Development of Crack Growth Rate at Multiple Overloads

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Abstract

To improve the knowledge of fatigue crack propagation the development of the crack growth rate at multiple overloads with constant stress intensity, K, in steels has been experimentally studied. To keep K constant, a special test equipment has been developed at the Institute of Materials Science. Using a very high-resolution DC-potential drop method and recording the potential signal about 50 times per load amplitude, the crack propagation could be observed continuously with a cycle by cycle resolution of about 1µm. In multiple overloads the crack propagation within the first cycle $\Delta a_{OL,1}$ was found to be about hundred times greater than in the following cycles. This behaviour cannot be explained by LEFM. It was found that $\Delta a_{OL,1}$ may be explained by the crack tip opening displacement. However, in the following overload cycles the dislocation structure in front of the crack tip seems to control the crack growth as assumed by J. Weertman.

Keywords

Fatigue crack propagation, multiple overload, steel, lifetime prediction

1 Introduction

It is well known that in consequence of the fatigue of materials fracture occurs and leads to the failure of structures. However, up to now the development of cracks and their growth under variable amplitude loading is not fully understood, even than it has been studied intensively in recent years [1]. In order to improve the specialized knowledge on fatigue crack propagation the influence of multiple overloads (MOL) with constant stress intensity (K) on the crack growth rate has been studied in experiments on the steels X5CrNi18-10 and C45E. In these experiments especially the development of the crack growth rate during the overload cycles has been analyzed exactly.

2 Experimental Procedure

The influence of overloads on the crack growth rate can be analyzed in more detail when the crack growth rate is kept constant before and after the overload. To keep the crack growth rate constant in a fatigue experiment the stress intensity has to be controlled during the whole experiment. As the latter is not possible by standard dynamic testing machines a special test equipment has been developed at the Institute of Materials Science of the Bundeswehr University, Munich to carry out those experiments. The so-called Erika ("Ermüdungsrissausbreitung in korrosiver Atmosphäre" German for "fatigue crack propagation in corrosive atmosphere"), shown in Fig. 1, satisfies the desired requirements.

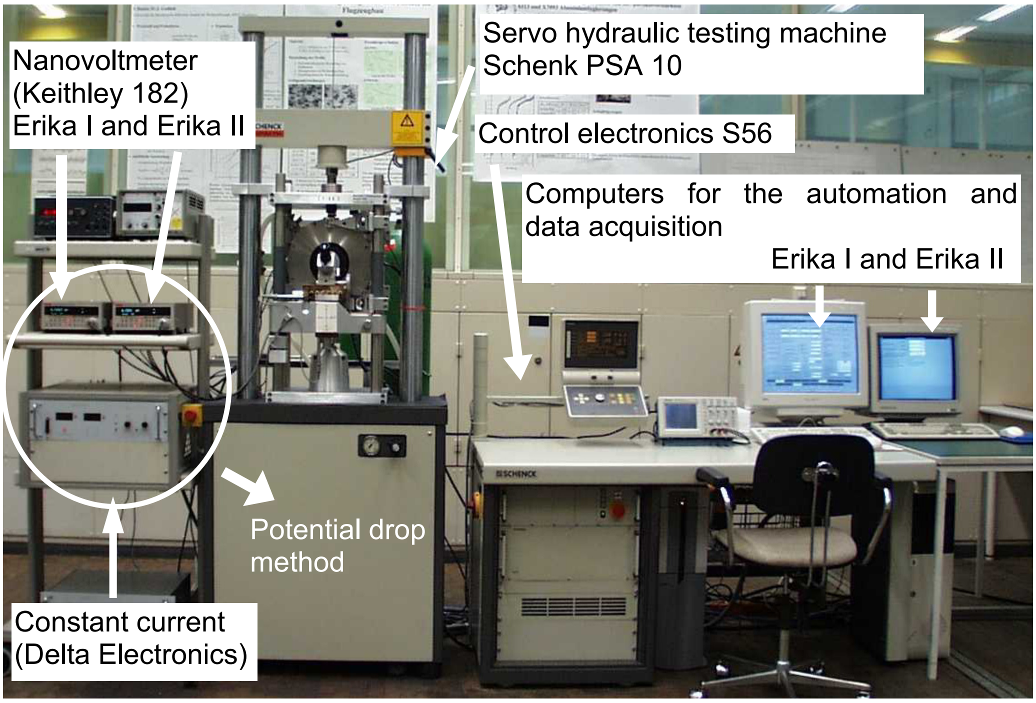

Fig. 1: Special test equipment for fatigue crack growth test, the Erika

The control of the stress intensity becomes possible as the crack length, which is measured by the potential drop method, is automatically logged by the two computers Erika I and II and the load is controlled by a proprietary software in reference to the actual crack length. During the overload experiment the data acquisition system Erika II records both the potential signal, which can be converted into the crack length by solving the potential equation with the function of Johnson [2], and the load data about 50 times per load amplitude. The load frequency is set to be 0.5 Hz during overloading.

The recorded data during a multiple overload obtained from an experiment carried out on X5CrNi18-10 are shown for example in Fig. 2. Here, the stress intensity which can be calculated from the recorded data is plotted, too.

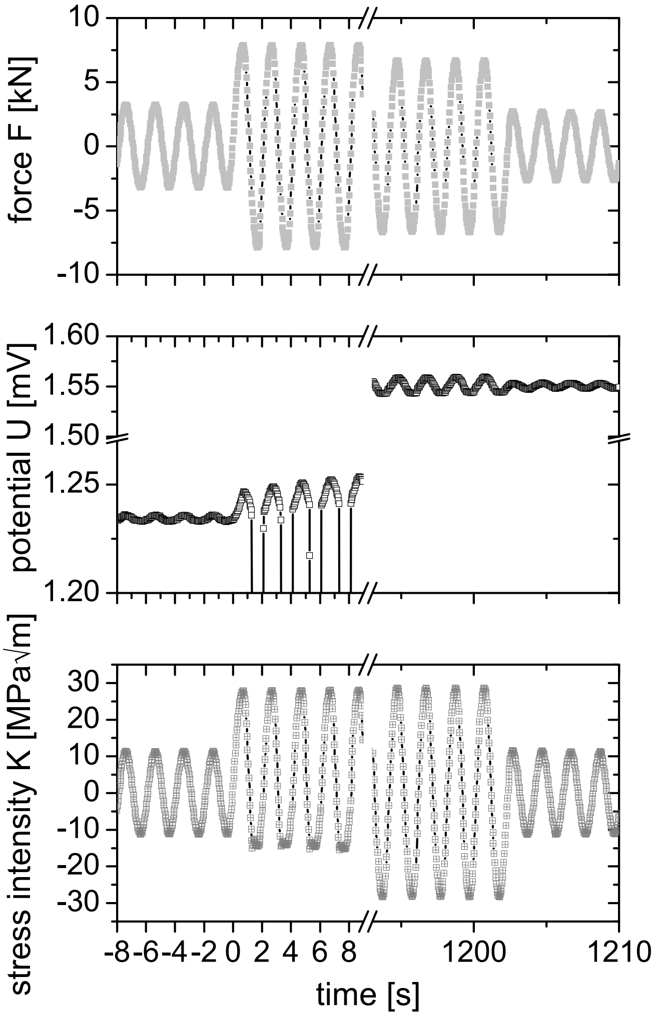

Fig. 2: Recorded load- and potential-data during a multiple overload test and the calculated stress intensity (X5CrNi18-10)

Fig. 2 shows in the upper part that the applied force is reduced during the overload cycles so that the stress intensity which is plotted in the lower part remains on a constant level during the whole multiple overload experiment.

By using the data acquisition system Erika II the crack propagation can be observed continuously during the whole experiment (cp. Fig. 3). Consequently, the crack propagation within the single overload cycles can be calculated from the data as it is shown in Fig. 3.

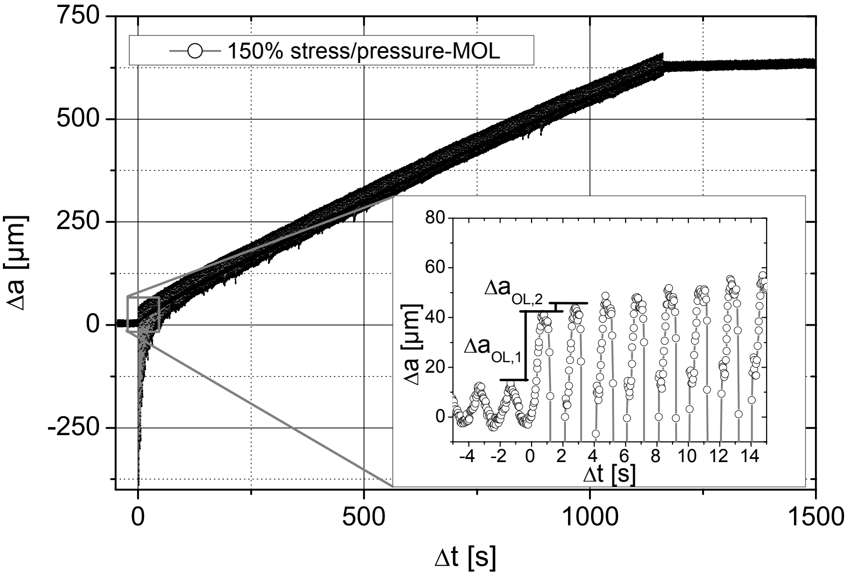

Fig. 3: Calculated crack length from potential-data of the data acquisition system Erika II during a multiple overload (MOL) test (C45E)

The crack propagation at the first overload cycle $\Delta a_{OL,1}$ is the difference form the maximum crack length at the first overload cycle to the maximum crack length of the last baseline cycle. The difference from the maximum crack length at the next overload cycle to the maximum crack length of the preceding one is the crack propagation at the next overload cycle $\Delta a_{OL,i}$. Thus the crack growth rate at a MOL can be determined with a resolution of about 1µm. This high resolution is due to the used nanovoltmeters and the constant temperatures within the specimen environment. Further details to the machine and their features for crack propagation experiments can be found elsewhere [3, 4].

3 Experimental Result

It was the aim to study the influence of multiple overloads on the crack growth rate in detail. Therefore, the baseline crack growth rate ($\frac{\Delta a}{\Delta N}_{BL}$) and the baseline stress intensity level ($K_{max,BL}$), respectively, has been varied. Furthermore, two different R-ratios of the baseline stress intensity level (R_{BL}) have been used and the overload level ($K_{max,OL}$) has been increased in the experiments carried out on both steels. Tab. 1 summarizes the matrix of experimental conditions used in the experiments and, simultaneously, gives an overview of the investigated parameters. The multiple overloads had a size of 600 cycles.

$\frac{\Delta a}{\Delta N}_{BL}$ [m/cycle]	X5CrNi18-10		C45E		Overload level $K_{max,OL}$ [MPa√m]	Overload level $[\%] = \left(\frac{K_{\max,OL}}{K_{\max,BL}} - 1\right) \cdot 100$
	$K_{max,BL}$ [MPa√m]	R_{BL} [-]	$K_{max,BL}$ [MPa√m]	R_{BL} [-]		
10^{-8}	11.5	-1	11	-1	16.5 – 28.75	50 - 150
$3 \cdot 10^{-9}$	8	-1	7.9	-1	11.85 – 24	50 - 200
$3 \cdot 10^{-9}$	14	0.6	16.5	0.6	21 – 33	50 - 100

Tab. 1: Matrix of overload experiments

Analyzing the development of the crack growth rate at multiple overloads it was found that in both steels the first overload cycle $\Delta a_{OL,1}$ is much greater than the crack propagation in the following overload cycles, as could already be seen in Fig. 3. Before analyzing the development of the crack growth rate more exactly, at first, $\Delta a_{OL,1}$ has to be studied.

It was found that during the first overload cycle of a multiple overload (MOL) and the overload cycle of a single overload (SOL) the crack propagates in a similar manner. In addition, the distances were almost equal as it is demonstrated in Fig. 4, where the experimental results of the steel C45E can be seen.

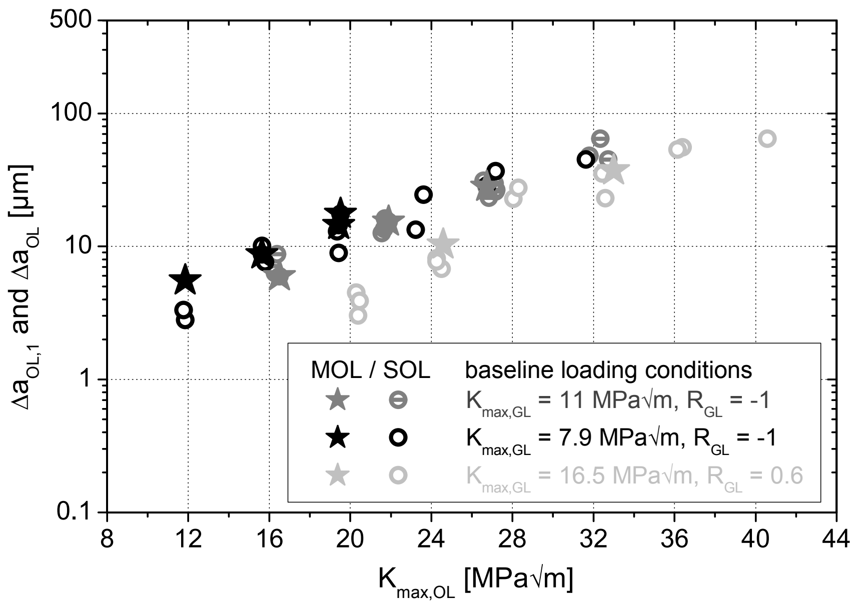

Fig. 4: Comparison of Δa_{OL} and $\Delta a_{OL,1}$, influence of $K_{max,OL}$, $K_{max,BL}$ and R_{BL} on both quantities (C45E)

Fig. 4 shows, that Δa_{OL} and $\Delta a_{OL,1}$ are primarily influenced by stress intensity factor of the overload cycle, $K_{max,OL}$, and increase with increasing $K_{max,OL}$. In addition, R_{BL} has an influence on Δa_{OL} and $\Delta a_{OL,1}$, too. The baseline stress intensity level $K_{max,BL}$, however, don’t influence Δa_{OL} and $\Delta a_{OL,1}$ remarkably.

After the first overload cycle of the MOL the crack growth rate decreases strongly as visible in Fig. 3. Within the next 20 to 180 cycles, depending on the overload level, the crack growth rate stabilizes on a quit lower level, as it can be seen in Fig. 5. In the following overload cycles the crack growth rate decreases slowly more and more, and, finally, after 600 cycles nearly the cyclic crack growth rate $\frac{\Delta a}{\Delta N_{cyc}}$ (the crack growth rate that occurs at crack propagation curves under equal loading parameters as in the overload) is reached [5]. An influence of $K_{max,BL}$ and R_{BL} on this behaviour was not found.

As a next step the development of the crack growth rate at multiple overloads was compared with those experiments carried out on the aluminum alloy 6013 by Broll [6]. The alloy 6013 is generally more sensitive to fatigue crack propagation than the both steels. Consequently, a comparison of experiments carried out on the aluminum alloy and the steels, based on similar stress intensity factor values is not helpful. Therefore, in Fig. 5 multiple overload experiments were compared in which overload levels have been applied that would cause as cyclic loading a crack growth rate of about 10^{-7} m/cycle. The crack growth rate, which is plotted in Fig. 5 versus the number of cycles of the multiple overloads, has been determined as it is demonstrated in Fig. 3.

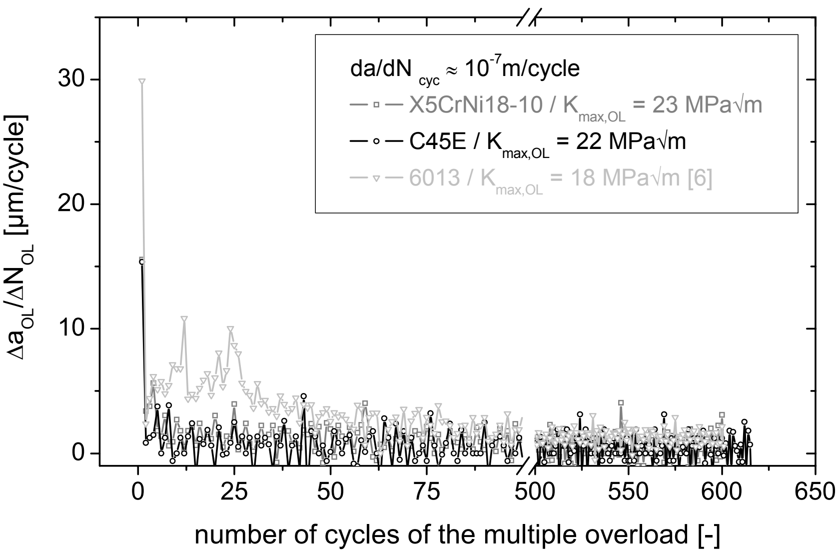

Fig. 5: Development of crack growth rate at multiple overloads

While for the two steels a steep decrease of the crack growth rate is visible, the crack growth rate decreases in the aluminum 6013 more continuously. But the great difference between $\Delta a_{OL,1}$ and the crack growth rate at the end of the multiple overloads ($\Delta a_{OL,n}$) is obviously existent in the three materials. The difference is nearly a factor of 100. This behaviour of the crack cannot be explained by linear elastic fracture mechanics.

4 Discussion

The multiple overload experiments have shown primarily that within the first overload cycle a crack extension occurs that is about hundred times greater than the expected one. As this effect cannot be explained by conventional fracture mechanic concepts, efforts have been undertaken to find an explanation for this effect. Because of the great difference between $\Delta a_{OL,1}$ and $\frac{\Delta a}{\Delta N_{cyc}}$ for the same ΔK-value, it was assumed that this should be caused by different mechanisms. In order to figure out which mechanisms influence the crack propagation the following suggestions have been made.

On the one hand, it was assumed that $\Delta a_{OL,1}$ could be related to the size of the plastic zone and therefore could be calculated by the function $\Delta a_{OL,1} \cong K^2 / \sigma_{ys}^2$. But the size of $\Delta a_{OL,1}$ has been over estimated by this equation. On the other hand, different scientist attribute continuously crack growth to the crack tip opening displacement δ_t. Consequently they probate that $\Delta a \sim \delta_t$, taking $\delta_t = \beta \cdot K^2 / (E \cdot \sigma_{ys})$ into account [7, 8]. It was found that Δa_{OL} and $\Delta a_{OL,1}$ measured in experiments on the steels C45E and X5CrNi18-10 and in the aluminum alloy 6013 could be calculated rather well by this approach, as can be seen in Fig. 6, where the experimental data of C45E and 6013 are shown. Additionally, the approach of Weertman for δ_t is presented in Fig. 6 [9].

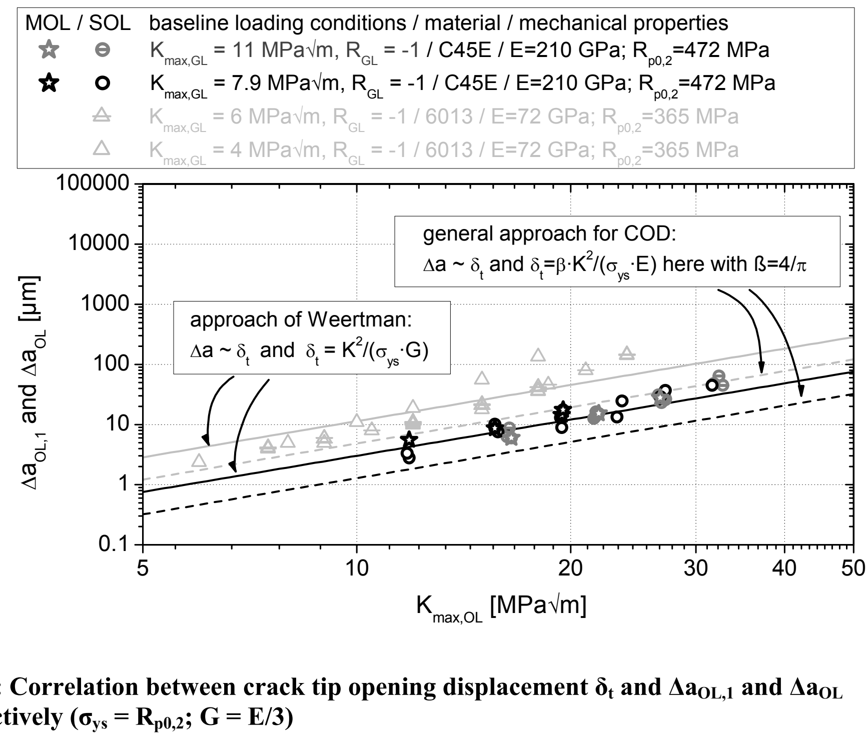

Fig. 6: Correlation between crack tip opening displacement δ_t and $\Delta a_{OL,1}$ and Δa_{OL} respectively ($\sigma_{ys} = R_{p0,2}$; $G = E/3$)

Fig. 6 shows that the best correlation between $\Delta a_{OL,1}$ (Δa_{OL}) and δ_t exists, when the approach of Weertman for crack tip opening displacement has been used. The approach of Weertman is based on his suggestion that $\delta_t = \beta \cdot \frac{K^2}{\sigma_{ys} \cdot G}$ with $\beta = 1$, where the plastic zone boundary crosses the crack plane behind the crack tip [9]. Changing E into G he considers the dislocation movement within the plastic zone in his approach. His explanations to this approach are quite inaccurate and have to be confirmed by additional microstructure tests. Never the less the best correlation between experimental results and model calculations have been found for his approach for δ_t.

As the difference between the crack growth rate within the first overload cycle $\frac{\Delta a_{OL}}{\Delta N_{OL}}$ and $\frac{\Delta a}{\Delta N_{cyc}}$ has been found to be a factor of hundred, it is obvious that $\frac{\Delta a}{\Delta N_{cyc}}$ cannot be explained by the crack tip opening displacement, too. To understand the mechanism that governs $\frac{\Delta a}{\Delta N_{cyc}}$, crack propagation models of Weertman that incorporate the dislocation interaction in front of crack tip directly have been taken into account [9, 10]. The comparison of crack growth calculated from these models and the δ_t of Weertman with the experimental data for $\frac{\Delta a_{OL}}{\Delta N_{OL}}$ and $\frac{\Delta a}{\Delta N_{cyc}}$ is given in Fig. 7. As this comparison looks for all three materials, the X5CrNi18-10, the C45E and the 6013, quasi equal in Fig. 7 as an example the steel C45E is shown. For the calculation, ΔK was assumed to be equal to K_{max} and the shear modulus G was estimated from the Young's modulus E, which has been found to be 210 GPa in the steel C45E, to G = E/3. For the yield strength σ_{ys} the determined value for $R_{p0,2}$ has been taken into account ($R_{p0,2}$ = 472 MPa).

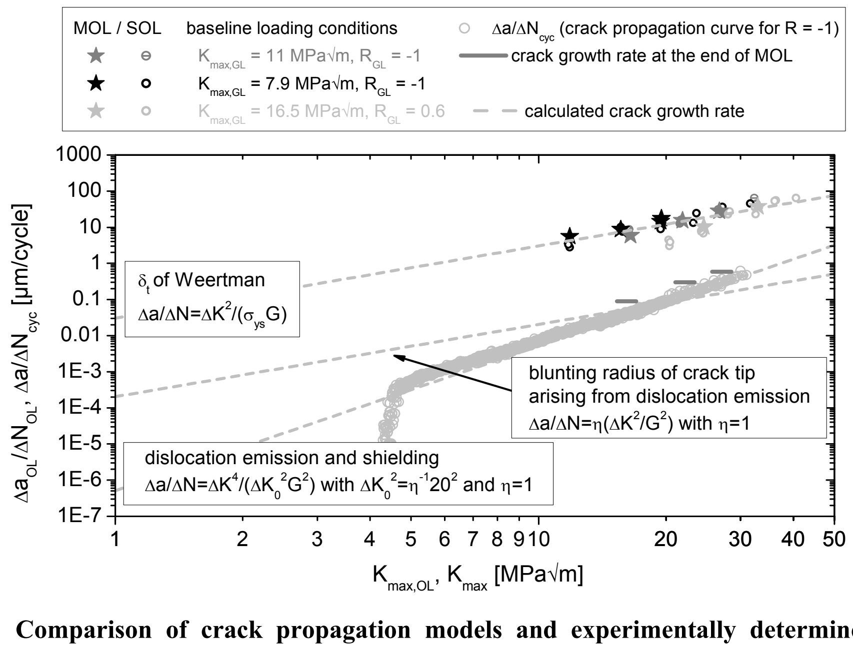

Fig. 7: Comparison of crack propagation models and experimentally determined crack growth rate (C45E)

Fig. 7 shows that $\frac{\Delta a}{\Delta N_{cyc}}$ correlates with the models that are based upon the dislocation interaction at the crack tip. Whereas the function for the crack growth rate, which results from a model for discontinuously crack propagation that considers besides dislocation emission at crack tip dislocation shielding near the crack tip additionally, describes the crack propagation curves over a greater part.

Consequently, the difference between the crack growth rate within the first overload cycle and the crack growth rate which develops in the following cycles can be traced back indeed to different mechanisms. While the crack propagation at the first overload cycle correlates with δ_t, in the following cycles the dislocation structure, their movement and shielding, respectively in front of the crack tip dominates the crack propagation. Unfortunately, the model of Weertman includes the parameters K_0 and η which have to be found by fitting the model to the experiment. Consequently, it is not possible to predict the fatigue crack propagation behaviour of a material when the quantities E, G and $R_{p0,2}$ are solely known. To gain K_0 and η, the fatigue crack propagation behaviour still has to be determined in an experimental manner.

5 Conclusion

The analysis of the development of the crack growth rate within multiple overloads with constant K-values showed that the crack growth at the first overload cycle is about hundred times greater than in the following ones. This effect is not explainable by LEFM. It was found that during the first overload cycle the crack propagation seams to be dominate by the crack tip opening displacement whereas in the following cycles the dislocations in front of crack tip control the crack growth directly. The crack propagation model of Weertman that considers dislocation emission at crack tip and dislocation movement as well as dislocation shielding in front of the crack tip correlates best with the experimental determined crack propagation at the end of the multiple overload. The model which works very well for both steels and the aluminum alloy 6013 still incorporates fit parameters. Furthermore, the influence of the mean stress is yet not incorporated into the model. Therefore, future investigation on fatigue crack propagation should gain to study especially the dislocation structure in front of the crack tip in more detail to develop a general model for fatigue crack propagation based upon these structures.

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