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Multiaxial fatigue assessment based on a short crack growth concept

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ABSTRACT

The fatigue life to initiate a crack of technical size is interpreted as a pure growth process of a mechanically short crack. A set of equations and corresponding simulation procedures are outlined which can be used to assess multiaxial, in especially including non-proportional variable amplitude loading of notched components. The prediction accuracy of this approach is compared to the accuracy of other approaches. The comparison was performed using experimental data recently published in a comprehensive investigation performed by Franz and Xin.

1. Introduction

All fatigue cracks in metallic materials originate at defects. These defects may have very different sizes and shapes. Line defects, this means edge and screw dislocations, are the providers of irreversible slip. In high purity metals intrusions and extrusions at the material surface are formed by the slip bands. They are the nucleus of a fatigue crack. Grain boundaries and shrinkage cavities are examples for area defects where fatigue cracks can initiate. Often non metallic inclusions or pores are found. Generally, each type of microstructural notch may serve as microcrack initiation driver. Tiny notches of several origins add to the list of defects, like for example abrasion traces from wear, corrosion, marks from turning, etc.

The initiation of a technical crack is usually defined when the crack is visible without a microscope. This means that a defect has grown to a length of about 1 mm. Detailed investigations of this fatigue process have revealed that short cracks grow during the usable life [1]. Since Paris [2] the growth of longer cracks was described by fracture mechanics. For the stage of technical crack initiation – which itself might be split in microcrack initiation and short crack growth – conventional approaches like the local strain approach are applied which do not explicitly refer to the physical process of defect growth. Despite that this stage is treated as a ”black box” where the failure process is disguised behind strain or stress life curves, damage accumulation rules, and multiaxial failure hypotheses. In such simulations, the three major issues contribute to uncertainties in fatigue life estimations, the limited transferability of material data obtained in a laboratory for describing the fatigue behaviour of components, the lack of damage accumulation rules to realistically take into account the effects of various load sequences, and the uncertainty in the assessment of multiaxial stress states.

A large amount of research was dedicated to the investigation and accompanying modelling of short crack growth behaviour with the aim to reduce the inaccuracies of conventional fatigue life estimation approaches. The accuracy of damage accumulation under variable amplitude loading was significantly enhanced by modelling the sequence-dependent opening and closure of short cracks [3,4]. A similar way of modelling was applied by Topper et al. [5–7] and Lynn and DuQuesnay [8]. Origins of limited transferability of material data may be identified in residual stresses, surface roughness, non-homogeneous stress states, and size. Some of these influences can be well explained using a short crack approach. For example, the non-homogeneous stress field in notches affects the crack driving force. These stress fields can be explicitly taken into account [9–11]. Considerable efforts have been dedicated to model the effect of size, in particular the statistical size effect, on fatigue assessment. From the viewpoint of a short crack approach, the probability of exposure of a large, strength-reducing defect increases with the surface of the highly stressed material. Several procedures have been developed which also combined the consideration of the statistical size effect and the influence of non-homogeneous stress fields [12–17].

The short crack approach was introduced for the assessment of multiaxial fatigue [18] where an equivalent strain intensity factor, defined using the maximum shear strain range $\Delta\gamma_{\max}$ and the normal strain perpendicular to the associated plane were used as crack driving force. Reddy and Fatemi [19] linked the Fatemi and

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Nomenclature

a	crack depth
a_κ	parameter of the Weibull distribution
A	highly stressed surface
A_i	variables in crack opening stress equation
b	fatigue strength exponent
c	fatigue ductility exponent
c	half-length of surface crack
C	crack growth constant
E	Young's modulus
F	fading constant
J	J-Integral
k	Fatemi–Socie parameter
K'	cyclic strength coefficient
K_t	stress concentration factor
l^*	microstructural constant for short crack threshold description
m	crack growth exponent
n	number of applied fatigue cycles
n'	cyclic hardening exponent
N	number of fatigue cycles to failure
P	cumulative probability
R	ratio of minimum and maximum values in a fatigue cycle
R_m	ultimate tensile strength
$R_\mathrm{p0.2}$	stress at 0.2% plastic strain offset
S	normal net section stress
T	shear net section stress
U_eff	factor for calculating effective mode II and III ranges
W	strain energy density
Y	geometry influence function
x, y, z	axes of coordinates
Z	cyclic J-Integral
Δ	indicator for ranges of a fatigue cycle
ε	normal strain
ε'_f	fatigue ductility coefficient
γ	engineering shear strain
κ	Weibull-exponent
μ	friction constant
ν	Poisson ratio
σ	normal stress
σ_F	yield stress average
σ'_f	fatigue strength coefficient
τ	shear stress
τ_F	shear yield stress average
τ_act	shear stress threshold value according to crack face indentation

Indices

0	initial value
I, II, III	crack opening modes
cl	value at crack closure
eff	effective value
eqv	(von Mises) equivalent value
E	endurance limit
f	final value
fric	value according to friction
F	value according to yield
FS	according to Fatemi and Socie
LC	value according to long cracks
max	maximum value
min	minimum value
n	value in normal direction
op	value at crack opening
ref	reference value
SC	value according to short cracks
SWT	according to Smith, Watson and Topper
th	threshold value
VA	variable amplitude
x, y, z	axes of coordinates

Socie [20] parameter with the strain intensity factor. The Fatemi–Socie parameter belongs to the critical plane class of multiaxial failure hypotheses. Crack initiation, growth and failure are supposed to occur in a specific plane which is oriented in way that it delivers shortest lives. Generally, short crack growth modelling is closely related to critical plane approaches to multiaxial fatigue because the plane of fastest crack growth has to be identified, too. Critical plane approaches are popular since the early application of Findley [21] until today [22–26].

Socie and Furman [27] included microstructural influences in their assessment. Using this approach, not only the growth of a single crack but also the initiation and coalescence of many such cracks is taken into account. Zenner et al. [28,29] proposed a similar model. Hoshide and Socie [30,31] employed a J-integral-based formulation. Matvienko et al. [32] proposed different equations for stages I and II of short crack growth where stage I means initial growth along slip planes and stage II means growth perpendicularly to the direction of the maximum principal stress. McDowell et al. [33–35] extended the work of Hoshide and Socie. A survey of failure criteria was published by Rozumek and Macha [36]. For describing long fatigue crack growth under mixed mode loading a survey on experimental and numerical work was collected by Zerres and Vormwald [37].

For the important special case of proportional loading, Savaidis and Seeger [38,39] developed a short crack model based on the uniaxial model of Vormwald et al. [3,4]. Using the short crack model proposed by Döring et al. [40–43], non-proportional loading can also be assessed. The short crack approach was extended to take the size effect for notched components into account [44]. A further extension was proposed for application to multiaxial variable amplitude loading [45]. In particular, the load sequence effects due to crack closure, as modelled previously [3,4], were taken into account. This model addresses the three aforementioned issues that contribute to the uncertainty in fatigue life estimations. In the present paper, the model is applied for calculating the fatigue lives to technical crack initiation of specimens experimentally investigated recently by Franz and Xin [46]. The present study is intended to increase the experience with the prediction accuracy of the model. Comparisons of experimentally and numerically determined lives are not only provided for the short crack model but also for two common multiaxial damage parameters, the Fatemi–Socie [20] and the multiaxial version of the Smith-Watson-Topper [47,48] parameter.

2. Short crack model

The comprehensive description of the model is given in Ref. [45]. Here, the basic features are recapitulated.

2.1. Local stresses and elastic–plastic strains

The local stresses and elastic–plastic strains under multiaxial constant and variable amplitude loading are basic model input information. The information has to be provided for the fatigue crit-