FATIGUE LIFETIME PREDICTION OF A NORMALIZED CARBON STEEL BASED ON SHORT AND LONG CRACK PROPAGATION

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In two levels cyclic loading, the length of the loading blocks, during which the loading parameters are kept constant, have a marked influence on the lifetime of the loaded parts. This effect can be explained and predicted by a short crack growth model which takes in account the crack arrest before microstructural barriers. The lifetimes after two levels cyclic block loading are calculated for a normalized carbon steel on the base of constant level data and found to be in good agreement with the measured lifetimes.

INTRODUCTION

Many attempts have been made to calculate lifetime in multi-level or random fatigue loading on the base of constant amplitude and mean stress or strain data. The earliest damage accumulation theory was formulated by Palmgren (1) and Miner (2) who defined the reciprocal value of the constant level lifetime as damage increment for one cycle. This means that the damage increment in random and multi-level loading is independent from the load history which is not conform with reality. If fatigue loading is applied in blocks with different loading parameters, the block length has a pronounced influence on fatigue lifetime (3).

Today, it can be assumed that the damaging process during fatigue of metals can be described as the initiation, propagation and in some times linking of cracks. The propagation has to be divided into two phases depending on the crack length. The propagation of small cracks is strongly influenced by the microstructure and often crack arrest was observed, when the crack tip reaches a microstructural barrier like a grain or a phase boundary (4-5). Linking of cracks can be observed in low and medium strength alloys when a certain crack density is reached during fatigue (6).

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EXPERIMENTAL RESULTS

Experimental work was carried out on the plain carbon steel with 0.45 % carbon in a normalized condition. The grain size was 8 ± 1 μm.

The specimens for fatigue tests had a rectangular cross section of 6 x 10 mm^2. The surfaces were ground. The fatigue loading was exercised in the push-pull mode with a frequency of 1 Hz, different mean stresses and load sequences. Table 1 shows a summary of the loading conditions and the resulting lifetimes. Figure 1 shows as an example the loading HL18.

loading type	σ_m MPa	σ_a MPa	N_H	N_L	N_f
H	140	240			38 782 ± 8 375
L	0	240			107 455 ± 22 980
HL18	0/140	240	5	13	24 525 ± 5 287
HL10800	0/140	240	3000	7800	76 258 ± 4 036

Table 1: Loading conditions and resulting lifetimes

Figure 2 shows measured crack propagation rates of short cracks under constant level loading. Crack stop was observed at pearlitic islands at the grain boundaries and ocurred at crack lengths till 140 μm. Figure 3 shows the density of cracks longer then 50 μm as a function of the number of cycles. Two-level loading with short block lengths leads to unexpected high crack densities.

CRACK GROWTH MODEL

The presented model for the growth of short cracks under cyclic loading is similar to that proposed by Grabowski and King (7). It is assumed that the effect of the loading on the crack propagation can be summarized by the Smith-Watson-Topper parameter:

$$p = [(\sigma_m + \sigma_a)\, \epsilon_a\, E]^{1/2}$$

The propagation rate is described by the following equation:

$$da/dN = v_{max} - (v_{max} - v_{min})\, a'/d$$

In the short crack region ($a < a_{th} = 1/\pi\ [\Delta K_{th}/2pY]^2$) the maximum and the minimum crack velocity are described as a function of the Smith-Watson-Topper parameter:

$$v_{max} = c_1\, p^{e_1}$$
$$v_{min} = c_0\, p^{e_0}$$

In the long crack region ($a_{th} < a < a_f$) a long crack term, which contains the crack length exceeding the threshold value, is added:

$$v_{max} = c_1\, p^{e_1} + c_2\, p^2\, (a-a_{th})$$
$$v_{min} = c_0\, p^{e_0} + c_2\, p^2\, (a-a_{th})$$

Figure 2 shows the modelled crack velocity as a function of the crack length. If crack linking has to be considered the maximum and minimum crack velocities have to multiplied with the term

$$1+d/(\delta^{-0.5}-a)$$

APPLICATION OF THE MODEL

Table 2 gives a view over the governing crack propagation parameters in the short crack region. The damage parameter after Smith, Watson and Topper was calculated on the base of strain amplitudes values that were taken from thesis of Walla (8). The threshold crack lengths were calculated from the threshold intensity factor measured by Hobson, Brown and de los Rios (4): $\Delta K_{th} = 6.0$ MPa$\sqrt{m}$. It was assumed that the cracks are semicircular and thus have a geometry factor of $Y = 2/\pi$. The values for the minimum and maximum crack velocity in the short crack regime without regarding crack connection were fitted to the experimental lifetimes. In this calculation the grain size was taken as the distance between the microstructural barriers.

loading type	p MPa	a_{th} μm	v_{min} nm	v_{max} nm
T	510	27	0.014	54
H	366	52	0.002	20
L	291	83	0.0005	10

Table 2: Parameters of the short crack propagation model ($a < a_{th}$)

From the long crack data of Hobson, Brown and de los Rios (4) $c_2 = 5.9\mathrm{x}10^{-10}$ was derived. On this base the crack velocity for long cracks was calculated. Failure was defined as a crack depth $a_f = 200\ \mu m$. For the calculation of the lifetime under block loading a transition cycle had to be taken into account due to the high stress range in the cycle of changing mean stress between two blocks. Table 2 shows also the features of this transition level. The consideration of crack connection due to high crack density was only for the short block loading of importance. Figure 4 shows all calculated lifetimes according to the Miner rule and the presented crack propagation model.

CONCLUSIONS

During cyclic block loading of a normalized carbon steel the lengths of the loading blocks have a marked influence on the lifetime. This effect can be explained by three mechanisms:

1. Between two loading blocks a transition halfcycle occurs with a stress range higher than in the constant level tests.
2. Short cracks often stop at microstructural barriers. An increase of the mean stress or the stress amplitude due to the beginning of a new loading block may help the crack to overcome the barrier.
3. The crack density was observed to be comparatively high in the short block loading: This may lead to a certain probability of crack connection and thus to an increased crack propagation rate.

The observed mechanisms can be described by a crack propagation model which is in good agreement with the measured lifetimes.

SYMBOLS USED

a = crack length (depth)
a' = crack length from the last barrier
a_f = crack length at failure
a_{th} = crack length according to the long crack growth threshold
cc = crack connection
d = distance between two microstructural barriers
E = elastic modulus
H = constant amplitude loading with high mean stress
HL10800 = block loading with with a sequence length of 10 800 cycles
HL18 = block loading with with a sequence length of 18 cycles
L = constant amplitude loading with low mean stress

N_f = number of cycles to failure
N_H = length of the loading blocks with high mean stress
N_L = length of the loading blocks with zero mean stress
p = Smith-Watson-Topper parameter
T = transition loading between two loading blocks
v_{max} = crack velocity after crossing a barrier
v_{min} = crack velocity before crossing a barrier
Y = geometry factor for stress intensity calculation

δ = crack density
ΔK_{th} = threshold of stress intensity factor for long crack growth
ϵ_a = strain amplitude
σ_a = stress amplitude
σ_m = mean stress

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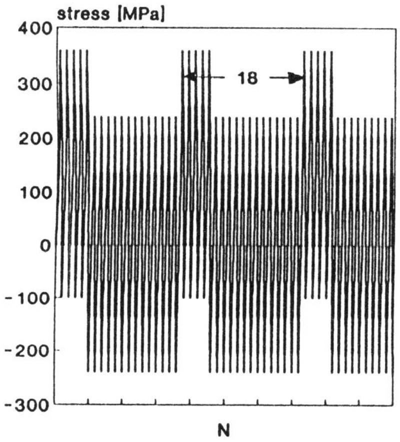

Figure 1: Stress course in the short block loading sequence HL18

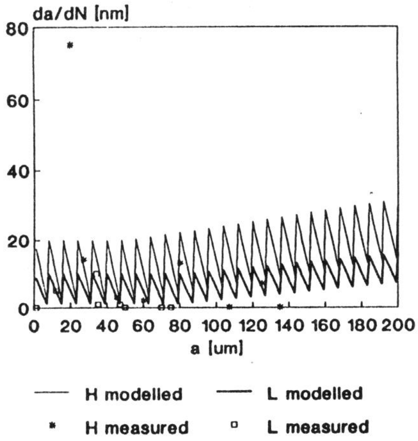

Figure 2: Measured and modelled crack velocities

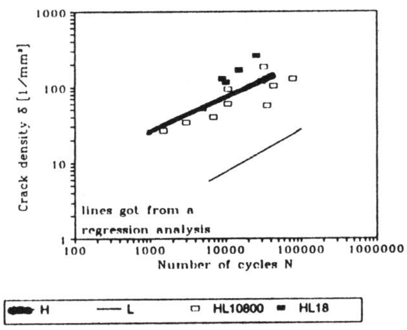

Figure 3: Density of cracks longer than 50 μm

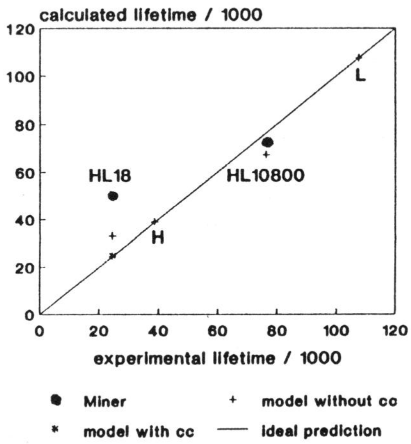

Figure 4: Calculated lifetimes after the Miner rule and after the presented crack propagation model