Experimental investigations on crack initiation and threshold values

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ABSTRACT. *The beginning of the fatigue crack growth of so-called long cracks is defined by the threshold value of the material. For the determination of the threshold values different standards, e.g. ASTM E 647, are available. In these standards load-shedding methods are proposed with an exponential decrease of the load. The slope is defined as follows:* $C_{ASTM} = (1/K)(dK/da) \geq -0{,}08mm^{-1}$. *The R-ratio is kept constant during the whole experiment. However, the initial value of the stress intensity factor* $K_{max,0}$ *is not specified. Within the scope of this paper the influence of* $K_{max,0}$ *as well as a linear decrease of the force is investigated. Moreover the influence of the slope C is analysed using different materials. For the investigation of the crack initiation SN-curves are determined with notched and cracked specimen for different loading situations.*

INTRODUCTION

The whole lifetime of a component or a structure is composed of the initiation and the crack growth phase. The crack growth life starts with the exceedance of the long crack threshold value. For the determination of the threshold value many methods are available, which will be discussed within the scope of this paper. The problem of the different methods is that not all necessary parameters are well defined by standards. Therefore some investigations are presented, which show the influence of some parameters. The threshold value is of great importance, because besides the classical strength parameters like the tensile strength or the fatigue strength also fracture mechanical parameters come into the focus in the field of mechanical and traffic engineering. Thereby the threshold value of fatigue crack growth represents a significant design concept. However, crack growth is also observable below the long crack growth threshold, the so-called initiation. To determine this initiation lifetime different experiments are carried out with cracked as well as notched specimen. From the results SN-curves can be obtained, which then can be used for the calculation of the number of initiation cycles.

METHODS FOR THE DETERMINATION OF LONG-CRACK GROWTH THRESHOLD VALUE

In the literature [e.g. 1-6] different methods for the threshold determination are described. The methods can be divided into two main groups: methods I) with decreasing and II) with increasing stress intensity factor.

According ASTM E 647 [1] of the American Society for Testing and Materials the threshold value has to be determined with a decreasing stress intensity factor. This can be obtained with a constant stress ratio R or with a constant maximum stress intensity factor K_{max}. If the method with R = const. is used the cyclic stress intensity factor (SIF) ΔK is reduced using the following exponential function (Fig. 1a):

$$\Delta K = \Delta K_0 e^{C_{\mathrm{ASTM}}(a-a_0)} \tag{1}$$

i.e. both the maximum and minimum SIF are decreased. The slope C_{ASTM} is defined as follows:

$$C_{\mathrm{ASTM}} = \frac{1}{K} \cdot \frac{\mathrm{d}K}{\mathrm{d}a} \tag{2}$$

ΔK_0 in Eqn. 1 is the cyclic SIF and a_0 the corresponding crack length at the beginning of the threshold experiment. In order to avoid interaction effects due to the load reduction the load increments have to be chosen appropriately. This requirement is obtained by limiting the slope C_{ASTM}, i.e. $C_{\mathrm{ASTM}} \geq -0{,}08\ \mathrm{mm}^{-1}$. Moreover the load steps should not exceed 10% of the previous load and the width of the steps should at minimum 0,5 mm.

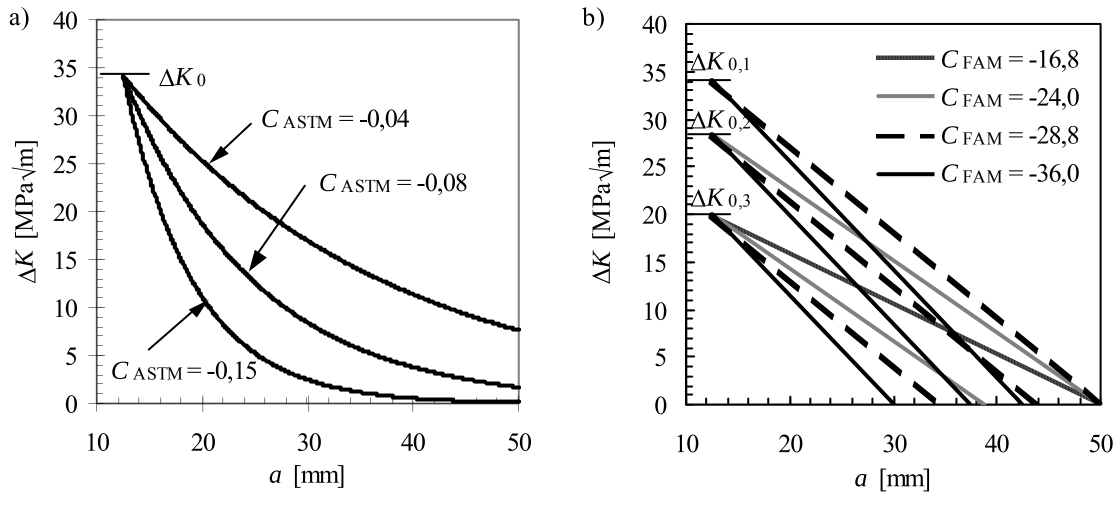


Figure 1. Load decreasing methods
a) Exponential decrease of ΔK with different slopes C_{ASTM}
b) Linear decrease of ΔK with different slopes C_{FAM}

At the Institute of Applied Mechanics of the University of Paderborn a linear decrease of the SIF is used (Fig. 1b), where the slope C_{FAM} is defined as follows:

$$C_{FAM} = \frac{d\Delta K}{da} = \frac{\Delta K - \Delta K_0}{a - a_0} \tag{3}$$

In contrast to the ASTM standard a crack growth increment of 0.05 mm is used. It can be shown that due to a crack growth increment of 0.5 mm the load step leads to interaction effects.

Besides the methods with $R = \text{const.}$ the threshold also can be determined using experiments with a constant maximum SIF. For the load reduction starting from a high cyclic SIF the minimum SIF is continuously increased. Due to the increase of K_{min} the R-ratio is changed, i.e. the R-ratio, at which the threshold value is reached, is not defined in advance. Döker [2] has shown that the threshold values are independent of the used method. In particular at high R-ratios the method with $K_{max} = \text{const.}$ should be preferred.

Tabernig and Pippan [3, 4] alternatively propose a load increasing method in order to avoid compressive residual stresses and crack closure due to load interaction effects caused by the load reduction. Based on a precrack, which is initiated with compressive cyclic loading, the loading is increased as long as the crack is growing. Tabernig und Pippan distinguish between the effective threshold value $\Delta K_{th,\,eff}$ and the threshold value ΔK_{th} for long crack growth. For $\Delta K_{th,\,eff} < \Delta K < \Delta K_{th}$ the crack is initially growing, but stops after a certain crack growth. From that load step, at which the crack is growing continuously, the threshold value ΔK_{th} is reached and the experiment can be continued for the determination of the crack growth curve.

EXPERIMENTAL SETUP AND PERFORMANCE

The central unit of the experimental setup consists of a servo hydraulic testing system with the appropriate controller and a PC with the interactive program system ^{FAM}Control for measurement data logging and controlling of the experiment [7]. For the crack length measurement using the potential drop method (DC) a constant current generator, a switch, a pre-amplifier and a modular interface system, consisting of an A/D- and a D/A-converter, is used. In order to avoid a potential drift, the current direction is switched after each measurement.

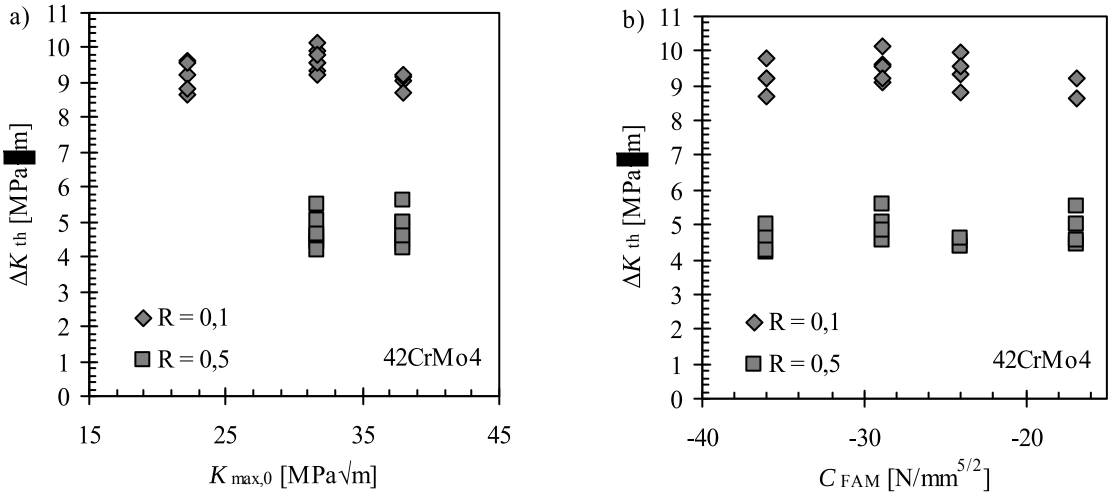
For the threshold measurements CT-specimen with a width $w = 72$ mm and a notch depth of 12.5 mm made from the quenched and tempered steel 42CrMo4 and the Aluminium alloy EN AW-7075-T651 are used. Both for the investigations of the influence of the slope C_{FAM} and the initial cyclic SIF $\Delta K_0 = (1 - R) \cdot K_{max,0}$ on the threshold values using a linear load decreasing different experiments with varying R-ratios are performed. Therefore the slopes $C_{FAM} = -16.8$, -24.0, -28.8 and –36.0 are combined with $K_{max,0}$-values of 22.14 MPam$^{1/2}$, 31.62 MPam$^{1/2}$ and 37.95 MPam$^{1/2}$. Furthermore the influence of the exponential decrease of the load is investigated. In order to investigate the validity of the requirement $C_{ASTM} \geq -0{,}08\ mm^{-1}$ following slopes are used: $C_{ASTM} = -0.04$, -0.08, -0.10 and -0.15, where $K_{max,0} = 37.95\ MPam^{1/2}$ and $R = 0.1$ is kept constant.

For the investigations of short crack growth a modified CT-specimen is used. The dimensions are kept constant, but a U-notch with a notch radius of 2 mm and a notch depth of 17 mm is used. The extension of the notch is necessary in order to compare the long crack growth of the CT-specimen with the short crack growth initiating at the U-notch. The so-called CTN specimen is made of the Aluminium alloy EN AW-7075-T651.

EXPERIMENTAL RESULTS

Long-crack growth threshold values

The results of the threshold experiments for the quenched and tempered steel, at which the load is linearly decreased, are shown in Figure 2.



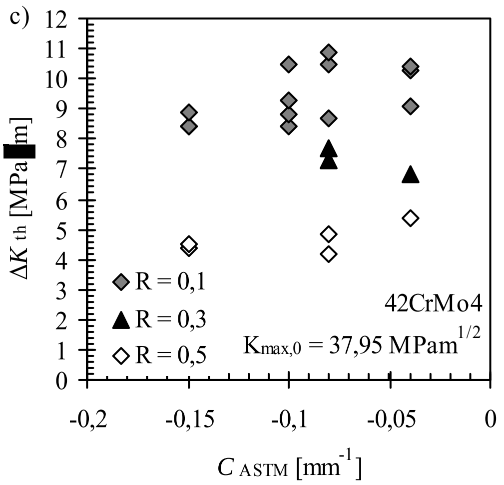


Figure 2. Threshold values for the quenched and tempered steel 42CrMo4 in dependence of

a) the initial maximum stress intensity factor $K_{max,0}$ (linear load reduction)
b) the slope C_{FAM} (linear load reduction)
c) the slope C_{ASTM} (exponential load reduction)

It becomes obvious that the threshold values determined with $K_{max,0}$ = 31.62 MPam$^{1/2}$ and an R-ratio of 0.1 on average are insignificantly higher than for the other used initial maximum SIF. This trend cannot be observed for an R-ratio of 0.5. Also the standard deviations show no correlation between ΔK_{th} and $K_{max,0}$ (Fig. 2a). Moreover no influence of the slope C_{FAM} on the threshold value is noticeable (Fig. 2b).

Using an exponential load reduction, the threshold is also not affected by the slope C_{ASTM} (Fig. 2c). However, the scatter of the data is much bigger than with a linear load-reduction. In particular the slopes C_{ASTM} of –0.08 and –0.1, which are permitted according to ASTM E 647, lead to standard deviations of 1.3 and 1.1 MPam$^{1/2}$, respectively. But on average the exponential and linear load-reduction methods lead to the same results.

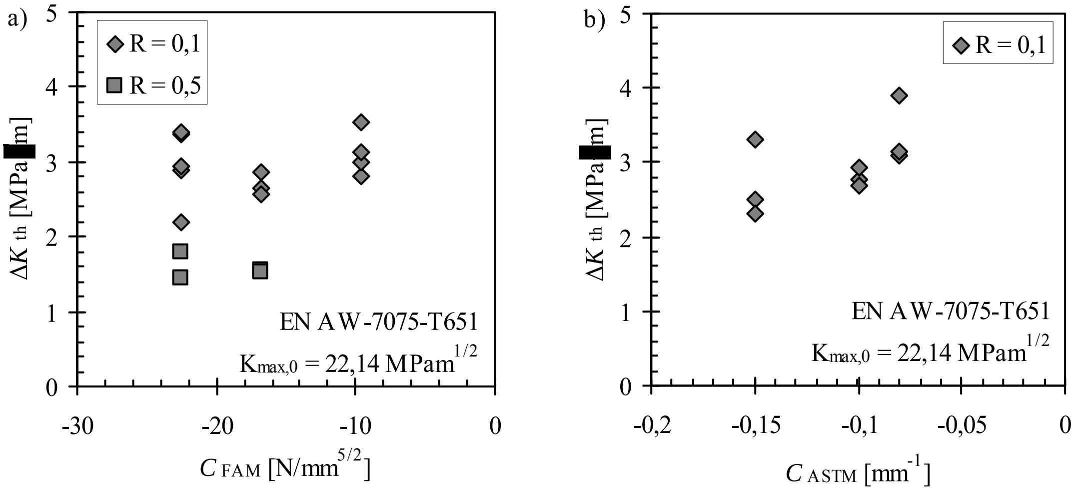


Figure 3. Threshold values for EN AW-7075-T651
a) linear and b) exponential load reduction procedure

In Figure 3 the threshold values for the Aluminium alloy EN AW-7075-T651 are given in dependence of the load reduction procedures and the appropriate slopes as well. It becomes obvious that both using a linear and an exponential load-reduction method the threshold values are changed with the slope. The higher the slope C_{ASTM}, the higher are the average threshold values (Fig. 3b). A linear load reduction leads to a more or less U-shaped curve. With an increasing slope C_{FAM} at first the threshold values decrease but later on they increase. In order to verify the statements further experiments will be performed.

Crack initiation

In order to investigate the crack initiation different experiments with CT and CTN specimen made from the Aluminium alloy 7075-T651 have been performed. In the first experiments a constant amplitude loading with varying mean load levels has been used. Figure 4 shows the SN-curves for the cracked (black triangles) and notched (grey rhombi) specimen. Moreover the SN-curve calculated with NASGRO for the appropriate CT specimen is given, which is in good agreement with the experimental results. The difference between the both SN-curves for CT and CTN specimen reflects the initiation cycles N_i. The slope of the SN-curve for the cracked specimen is 3.54, whereas the slope of the SN-curve for the notched specimen is 3.64.

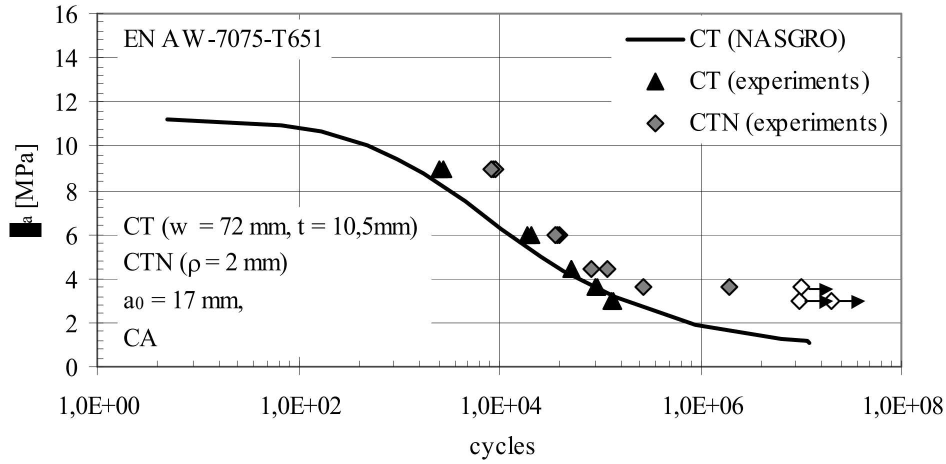


Figure 4. SN-curves for cracked and notched specimen under constant amplitude loading (CA)

In order to investigate the influence of overloads SN-curves have been determined from experiments, at which in a constant baseline level loading overloads with different overload ratios $R_{ol} = F_{a,ol}/F_{max}$ have been interspersed.

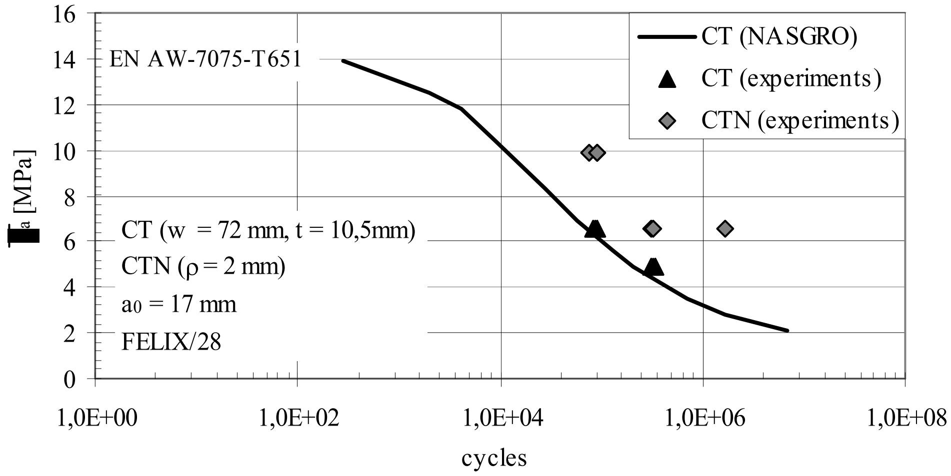


Figure 5. SN-curves for cracked and notched specimen under spectrum loading (FELIX/28)

The SN-curve of the notched specimen is almost not affected using the overload ratios of 1.5 and 2.0 and if the overload is applied at the first cycle. I.e. the crack initiation phase is not influenced as well. But for higher overload ratios a larger effect is observable. However, for higher stresses the overload ratio is limited by the fracture toughness K_{IC}.

Figure 5 shows the SN-curves for cracked and notched specimen under the standard load spectrum FELIX/28, whereby the negative loads are replaced by a positive value of 0.1 kN. It can be seen that the initiation cycles are much higher than under a constant amplitude loading (cp. Fig. 4). The slope of the SN-curve for the notched specimen is 6.44. Moreover the lifetime is extended due to the applied load spectrum.

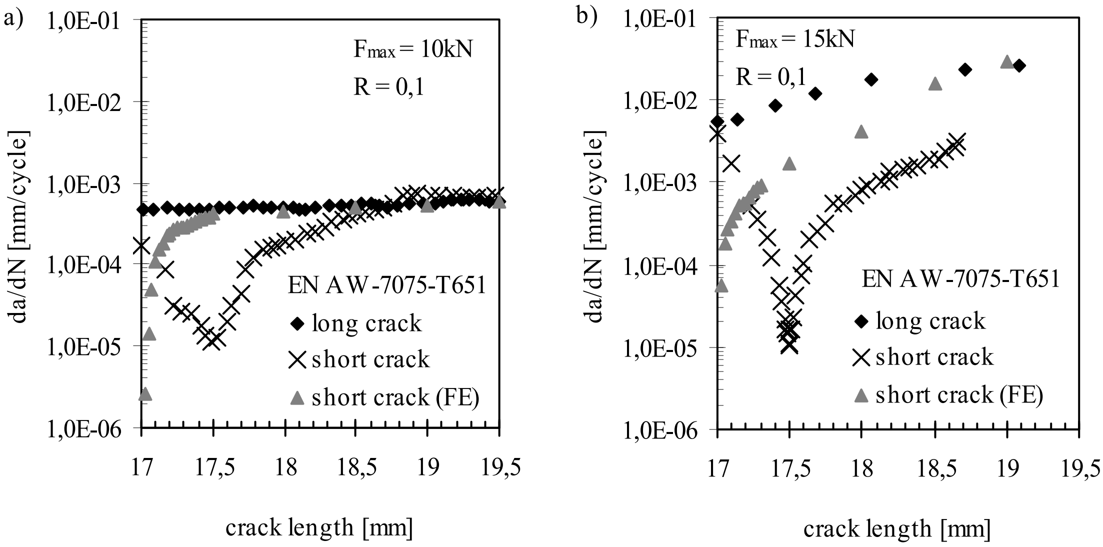


Figure 6. Comparison of experimental fatigue crack growth rates for long and short cracks as well as numerical fatigue crack growth rates for short cracks a) F_{max} = 10 kN and b) F_{max} = 15 kN

In Figure 6 a comparison of the fatigue crack growth rate *da/dN* of both a long and a short crack versus the crack length *a* is illustrated. It becomes obvious that at first the crack starts with a relative high fatigue crack growth rate, but retards afterwards. Later on the fatigue crack growth rate increases and converges to the long crack growth characteristics. The crack length increment, which is needed for such an adjustment, depends on the load level. Moreover Wingenbach [8] has shown for CTSN specimen that a dependence also exists on the notch radius. The larger the notch radius the smaller is the fatigue crack growth rate. In Figure 6 also numerically determined fatigue crack growth rates are given. These *da/dN*-values also converge on the long crack growth behaviour, but they show a different distribution than the appropriate experimental results. This difference is explained by the locations of crack initiation. Wingenbach [8] has demonstrated that in notched specimen the crack can initiate in the middle, eccentric or as a corner crack. Depending on the initiation location the distribution of the crack growth rate over the crack length is different (Fig. 7). If for instance the crack changes from an eccentric crack to a corner crack a steeper increase of the crack growth rate is observable [8]. Because this is not taken into account within a 2D finite element simulation the distributions are different.

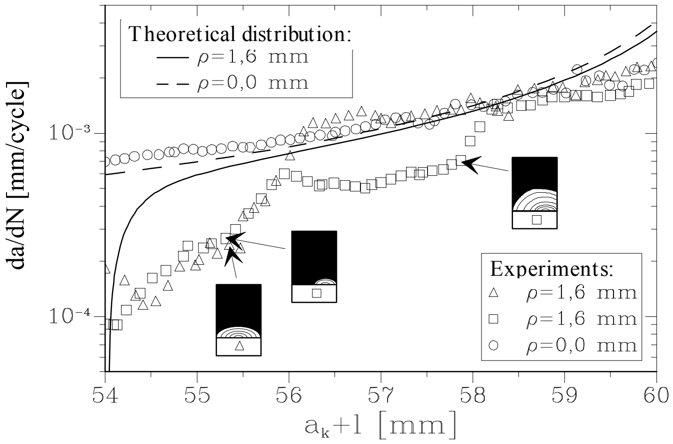


Figure 7.
Comparison of theoretical crack growth rates in the adjacencies of the notch with experimental data [8]

CONCLUSIONS

For the determination of threshold values different standards, e.g. ASTM E 647, are available. Within the scope of this paper different parameters of the threshold determinations have been investigated. It can be concluded that the initial value $K_{max,0}$ as well as the slope has no influence on the threshold values of the quenched and tempered steel, but there exists an effect on the investigated aluminium alloy. Moreover by means of SN-curve of cracked and notched specimen initiation cycles have been determined.

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