Crack initiation life of notched specimens

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Abstract. For the purpose of creating a technical structure or component it is necessary to attend both the structural analysis and the fracture mechanical analysis. In the context of the fracture mechanical analysis the crack initiation and propagation are investigated. Within the scope of this paper the characteristics of the different life phases and the influence of parameters, such as notch geometry and load, are determined. In this study regular CT specimens are modified by inserting different notches. These modified CT specimens, so called CTN specimens (compact tension notch), are fatigued with constant amplitudes to failure. During the tests the crack length is documented continuously, so that the crack length data versus cycles can be analysed. An initiation crack length is defined and the corresponding number of cycles is recorded as initiation life. The influence of the notch depth and size is shown in SN-curves. For the description of the crack propagation life SN-curves from cracked specimens (CT) are determined. The damage in the centreline of the notch is described by a conventional damage parameter. The input parameters are determined by a finite element analysis using the commercial software ABAQUS™. The damage parameter and the related fatigue life from the damage parameter SN-curve are used to determine the crack initiation life.

Introduction

A technical structure or component underlies nowadays very tough requirements. According to the lightweight construction guidelines the design should not be oversized, i.e. the material should be used to full capacity while meeting the very high demands of safety. To achieve this aim several concepts can be tracked. Within the stress-life approaches and the strain-life approaches the total life of a structure is divided into the life until an initial crack evolved and the propagation life, which describes the crack propagation until failure. According to the stress-life approaches the operating stress spectrum is divided into concrete load levels and for each load level the partial damage is determined with the help of the S-N-curve. The total damage is calculated by the summation of the partial damages and used to predict the lifetime of the specific component. There are a couple of theories to modify the usual S-N-curves to get the best results in prediction [1]. Using the strain-life approaches the total strain amplitude at the hot spot, i.e. the most stressed site in the structure, is the limiting factor concerning fatigue life. Such hot spots mostly are near notches like holes, drillings or cross-sectional variations. The elastic stress-strain situation at these locations can be determined using the stress concentration factor α and the nominal stresses or strains. Since also plastic deformations are present, analytical methods to detect the elastic-plastic stress-strain situation are used, for example Neuber´s rule [2] or the equivalent strain energy density (ESED) method from Glinka [3]. In addition, since high-performance computers are available, the stresses and strains can be solved numerically, for example by using the FE (finite element) method. To examine the damage accumulated at the hot spots a damage parameter is calculated and compared to an appropriate damage curve for investigating the crack initiation life. Such a damage parameter is for example the Smith-Watson-Topper parameter [4], the parameter of Vormwald [5] and the fatigue parameter of Golos and Ellyin [6].

However, the phase after crack initiation needs to be addressed, too. The crack growth regime can be divided into two parts: the growth of the so called small crack and the long crack. For describing the propagation life of long cracks fracture mechanical methods are applicable. If the crack growth curve is known, the remainig lifetime of a component can be calculated. But the transition phase between short and long cracks is not well understood, yet. Obviously the methods of long cracks cannot be adopted directly for short cracks [1]. Moreover, the situation becomes more difficult when complicated structures and geometries containing notches, weldings, etc. come into consideration.

The key objective of this study is to estimate the Smith-Watson-Topper damage parameter and to present the corresponding data pool concerning the initiation life. Keeping in mind that the hot spots often are in notches the influence of geometrical variations of notches on the initiation life and on the propagation life is determined. Moreover, the crack velocity of long cracks and short cracks results from notches are investigated.

Materials and methods

The specimens investigated are made of the commercial aluminum alloy EN AW-7075-T651, which is often used in aerospace industries because of the combination of high strength and low density. The chemical composition and the mechanical properties are shown in table 1.

Table 1: Chemical composition as defined in DIN 1725 and mechanical properties [1,7] of the aluminium alloy EN AW-7075-T651

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
0.40%	0.50%	1.2-2.0%	0.30%	2.1-2.9%	0.18-0.28%	5.1-6.1%	0.2%
E	$R_{p0,2}$	R_m	ν	ΔK_{th} (R=0,1)	ΔK_{th} (R=0,5)	K_{IC}	
70,656 MPa	517 MPa	579 MPa	0.34	3.1 $MPam^{1/2}$	1.4 $MPam^{1/2}$	32.9 $MPam^{1/2}$	
σ'_f	ε'_f	b	c	K´	n´		
1,231 N/mm^2	0.263	-0.122	-0.806	852 N/mm^2	0.074		

For the current investigations CT specimens in accordance to ASTM E 647 are modified by inserting a round notch. The geometry of the resulting CTN specimens is shown in figure 1. The notches are varying, the notch depth is $a_k = 17$ mm and $a_k = 37$ mm, respectively. For the radii the values $\rho = 2$ mm, 4 mm and 6 mm are chosen. These notches are manufactured by drilling. The notch root is grinded with silicon carbide papers (1200) to ensure a constant surface quality.

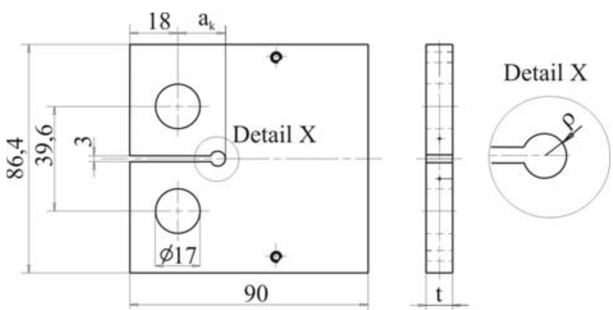


Figure 1: Schematic of the investigated CTN specimens

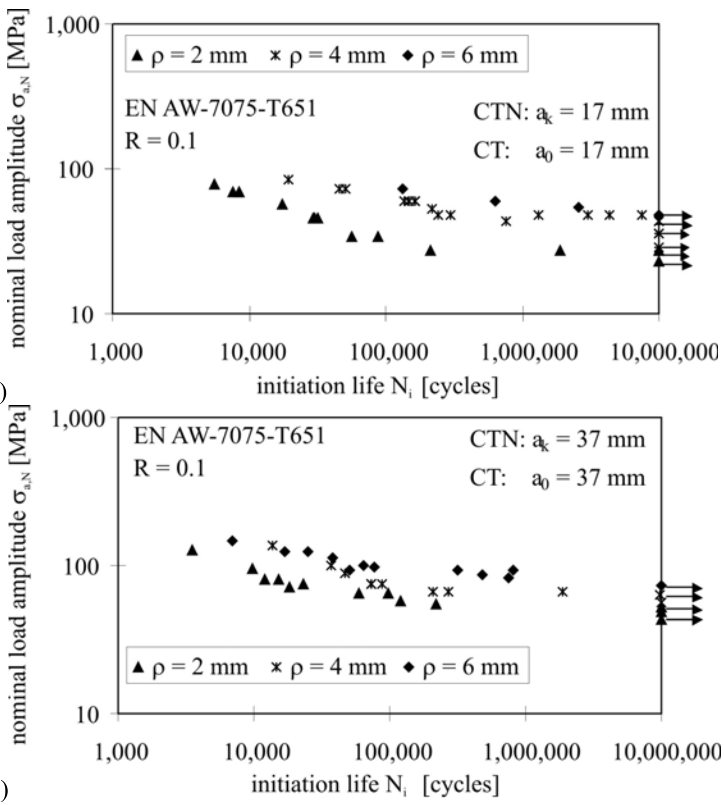
The specimens were fatigued under load-control with a sinusoidal loading waveform. The load amplitudes were constant for each test. Several tests were performed at different levels of load amplitudes. The R-ratio was R = 0,1 for all tests. Testing was carried out using a servo-hydraulic testing machine. Simultaneously to the tests the crack length was recorded by using the potential drop method. Further information on this is available in [8]. The crack length was recorded continuously, the crack initiation life is defined as the number of cycles, which is needed to obtain an initial crack length of $a_i = 0,5$ mm.

Results concerning initiation life

Experimental investigations. The S-N-curves in figure 2 display the effect of notch geometry on initiation life. The arrowed symbols represent CTN specimen, which show no crack initiation. In these plots the nominal stress amplitude is plotted against initiation life. The nominal stress resulting from the normal load and the bending moment in the ligament of the specimen is defined as follows:

$$\sigma_N = \frac{F}{A_{min}} + \frac{M}{W} = F\frac{4w + 2a_k}{(w - a_k)^2 t}. \tag{1}$$

It clearly can be seen that the initiation life of the CTN specimens increases, when the notch radius increases.



a)

b)

Figure 2: Experimentally determined initiation life against nominal stress amplitude for samples with a notch depth of
a) 17 mm and
b) 37 mm

However, the difference between the radius $\rho = 2$ mm and the other notch radii is quite large. The data for the higher radii are very similar, especially at high stresses. In the area of lower stresses, i.e. the region near the notch fatigue limit, the difference of the values is more pronounced. This observation is valid for both notch depths. Comparing the two plots in figure 2, for all considered notches the initiation life is higher, when the notch depth increases.

In table 2 the notch fatigue limits for the different notched specimens are listed. Notch initiation limit is the nominal stress level at which no crack initiated, that was capable to propagate. It is not statistically ensured that these data are real fatigue limits but they are in good accordance to the date shown in [9].

Table 2: Distinguished values for the initiation life curves of different CTN specimens used in this study

Notch depth a_k [mm]	Notch radius ρ [mm]	Slope k	Notch fatigue limit $\sigma_{a,nD}$ [MPa]	Cycles at notch fatigue limit N_{nD}
17	2	3.16	27.37	151,359
	4	5.81	43.11	958,908
	6	10.25	47.90	7,754,086
37	2	5.64	52.33	219,235
	4	7.04	56.45	1,279,679
	6	10.11	73.88	2,648,663

Smith-Watson-Topper parameter (P_{SWT}). Smith, Watson and Topper [4] proposed a simple parameter to correlate the damage and the real stress-strain response of the material. They expected the damage to be

$$P_{SWT} = \sqrt{\sigma_o \cdot \varepsilon_a \cdot E} = \sqrt{(\sigma_a + \sigma_m) \cdot \varepsilon_a \cdot E}\,, \tag{2}$$

i.e. the damage is proportional to the product of the maximum stress σ_o and the strain amplitude ε_a. This parameter can be plotted in terms of the damage parameter curve, which is defined as follows

$$P_{SWT} = \sqrt{\sigma_f'^{\,2} \cdot (2 \cdot N_i)^{2b} + \sigma_f' \cdot \varepsilon_f' \cdot E \cdot (2 \cdot N_i)^{b+c}}\,. \tag{3}$$

In this equation the total strain as the dominating damage factor is described by the approach of Coffin and Manson. Here σ'_f is the fatigue strength, ε'_f the ductility coefficient, b the fatigue strength exponent and c the ductility exponent. The data used for the current study is listed in table 1.

In the current study the stress-strain behavior in the notch root is calculated using the commercial FEM tool ABAQUS™/Standard. Figure 2 shows one of the 2D FEM models, which are used for the calculations. In the notch root the mesh is much finer than in the rest of the model, four-edge elements with linear displacement-approach are used. The element length at the notch root is 0.025 mm. The calculations are performed geometrical linear and plain stress is assumed. Since the Chaboche kinematic hardening method is used for simulation [10], the fitting parameters for this model are also given in figure 3. The actual procedure of the FEM calculations is very similar to the one presented in [9]. The highest stress occurs at the notch root. Therefore the stress-strain response at the first node in the centre line of the notch is calculated and the following analyses refer to this point.

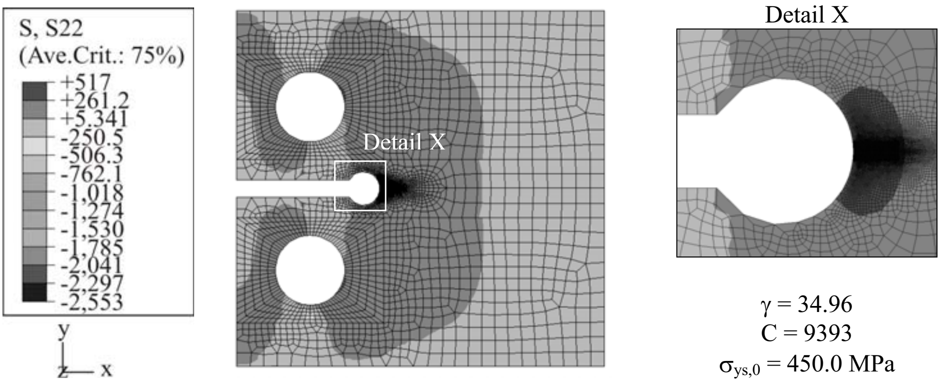


Figure 3: FE model and mesh of CTN specimen with a_k = 17 mm and ρ = 4 mm

With the simulated stress-strain response in the notch root, the Smith-Watson-Topper parameter is calculated. In figure 4 the calculated damage parameter is plotted against initiation life obtained from the experimental investigations. The black line represents the Smith-Watson-Topper (SWT) fit considering equation (3).

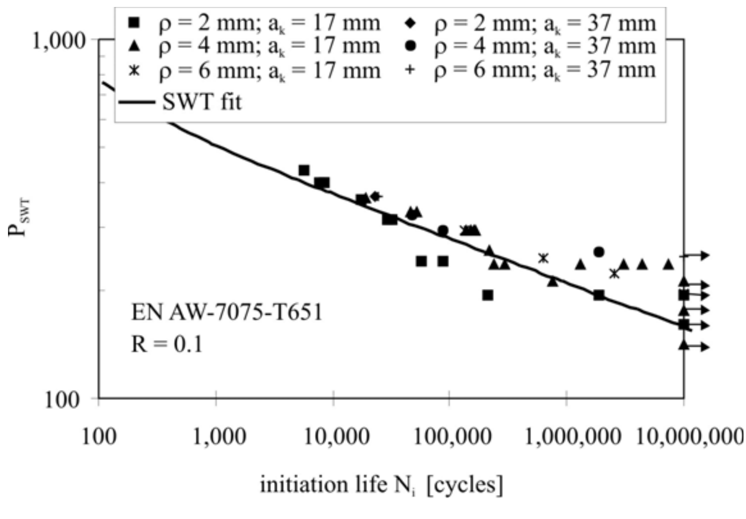


Figure 4: Smith-Watson-Topper parameter versus experimental initiation life for different notch geometries

Obviously the damage-S-N-curve fits well at high stresses. In the region of lower stresses the scattering of the experimental data increases, but the SWT fit is primarily conservative.

Results concerning propagation life

For the prediction of total life of a structure or specimen the propagation life has to be considered as well. The propagation life of a notched specimen is well described by the total life of a cracked specimen with similar geometrical attributes, such as the notch/crack depth.

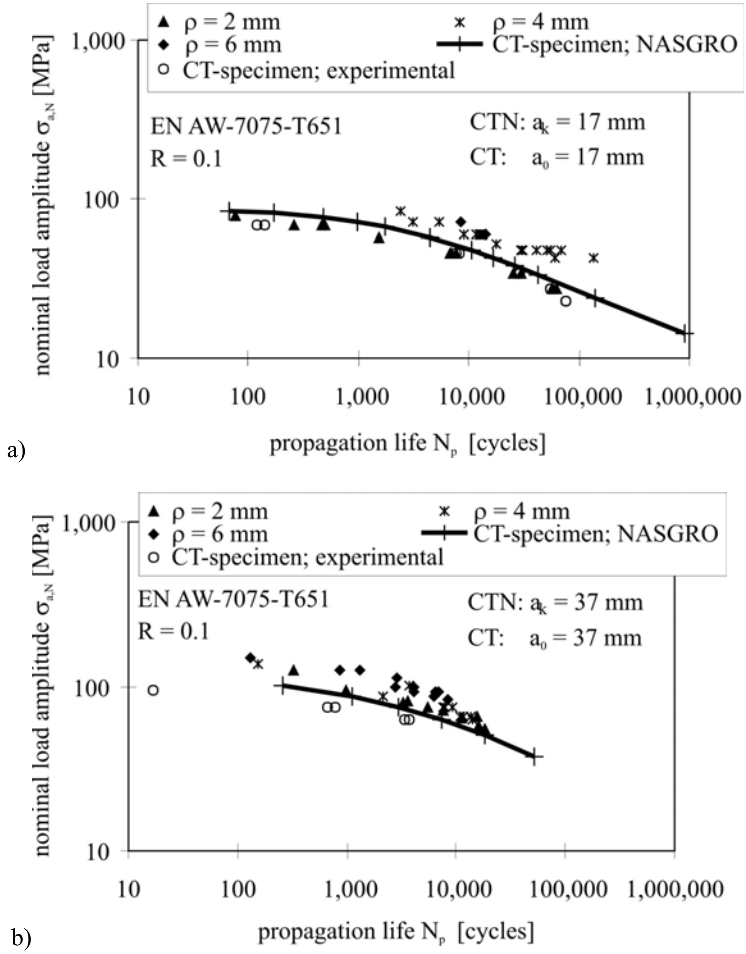
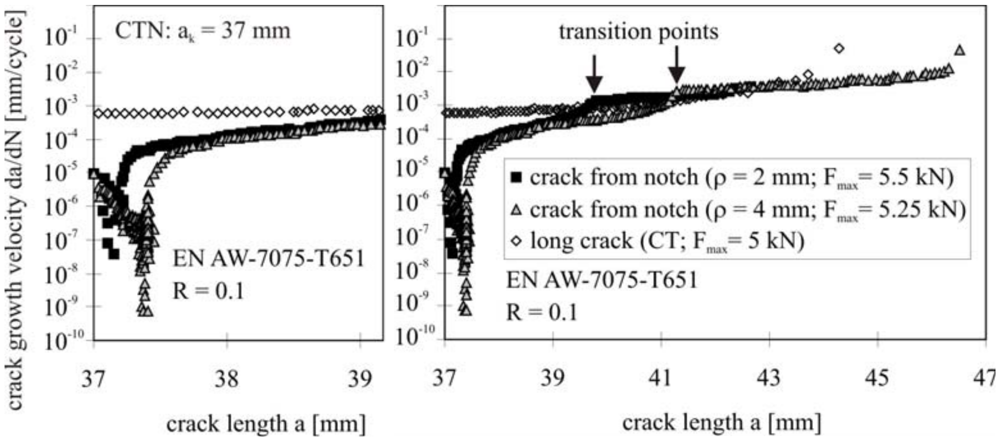


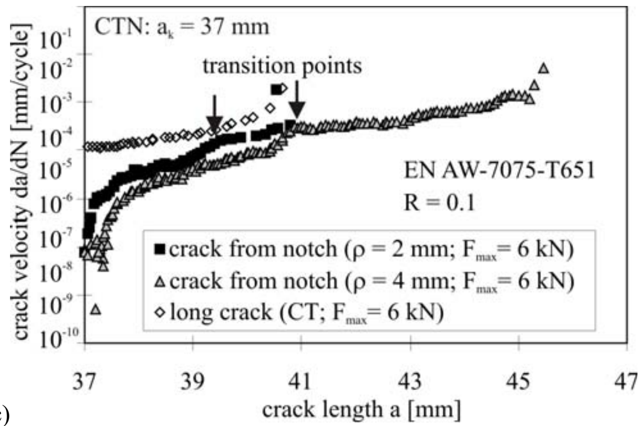
Figure 5: Comparison of the crack propagation life of CTN specimen and pre-cracked CT specimen for a notch depth of a) a_k = 17 mm and b) a_k = 37 mm

In figure 5 the propagation life of the CTN specimens compared to the total life of pre-cracked CT specimens is plotted. The data for CT is determined by experimental investigations marked by the blank circular symbols and by calculations with the program NASGRO, respectively. NASGRO is a tool developed by the NASA. It can be used for the examination of crack propagation behavior and total lives, while all the calculations are made on the basis of a huge underlying material database [11].

As shown in figure 5 the propagation life of the specimens with ρ = 2 mm can be described by the data of a cracked CT specimen. But with increasing root radius the deviation becomes more apparent as the notch has an increased influence on the stress distribution. Evidently, this effect is more pronounced for the longer notches as shown in figure 5b, especially at high stresses.



a) b)



c)

Figure 6:
Crack growth velocity versus crack length for
a) and b) a maximum load of ~ 5 kN, whereas a) is a detail of b) and
c) a maximum load of 6 kN

In figure 6 the crack growth velocity for long cracks and for cracks growing from a notch are shown. It clearly comes out, that the crack growth velocity of a short crack in vicinity of the notch (a_k = 37 mm, ρ = 2 mm and 4 mm) is lower than the velocity of an equivalent crack at the very beginning of growth in a CT specimen. For the small crack the velocity shows a minimum, then it increases again and converges to the level of the long crack. Similar observations are made in [12]. Moreover these results match the distribution of the stress intensity factor as shown in [1]. As indicated by arrows in figure 6b and c the transition to long crack velocity is abrupt and a kink is observed at this point. Here the crack is no more influenced by the notch and its growth behavior is similar to the CT counterpart. Obviously the point of transition is depending on the crack geometry as shown in figures 6b and c. With increasing notch radius a higher crack length is needed to achieve long crack growth level. As indicated by these plots the load situation seems to have no influence on the point of transition. The crack velocity of the smaller notch (ρ = 2 mm) achieves the long crack level and follows the according path. On the contrary, for the larger notch (ρ = 4 mm) long crack velocity level of the CT crack is reached as well, but the critical crack length for failure is higher than the one for CT long cracks. As shown in figures 6a-c the difference is dependent on the load level because the critical crack length for long cracks is strongly influenced by the load applied.

Conclusions

In the current study experimental investigations of CTN specimen containing round notches with different notch depths and notch radii are made. In respect to the two main phases of total life, i.e. initiation life and propagation life, the influence of the notch geometries is analysed.

The initiation life is highly dependent on the notch geometry. The specimens with larger notch radii show larger initiation lives, the same do the specimen with larger notch depths.

Regarding the initiation life within the actual study the Smith-Watson-Topper parameter is found to be a good approximation for evaluating the initiation lives at high stress levels for the investigated specimens. Even for lower stresses it can be used as it gives conservative results.

Crack growth in vicinity of the notch shows retardation at first, afterwards it is equal to the crack growth velocity of long cracks. For small notches the total life of pre-cracked specimen can be used to describe the propagation life of the notched specimen, while the propagation life of specimen with larger notches is higher due to the influence of the notch.

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