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Micromechanical investigation and numerical simulation of fatigue crack formation in welded joints

Carla Beckmann, Tobias Kennerknecht [1], Johannes Preußner, Majid Farajian, Michael Luke, Jörg Hohe *

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

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ABSTRACT

The present study is directed to the nucleation of micro cracks in polycrystalline metals due to fatigue. For this purpose, a micromechanics based numerical procedure is established. This procedure is based on the assumption that in the initial phase, the fatigue crack propagation follows the slip planes of the individual grains. The crack propagation is modelled in terms of a damage mechanics concept, assuming that fatigue damage is driven by the dissipated microplastic work. Using a generalized homogenization approach, the results of the micromechanical simulation are transferred to the macroscopic level. Using a stochastic finite element analysis, the corresponding uncertainty and scatter are assessed. The numerical scheme is validated against micromechanical experimental investigations of the crack formation using micro scale specimens with gauge sections in the range of 200 μm × 450 μm.

1. Introduction

In the design of welded joints, the assessment of the fatigue strength under cyclic loading conditions is an essential requirement. In structural application, different concepts have been established (see e.g. Hobbacher [11]). All these stress or strain based engineering concepts are based on S-N-curves, describing the number of cycles to fracture for a specified stress or strain amplitude level (Wöhler [31]). In this context, the S-N-curve depends on the type of weldment, loading conditions, stress ratios and other influence factors. As an alternative, the use of fracture mechanics concepts has been proposed by Maddox [20]. These concepts imply the advantage that all phases from macro crack formation to macroscopic crack propagation and final failure can be assessed in a similar manner. Nevertheless, the use of fracture mechanics concepts like the IBESS procedure (Madia et al. [21]) relies on the definition of an initial micro crack.

For determination of the initial micro crack sizes in fracture mechanics concepts, micromechanical approaches, modelling the initial crack growth through the polycrystalline microstructure, became increasingly popular during the past decades (e.g. Schick et al. [28]). Their advantage is their high precision due to the consideration of the real micromechanical processes during formation of micro cracks from nuclei to a reasonable size for valid assessment by macroscopic fracture mechanics approaches.

* Corresponding author.
E-mail address: joerg.hohe@iwm.fraunhofer.de (J. Hohe).

[1] Present address: Robert Bosch GmbH, Renningen, 70465 Stuttgart, Germany.

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Nomenclature

a	crack depth
a_i	initial crack depth for fracture mechanics fatigue assessment
c_1	material parameter
c_2	material parameter
D	damage parameter
J_2	second invariant of deviatoric stress
N	number of cycles
n	number of nuclei in Voronoï process
p_i	nucleus in Voronoï diagram
R	stress ratio
R_e	elastic limit stress
r_E	Euclidean distance
r_i	radius of surrounding sphere to nucleus p_i
r_L	distance in Laguerre geometry
t	time
V_i	Voronoï cell belonging to nucleus p_i
x_i	spatial coordinates
$x_i^{(j)}$	spatial coordinates of nucleus p_j
Δw	dissipated plastic work density per load cycle
σ	stress
σ_{ij}	effective stress components
σ_{ij}'	matrix stress components
σ_a	stress amplitude in cyclic loading
σ_max	upper value of cyclic stress
σ_min	lower value of cyclic stress
σ_mean	mean / average value of cyclic stress
$\Delta\sigma$	stress range in cyclic loading
ε	strain
ε_u	ultimate tensile strain

The initial fatigue crack growth from nuclei to macroscopic cracks occurs in two stages. In the initial stage I, the crack grows along slip systems and thus along the crystallographic directions of the respective grain. In the subsequent stage II, crack propagation occurs normally to the direction of the maximum principal stress. Thus, the growth of microstructurally short cracks with a crack depth in the order of magnitude of the grain size cannot be described by the standard models of fracture mechanics (Lankford [18]), but requires an explicit consideration of the polycrystalline microstructure. The subsequent growth of long cracks occurs in stage II. Provided that the plastic zone at the crack front is small compared to the crack length, their propagation can be described by standard fracture concepts. The transition between stage I and stage II usually occurs after crossing a limited number of grain boundaries (McEvily [22]).

Several models have been proposed for modelling the growth of short stage I cracks. In this stage, the crack propagation is controlled predominantly by dislocation dynamics (Laird [17] and Wilkinson et al. [30]). Hence, the crack propagation cannot be described using the methods available for long cracks directly. For this purpose, Wilkinson et al. [30] as well as Hasson and Melin [9] proposed a model for short fatigue crack propagation considering the dislocations in a slip plane in extension of the crack plane directly. The fatigue crack in this case is loaded in local mode II conditions. Dorquet [7] used an alternative approach including especially the barrier function of the grain boundaries. Riemelmoser et al. [27] proposed a dislocation based short crack model considering two inclined slip planes. With this type of approach, a realistic analysis of the initial stage of fatigue crack propagation becomes possible.

On the other hand, for the investigation of three-dimensional multi-grain problems, dislocation based models cannot be employed due to the numerical effort required for larger microstructures. For this purpose, finite element based microstructural models based on appropriate "effective" models are more popular. The short crack model presented by Navarro and de los Rios [24,25], based on an earlier approach by Taira et al. [29], employs a Dugdale [8] type modelling of the dislocation kinematics at the fatigue crack front. This model especially considers the barriers imposed by the grain boundaries. Based on their model, Schick et al. [28] performed a simulation of the propagation of short fatigue cracks through two-dimensional polycrystalline microstructures. This model has later been generalized to three dimensions by Köster et al. [15]. A similar short crack model has been presented by Hobson et al. [10] and later been improved by Angelova and Akid [2]. An overview has been provided by Hussain [12]. An overview can be found in a review paper by Christ et al. [6].