ON THE DESCRIPTION OF FATIGUE CRACK PROPAGATION IN THE STRESS FIELD OF NOTCHES

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For linear-elastic material, the endurance limit of notched specimens and the threshold values of small as well as macrocracks can be described using integral parameters that characterize the cyclic loading within a finite volume of material ahead of the notch root or crack tip, resp. As long as the plastic deformations at the notch root are small, the parameters controlling crack propagation in the stress field of notches are analogous to parameters derived for linear-elastic material.

INTRODUCTION

The loading state near cracks and sharp notches is characterized by a highly inhomogeneous and multiaxial stress state. Concerning elastic-plastic material behaviour this equally applies for the local strain and energy density distribution. The knowledge of the local stress and strain distribution, which is calculated by continuum mechanics methods, enables to derive integral loading parameters, which are suited to evaluate the limiting local loading state ahead of cracks as well as sharp notches.

Within the frame of linear-elastic fracture mechanics the loading state at a fatigue crack can be described by means of the cyclic stress intensity range. However, this single parameter description fails to be adequate for

- large-scale plasticity (with respect to the dimensions of the body)
- short cracks (compared to the microstructural size scale)
- mixed-mode loading and
- cracks emanating from sharp notches.

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Concerning local failure to be determined by plasticity and cracking processes over a microstructure related size scale even very different loading situations should become comparable on the basis of a locally avaraged loading parameter ΔB_{vm}

$$\Delta B_{vm} = \frac{1}{V*}\int_{(V*)}\Delta B_m(x,y,z)dV = \frac{1}{d*}\int_{d*}\Delta B_v(x)dx \tag{1}$$

where v^*, d^* - volume and distance, resp., of microstructural size scale (in Neuber`s microsupport approach: d^*= "Ersatzstrukturlänge")

ΔB_{vm} - equivalent loading parameter for the stress or strain state according to the relevant strength hypothesis and material

In spite of an overall proportionality to the grain size, which is sometimes claimed, a general and quantitative relation between d^* and v^*, resp., and a well defined microstructural size scale could not yet be established [3]. Therefore, this figure should merely be taken as an additional empirical parameter, which enables the description of strength phenomena under highly inhomogeneous loading situations. In principle, this parameter should be derivable from experiment, e.g.

- from the endurance limit of differently notched specimens
- from crack initiation data for notched specimens in the finite life range
- from the crack growth characteristics of mechanically short cracks

It could be shown by the authors [1,2], that the effects of cracks and notches on the endurance limit are successfully described using this generalized microsupport approach. In the following, the capability to adequately describe crack propagation is discussed.

From numerical calculations it could be shown, that the strain distribution at cracks and sharp notches for realistic material behaviour is very similar to the elastic case, if the near-tip plastic zones are not too large and the crack initiation (μm cracks) life time amounts to $N_A \geq 10^3$ [4].

CRACK GROWTH OF SMALL CRACKS ON SMOOTH SURFACES

Using the integral loading parameter ΔB_{vm}, the growth of mechanically short cracks can be deduced from the macrocrack behaviour, as shown in [2]. Ignoring for the first the crack closure phenomenon and assuming linear-elastic material behavior, we get for a crack in a large plate according to the main normal stress hypothesis

$$\Delta B_{vm} = \Delta\sigma_n\sqrt{1+\frac{2a}{d*}} \tag{2}$$

Using $\Delta K=\Delta\sigma_n\sqrt{\pi a}$ equ.(2) becomes for constant load cycling, i.e. $\Delta\sigma_n$=const.,

$$\Delta B_{vm} = \sqrt{\frac{2}{\pi d^*}} \cdot \sqrt{(\Delta K)^2 + \frac{\pi d^*}{2}(\Delta\sigma_n)^2} \tag{3}$$

Thus, the near-threshold crack propagation kinetics under a fixed load ratio R can be expressed by modifying well-known empirical equations as follows

$$\frac{da}{dN} = C\left[\Delta B_{vm}\sqrt{\frac{\pi d^*}{2}} - \Delta K_{th}\right]^m \tag{4}$$

or
$$\frac{da}{dN} = C_1\left[\left(\Delta B_{vm}\sqrt{\frac{\pi d^*}{2}}\right)^{m_1} - \left(\Delta K_{th}\right)^{m_1}\right] \tag{5}$$

In these equations C, C_1, m and m_1 are material dependent parameters. Adopting d^* as a free parameter allows a lower threshold of short cracks to be described adequately by these equations too. Obviously, a decreasing crack growth rate of short cracks, which might result from microstructural effects [7] or from a build-up of the crack closure phenomenon during initial crack advance, can not be predicted because those phenomena are outside this approach. Apart of this an in general sufficiently conservative evaluation of the short crack behaviour at smooth surfaces is provided.

The capability of the parameter ΔB_{vm} to describe short crack growth was proven in [2] by analysing experimental results for a carbon steel S10C in a fine grained as well as in a coarse grained condition [5]. The propagation of individual short cracks turned out to be described by equ.(4) with sufficient accuracy when using the macrocrack data ΔK_{th}=8,07MPa$\sqrt{m}$, C=9,80x10^{-11}, m=2,32 (da/dN in m/cycle), and adopting

- d^*= 180μm for the fine-grained steel (d_{mean}=24μm), and
- d^*= 250μm for the coarse-grained steel (d_{mean}=84μm), resp .

When determined from short crack data the value of d^* might, in principle, depend on the nominal cyclic stress level because of interfering crack closure and plasticity effects. But in the presented example an unique description proved to be adequate for the two material conditions in the whole nominal cyclic stress range applied, i.e. for $\Delta\sigma_n$= (360...620)MPa.

GROWTH OF SHORT CRACKS AT NOTCHES

The fatigue limit of severely notched bodies is usually much lower than that for smooth specimens. Taking the correspondingly lower nominal cyclic loading during testing into account, it should be possible to evaluate the crack propagation behaviour near sharp notches using loading parameters derived for a linear-elastic material. Refering to section 2, cracks at notches are termed mechanically short with respect to the above definition of the loading parameter, as long as they are small compared to d^*, or compared to the extent of the stress field of the notch. Combining the loading parameter for short cracks at notches according to [6] with the mean loading parameter as derived above gives (see Fig.1):

$$\Delta B_{vm} = \Delta\sigma_n \sqrt{\pi a\left(1+7{,}69\sqrt{\frac{a_K}{\rho}}\right)} \cdot Y \cdot \sqrt{\frac{2}{\pi d^*}} \cdot \sqrt{1+\frac{d^*}{2a}} \qquad (6)$$

$$for \quad a < 0.13\sqrt{a_K \cdot \rho} - \frac{d^*}{2}\left(1+0.13\sqrt{\frac{\rho}{a_K}}\right)$$

and

$$\Delta B_{vm} = \Delta\sigma_n \sqrt{\pi(a_K+a)} \cdot Y \cdot \sqrt{\frac{2}{\pi d^*}} \qquad (6a)$$

$$for \quad a > 0.13\sqrt{a_K \cdot \rho} - \frac{d^*}{2}\left(1+0.13\sqrt{\frac{\rho}{a_K}}\right)$$

The function Y represents a geometrical factor. For notches of equal depth but different notch tip radius this factor is taken as constant within the range of short cracks.

In Fig.2 experimental data on the early crack propagation at notches and on the near threshold growth behaviour of macrocracks (R=0) are shown for a constructional steel St45.8. The experiments were performed near the fatigue limit using bend specimens having an identical notch depth but different root radii. The measured crack growth rates are shown in Fig.2 in dependence on the formally calculated ΔK, with the actual crack length indicated at the curves (viz.[3]). Adopting again the term d^* in equ.(6) as a free parameter it is possible fit all curves of Fig. 2 by using a d^*=150µm. The result is demonstrated graphically in Fig. 3. Obviously, all data points describing the growth of short cracks at the notch root fall into a narrow scatter band around the macrocrack growth curve, which is given by equ.(5) with ΔK_{th}=8,7MPa√m, C_1=1,93x10^{-13}, and m=4,0. Additionally it is interesting to note, that the value d^*=150µm is in reasonable agreement with the value d^*=122µm, that was determined from the fatigue limit data of differently notched specimens of the same steel.

ACKNOWLEDGEMENT

The financial support of this research by the Deutsche Forschungsgemeinschaft is gratefully acknowledged.

REFERENCES

[1] S. Sähn, Th. Pyttel: "Berechnung von Kerbwirkungszahlen und Kurzriß-verhalten bei zyklischer Belastung"; 17.MPA-Seminar, Stuttgart 1991

[2] S. Sähn: "Festigkeitsverhalten von Bauteilen mit kleinen Rissen und Kerben bei zyklischer Belastung"; Konstruktion 43(1991), 9-16

[3] P. Seliger: "Rißbildung und -ausbreitung an Kerben unter zyklischer Belastung"; Dissertation A, TU Dresden, 1989

[4] V.B. Pham: "Beanspruchungszustand an scharfen Kerben und Rissen unter zyklischer Belastung für elastisch-plastisches Materialverhalten / numerische Berechnungen mit dem Programmsystem MARC"; 1993, unpublished work

[5] K. Tokaji, T. Ogawa, Y. Harada: "The growth of small cracks in a low carbon steel, effect of microstructure and limitations of linear elastic fracture mechanics"; Fat. Fract. Eng. Mat. Struct. 9(1986) 3, 205-217

[6] R.A. Smith, K. J. Miller: "Fatigue cracks on notches"; Int. J. Mech. Sci. 19(1977), 11-22

[7] K. J. Miller: "The behaviour of short fatigue cracks and their initiation"; Fat. Fract. Eng. Mat. Struct. 10(1987), 75-113

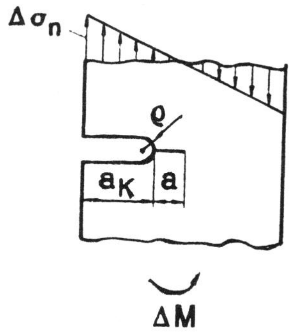

Fig. 1: Notched specimen with a crack at the notch root under a cyclic bending moment ΔM

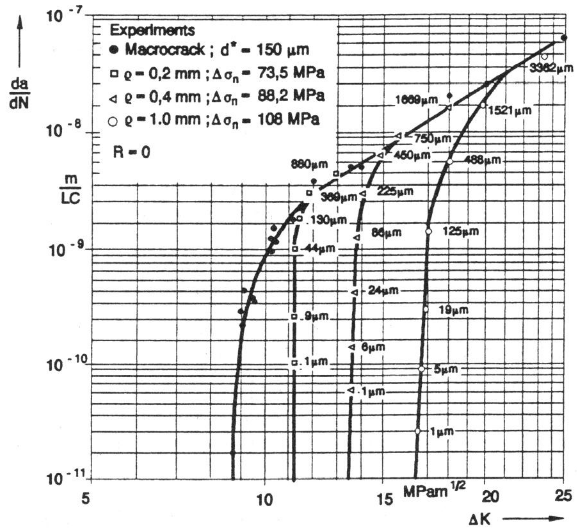

Fig. 2 Near-threshold fatigue crack propagation of macrocracks and short cracks at notches, $\Delta K = f(a_K + a)$, ferrititc-pearlitic steel

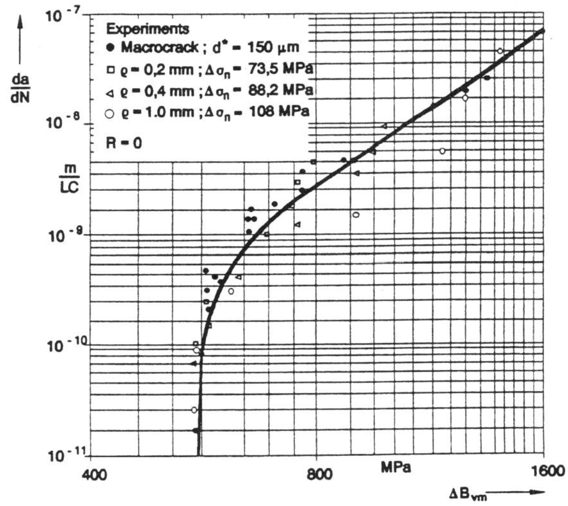

Fig. 3 Fatigue crack propagation of macrocracks and short cracks at notches, loading parameter ΔB_{vm}, data from Fig. 2