FATIGUE CRACKS AT SHARP NOTCHES

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Abstract: The initiation and propagation of cracks at sharp notches and the influence of overloads are investigated experimentally and with FEM analysis. The inadequacies of the ΔK_{eff}-concept with the usually defined value K_{op} are shown. It is suggested to estimate the fracture parameter from the local cyclic straining ahead of the crack tip.

INTRODUCTION

The fatigue life of cyclic loaded components comprises of both crack initiation and propagation stages. The proportions of these stages in the total life depend on the component geometry (smooth, notched), on material and on the load level. A subdivision of the propagation stage in small and long crack growth is necessary in a phenomenal description because of the different crack closure behaviour.
The crack initiation is well described by the local cyclic strain range, averaged over an on the microstructure dependent area (d^*), [1].
In this paper, the description of the crack propagation is investigated by local straining.

EXPERIMENTS

Table 1 and Fig.1 show the specimen and notch geometries. In Table 1 the used testing machines are also specified ([3, 4]).

Table 1: Specimen geometry

	Testing machine		
	REA 3		Cracktronic70
b/mm	20	20	10
d/mm	5	10	5
a_K/mm	4	4	2
ϱ/mm	0.25 0.5 1.0	0.25 0.5 1.0	0.25 0.5 1.0
γ_K	45^o und 0^o		

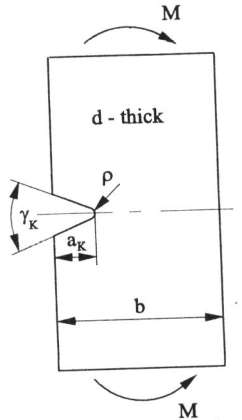

Fig. 1: Specimen and notch geometry

The materials used in this study are the fine grain alloy Metasafe 900 and the austenitic alloy X6CrNiTi18.10. The chemical composition and the strength and material characteristic values are shown in Tables 2 and 3. k and k', n and n' are the constants of the Ramberg-Osgood relation.

- *Table 2: Chemical composition in weight% of METASAFE 900 (*) and X6CrNiTi18.10 (**)*

	C	Si	Mn	S	P	Cr	Ni	Ti	Mo	Cu	Al	V
(*)	0.29	0.12	1.78	0.037	0.012	0.29	0.07		0.06	0.19	0.041	0.10
(**)	0.097	0.76	1.27	0.026	0.006	17.5	11.15	0.52				

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• *Table 3: Strength and material characteristic values*

	E [MPa]	$R_{p0.2}$ [MPa]	R_m [MPa]	A_g [%]	A_5 [%]	Ramberg/Osgood			
						quasi static		cyclic	
						k/[MPa]	n	k'/[MPa]	n'
(*)	$2.09.10^5$	630	900	7.6	19.1	1251	0.1093	1608	0.165
(**)	$2.0.10^5$	232	623	53	58	1275	0.113	1363	0.195

For Metasafe 900 and R=0 there are also known: $\Delta\sigma_D = 700$MPa and $\Delta K_{S0} = 5.1$MPa$\sqrt{m}$.

CRACK INITIATION AT SHARP NOTCHES

The crack initiation is well described by Eq.(1) ([1, 2, 4]):

$$\left(\Delta\varepsilon_{vm} - \Delta\varepsilon_D\right)^n N_A = K_1\left(1 - \frac{\varepsilon_{vm}}{\varepsilon_{crit}}\right) \tag{1}$$

$$\Delta\varepsilon_{vm} = \frac{1}{d^*}\int\limits_{(d^*)} \Delta\varepsilon_v(r)\,dr \tag{2}$$

d^* - characteristic length depending on the microstructure (Neuber: Ersatzstrukturlänge), d^*=20μm for Metasafe 900 and d^*=100μm for the austenitic steel.
$\Delta\varepsilon_v$ - cyclic equivalent strain range
ε_{vm} - quasi static strain in notch root area
$K_1, n, \varepsilon_{crit}$ - material characteristic values

$\Delta\varepsilon_v$ in the notch root is received from FE analysis or from different approaches ([3, 4]).
The local cyclic strain range $\Delta\varepsilon_v(l^*)$ in a distance l^* from the notch root or the crack tip depending on the microstructure is a comparable measure:

$$\Delta\varepsilon_{vm}(d^*) \approx \Delta\varepsilon_v(l^*)$$

For elastic material behaviour is $d^* \approx 4l^*$.
Overloads influence the crack initiation by the residual stresses which lead to a modification of $\Delta\varepsilon_D$:

$$\Delta\varepsilon_D = \frac{\Delta\sigma_D}{E} = \frac{2\sigma_W}{E}\sqrt{1 - \frac{\sigma_{vm}}{R_m}C_0} \tag{3}$$

For example $\Delta\varepsilon_v = \Delta(\varepsilon_1 - \varepsilon_3)$, $\sigma_{vm} = \frac{\sigma_{1m}+\sigma_{3m}}{2}$, C_0=2.
At the same time, an overload produces a quasi static damage ε_{vm}.
In comparison with the experimental observations the results of Eq.(1) show good coincidence for different loadings (Table 5).

CRACK PROPAGATION FROM SHARP NOTCHES

The simulation of crack propagation is performed by finite element (FE) analysis with the commercial program MARC. The crack is assumed to propagate from the notch root in the symmetry plane (in the ligament). Due to the symmetry, only one half of the specimen needs to be considered in the FE analysis. The mesh is comprised of 1333 isoparametric quadrilateral elements with 4360 nodes. The size

of the smallest elements in the ligament is 0.01mm. Thus, element lengths near the crack tip are 0.0005 of the total mesh width.
The crack is simulated to extend one element length at the maximum load during the cyclic loading by releasing the appropriate nodes. Gap elements are used in the ligament to avoid penetrating of crack faces.

The crack closure phenomenon, according to which fatigue cracks also close by cyclic tensile-tensile loading, is rendered principal correctly with the FE model. Plasticity-induced crack closure is caused by residual plastic deformations left in the wake of an advancing crack, which also lead to alternating stresses immediately ahead of the crack tip. A small crack does not have the prior plastic history to develop closure. Thus, small cracks are opened for a lower loading level than a larger crack. The different behaviour of small and macro cracks is represented in Table 4. σ_{op} is the stress, for which the crack is fully opened. For macrocracks and R=0, $\Delta K_{eff}/\Delta K$=0,54 for Metasafe and 0,53 for X6CrNiTi18.10, which is known from experiments.

Table 4: σ_{op}/σ_{max} for smooth ($\Delta\sigma_n$=234.4 MPa) and notched specimens ($\Delta\sigma_n$=150 MPa) dependent on crack length a, X6CrNiTi18.10, R=0, ESZ, σ_{op}: crack opening stress, σ_{max}: maximum stress, $\Delta\sigma_n = \frac{6\Delta M}{db^2}$

a [mm]	smooth specimen	notched specimen		
		without overload	200% overload	200% underload
0.01	0	0.267	0.4	0.333
0.03	0.021	0.267	0.433	0.367
0.05	0.191	0.3	0.467	0.367
0.07	0.234			
0.09	0.277			
...	...	...	...	...
0.45	0.404	0.467	0.9	0.367
...	...	...	...	...
1.50	0.426	0.467	0.733	0.4

The advance of the ΔK_{eff}-concept is its simplicity. Its inadequacies will be shown in the following two points:

- Crack closure and crack opening are continuous processes and the determination of σ_{op} and σ_{cl} is therefore difficult. Fig. 2 shows the crack face displacements in loading direction dependent on the applied load. It is difficult to point out the transition point to the fully opened crack or to the begin of crack closure.
- The load sequence below σ_{op} supplies also a contribution to the entire cyclic straining and hence to the damage. This is shown in Fig. 3, in which the development of the local straining (here ε_y in a distance l^*) ahead of the crack tip and the crack face displacement during a load cycle is represented.

Because firstly σ_{op} is difficult to determine and secondly the load sequence below σ_{op} also contributes to the total cyclic straining, one will find in literature different measurement and estimation methods for determination of σ_{op} from the load-displacement-diagram. For example [5]: σ_{op} is defined as the *intersection point of two tangent lines*, as the point of 5% *variation of the slope* or as the *transition point* from a linear part (according to the fully opened crack) to a second order part (according to the partially opened crack).

Thus, the definition of the closure load or opening load is somewhat arbitrary in such cases. At present, there are still efforts to find the most appropriate definition K_{op} and to determine σ_{op} "exactly", i.e. to estimate the proportion below σ_{op} more exactly. Generally that does not seem possible, because the proportion below σ_{op} of the entire straining depends on many influences like the material, the stress ratio R, the load level σ_{max} etc. This is one of the reasons for different, partially even opposite observations in the literature ([6]).

DISCUSSION

At first the question arises, in which area the global parameters like ΔK_{eff} are capable to describe the crack growth. A restriction is given by the crack size. These parameters are suitable only for macro cracks, for which a constant closure behaviour independent on the crack size can be assumed. However, the definition of a macro crack is not independent on the microstructure of the material.

A further limitation to the application of these parameters is given by the cyclic load level. Under conditions of cyclic small scale yielding ΔK_{eff} can be used for the description of the propagation of macro cracks also after preceeding overloads, if succeeds entering the influence of the produced residual stresses on the crack closure. On the basis of a parameter receiving for small cracks from the exact solution for linear elastic material, a parameter can be indicated for life time prognosis, which contains an additional free parameter d_0^*:

$$\frac{da}{dN} = C\left[\Delta K_{eff}\sqrt{1+\frac{d_0^*}{2a}} - \Delta K_{th,eff}\right]^m \tag{4}$$

or

$$\frac{da}{dN} = C\left[\left(\Delta K_{eff}\sqrt{1+\frac{d_0^*}{2a}}\right)^m - \Delta K_{th,eff}{}^m\right] \tag{4.1}$$

While C and m as well as $\Delta K_{th,eff}$ are material constants for the description of the macro crack growth, d_0^* is used for adjusting the small crack behaviour. d_0^* depends:

- on the microstructure (Neuber: Ersatzstrukturlänge d^*)
- on a plasticity correction and
- on the different closure behaviour of small and macro cracks

and should therefore depend on the load level. Within a relatively large area a conservative description of crack growth succeeds with $d_0^* \approx const.$ for the respective material.

This parameter, developed on continuum mechanical basis, is not able to describe the microstructure-dependent propagation behaviour of small cracks (thus, e.g. the crack growth retardation or the crack stop at microstructure barriers).

The global parameter $\Delta K_{eff}\sqrt{1+\frac{d_0^*}{2a}}$ characterizes the local strainings ahead of the crack tip in an area which is important for the damage development and thus for the crack growth. Inversely the above mentioned or similar parameters can be therefore gathered from the local cyclic strainings $\Delta\varepsilon_v(l^*)$. l^* depends on the microstructure. In Fig. 5 the cyclic equivalent strain range $\Delta\varepsilon_v = \Delta\varepsilon_y$ is represented as a function of the crack length for different load cases (Fig. 4).

From this picture it can be seen that the influence of the notch or the over-/ underloads continues to extend as the expansion of the plastic zone of the notch or the over-/ underloads do. This is the consequence of the plastic deformations in the crack wake, which also still influence the crack closure if the crack is out of the plastic zone.

The advantage of this strategy is that global parameters can be got from the local straining independently on the crack size within an area which is important for the damage. The disadvantage is the large expenditure with the help of numeric methods. Target of further investigations will be therefore to derive global generalizationable parameters from the local strainings ahead of the crack tip.

A formal derivation of ΔK_{eff} from the local strainings ahead of the crack tip e.g. for linear dependency and an adjustment of d_0^* for the small crack behavior supplies already a good coincidence with the experiments for different load cases (Table 5).

Table 5: Comparison of fatigue life from Eq.(1) and (4.1) with experimental results, notched specimen, ϱ*=0.5mm,* a_K*=2mm, b=10mm, d=5mm, Metasafe, R=0,* ΔM*=18Nm,* ΔM_{ov}*=45Nm,* ΔM_{un}*=45Nm*

Load case	a=10μm		a=500μm		a=2mm	
	Eq.(1)	exp.	Eq.(1)+(4.1)	exp.	Eq.(1)+(4.1)	exp.
1	$4.65\ 10^4$	$6.33\ 10^4$	$8.87\ 10^4$	$1.18\ 10^5$	$1.16\ 10^5$	$1.37\ 10^5$
2(overload)	$1.80\ 10^5$	$4.22\ 10^5$	$5.71\ 10^5$	$1.09\ 10^6$	$6.53\ 10^5$	$1.12\ 10^6$
4(underload)	$4.11\ 10^4$	$2.40\ 10^4$	$6.92\ 10^4$	$4.37\ 10^4$	$9.25\ 10^4$	$6.17\ 10^4$

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References

[1] S. Sähn and V.B. Pham, Fatigue'96 Berlin, Proc. of the 6.ICF, pp.129-134

[2] S. Sähn and V.B. Pham et al., Proc. of ECF 11, pp.1093-1098

[3] B. Wurm, S. Sähn and V.B. Pham: *Initiation and propagation of cracks at sharp notches under cyclic loading*, LCF 4, 1998

[4] T. Hamernik: *Einflußvon Überlasten auf die Bildung und Ausbreitung von Rissen an scharf gekerbten Proben*, Ph.D thesis, TU Dresden, 1997

[5] W.Yisheng and J.Schijve: *Fatigue Fract. Engng. Mater. Struct.* Vol.18, No.9, pp.917-921, 1995

[6] R. Kumar: *Engng. Fract. Mech.* Vol.42, No. 2, pp. 389-400, 1992

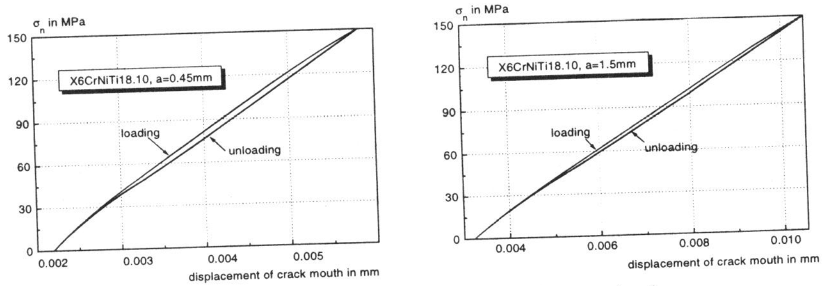

Fig. 2: Crack face displacement in load direction dependent on load

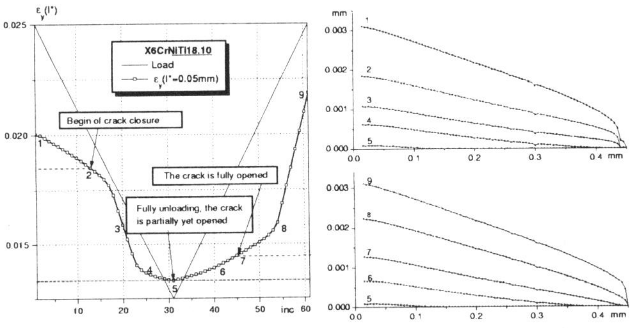

Fig. 3: Local strain in a distance $l^* = 50\mu m$ ahead of the crack tip and crack face displacement in load direction dependent on load

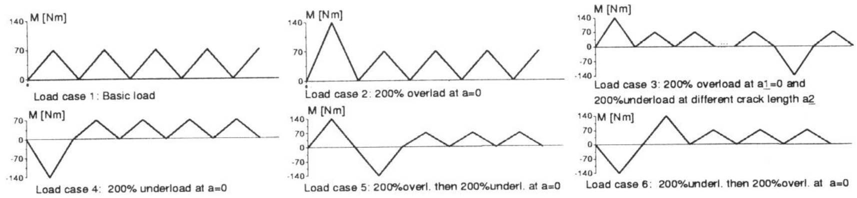

Fig. 4: Load cases

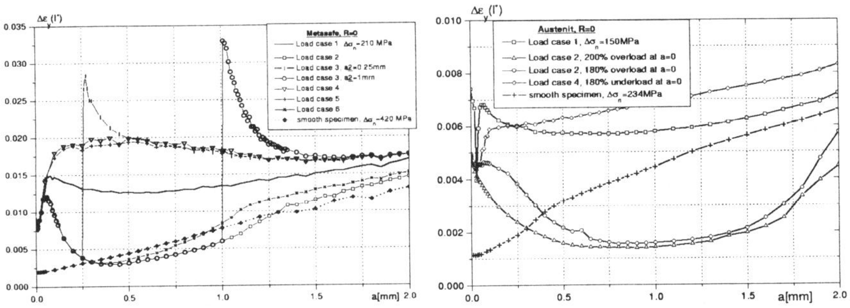

Fig. 5: Cyclic strain range in a distance l^* ahead of the crack tip for different load cases, R=0, notched specimen, ϱ=0.25mm, a_K=4mm, b=20mm, d=5mm, Metasafe 900: ΔM=70Nm, ΔM_{ov}=140Nm, ΔM_{un}=140Nm, $l^* = 15\mu m$; X6CrNiTi18.10: ΔM=50Nm, ΔM_{ov}=90Nm, ΔM_{un}=90Nm, $l^* = 50\mu m$, plain stress, combined hardening