the fact that the crack runs through a very huge grain along a slip band which orientation differs widely from the direction perpendicular to the loading direction. Hence, a huge number of cycles cause only a small growth of the projected crack length.

The example shows how a distribution of the number of cycles upto a pre-defined crack length is determined based on microstructure models. In this study an initial crack length of $50\ \mu m$ is assumed. Although the crack growth of all computed models is up to this crack length is very similar, a significant spreading is given as shown in the distribution in **Fig. 5b**. In this loading case the range of number of cycles which are necessary to achieve the assumed initial crack length is 44000 to 98000 number of cycles $\bar{N}$.

Furthermore, the comparison of model 2 and 4 in **Fig. 5a** shows that not only the time of damage initiation is the crucial factor but also the damage evolution – affected by the grain sizes and orientations as well as the potential slip band directions – has a huge influence.

5. CONCLUSIONS

The present study is concerned with the development of a numerical model in order to determine distributions of the number of cycles upto a pre-defined crack length in welded joints. The applied microstructure models are based on randomly generated grain structures and grain orientations. Crack initiation on the surface in the area of the heat affected zone is considered. The crack growth direction is predefined by potential slip bands which orientation is dependent on the grain orientations. The determination of the crack path in each randomly generated microstructure due to cyclic loading leads to similar results for the crack growth development but a significant spreading is observed. The crack length perpendicular to the loading direction is analyzed in dependence on the number of cycles. Based on these data a distribution of the number of cycles upto a pre-defined crack length could be derived which can be employed as an input parameter for different fracture mechanics evaluation concepts.

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