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INFLUENCE OF DIFFERENT LOADING CONDITIONS ON THE FATIGUE CRACK GROWTH IN STEELS AND ALUMINIUM ALLOYS

EINFLUSS UNTERSCHIEDLICHER MECHANISCHER BELASTUNGEN AUF DAS ERMÜDUNGSRISSWACHSTUM IN STÄHLEN UND ALUMINIUMLEGIERUNGEN

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Abstract

For the lifetime prediction of light weight structures the knowledge of the fatigue crack growth behaviour in the used materials is essential. As the fatigue crack growth depends on the loading conditions, a lot of experiments have to be carried out prior to the lifetime prediction. To reduce the number of experiments for the determination of the crack growth behaviour of a metallic material the fatigue crack growth was analyzed under constant (single-level) loading for different mean stresses (for variable R-ratios) and stress intensity factors in the steels X5CrNi18-10 and C45E. Therefore, a wide range of loading conditions has been applied in experiments that were carried out with a special test-equipment, specifically designed for fatigue crack propagation tests. The experiments showed that the crack growth rate da/dN is influenced by the mean stress (the R-ratio) as well as the maximum stress intensity K_{max}. To plot the da/dN-curves in reference to this dependence a 3D-presentation was introduced and an equation for the crack propagation rate in dependence on the R-ratio and K_{max} was deduced. Consequently, it is possible to predict the crack propagation rate for stress intensities starting form threshold level K_{th} up to K-levels of the upper Paris range for all possible mean stresses (R-ratios). For the calculation only two special crack propagation experiments are necessary. Furthermore, a new basic approach for the threshold behaviour $K_{max,th}(R)$ was developed to express its behaviour for ferritic and austenitic steels and age-hardened aluminium alloys used in aircraft industry. The presented prediction model works very well for both steels and has been successfully used to predict the crack propagation behaviour of the aluminium alloy 6013. Thus a helpful tool for the prediction of the crack growth rate for any R-ratio and K_{max} has been developed.

1. INTRODUCTION

The lifetime of air craft structures and inspection intervals are predicted nowadays by the principles of damage tolerance. It is assumed that a crack may propagate form a hole in the structure. Therefore, the knowledge of the fatigue crack growth behaviour is essential. As the fatigue crack propagation depends on the kind of material in use, the atmosphere (also known as environmental effects) and the loading conditions (especially at different mean stresses), a lot of experiments have to be undertaken prior to the prediction of the lifetime [1]. Up to now, the phenomenon of the fatigue crack propagation is still not fully understood and until nowadays terrible accidents in consequence of fatigue crack propagation occur [2-4]. Consequently, the present paper deals with the prediction of the fatigue crack growth behaviour of metallic materials for an expanded range of different loading conditions (R-ratios from -2 to 1) on the basis of experimental results. It can be shown that only some special crack propagation experiments are necessary to predict the thresholds for different mean stresses and to determine the crack growth rate (da/dN) as a function of the maximum stress intensity factor (K_{max}) and the stress ratio (R-ratio).

The experiments presented within this paper have been undertaken primarily on the steels X5CrNi18-10 and C45E and on the age-hardened aluminum alloy 6013. The investigations have shown that the developed model is working for ferritic and austenitic steels as well as aluminum alloys and consequently, it is a useful tool for the air craft industry.

2. EXPERIMENTAL PROCEDURE

Within the scope of investigations to predict the crack propagation of a material for different mean stresses (R-ratios) and stress intensities two types of experiments (method A and method B) have been carried out. The experiments were undertaken using a specially designed test equipment at the institute of materials science at the Bundeswehr University, Munich. The testing machine is based upon of a servo hydraulic testing machine (type Schenk PSA 10 and a control unit S 56) and a DC-potential drop method for crack detection. To measure the crack extension and control the experiments, a computer with a proprietary software is used. More details to the testing system, which is called "Erika – Ermüdungsrissausbreitung in korrosiver Atmosphäre" (German for crack propagation in corrosive atmosphere) and of their experimental options are described in the papers [5-7].

The usual way to determine the crack growth behaviour is to carry out threshold measurements as described in ASTM E 647 and known as the load shedding method [8]. In this kind of experiment (method A) the load amplitude is reduced stepwise. Simultaneously, the R-ratio is kept constant. The tests using Method A were carried out on the steels X5CrNi18-10 and C45E for different R-ratios (R = -1.5, R = -1, R = 0.6, R = 0.1). To minimise the influence of the plastification in front of crack tip, it has got to be kept as small as possible. Consequently, the load amplitude was reduced only by 2% after every extension of crack length at 0.05 mm.

During the other type of experiment (method B) K_{max} was kept constant for the whole test, while K_{min} was increased. Consequently, the R-ratio increases and the cyclic stress intensity factor ΔK decreases until a threshold is reached. All thresholds determined by method B are normally thresholds for high K_{max}-values and R-ratios greater than 0.7. As K_{max} is kept constant during this experiment, the measured threshold is less influenced by plastification induced crack closure and load sequence effects [9]. In order to cover a wide range of loading conditions this type of experiment has been untertaken on each material for three different K_{max} levels (K_{max} = 7, 10 and 20 MPa√m).

3. RESULT OF EXPERIMENTS

By comparing the results of all test it has been found that the two steels behave similar [10]. Consequently, in the following presentation of the experiments mainly the results obtained from the steel C45E are shown.

To analyse the influence of the R-ratio and the stress intensity on the crack propagation rate, the crack growth data obtained from crack propagation tests undertaken with method B were plotted versus ΔK as shown in the following figure.

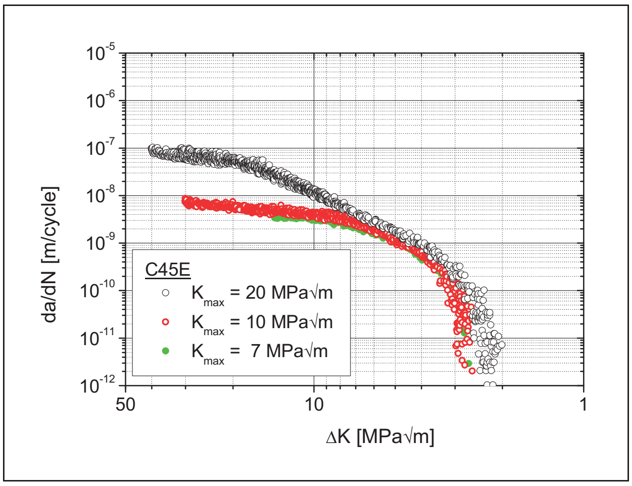

FIG. 1. Crack propagation test under K_{max} control (method B) on C45E da/dN vs. ΔK

Figure 1 clearly shows that at ΔK values below 5 MPa√m the influence of K_{max} on the fatigue crack growth rate becomes minor important. For ΔK values above 5 MPa√m, however, da/dN strongly depends on the K_{max} level. The higher the K_{max}-value the higher da/dN has been found. The increase of R during the experiment is correlated with increasing K_{min} and the reduction of ΔK. This leads to continuously declining da/dN-values. Consequently, both parameter R and K_{max} have an influence on the crack growth rate. To show the crack growth data, respectively to the dependence on the R-ratio and K_{max}, a 3D presentation has been introduced. In figure 2 the da/dN-data from those experiments that were carried out on the steel C45E are plotted vs. K_{max} and R.

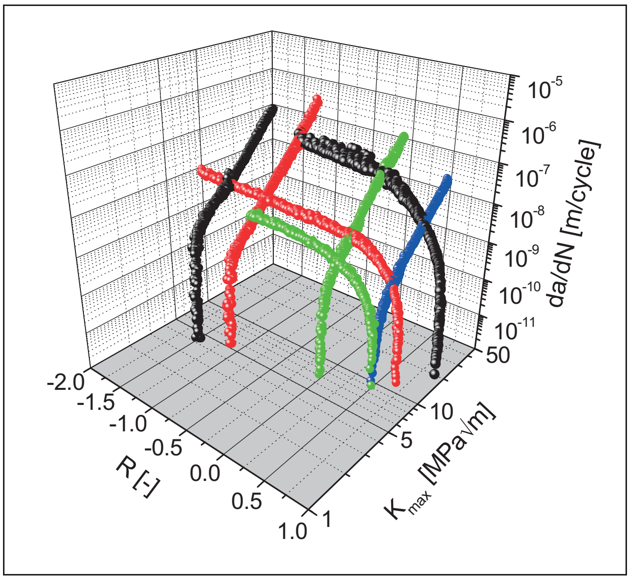

FIG. 2. Crack propagation experiments on C45E as da/dN vs. K_{max},R (3D presentation)

Each of the shown curves in figure 2 results from a single experiment. Experiments resulting from method A are represented by the four curves with a constant R-ratio, while experiments form method B are those three curves, where the K_{max} is constant. All curves taper to da/dN-values lower than 10^{-11} m/cycles. That is when the threshold ($K_{max,th}$) is reached.

Besides analysing the crack propagation curve special attention has been drawn to the determined thresholds and their dependence on the R-ratio. In figure 3 the threshold values $K_{max,th}$ of the steels are plotted vs. the R-ratio. They are presented in comparison to threshold-data of different aluminium alloys from investigations of Volpp and Rödling [11, 12].

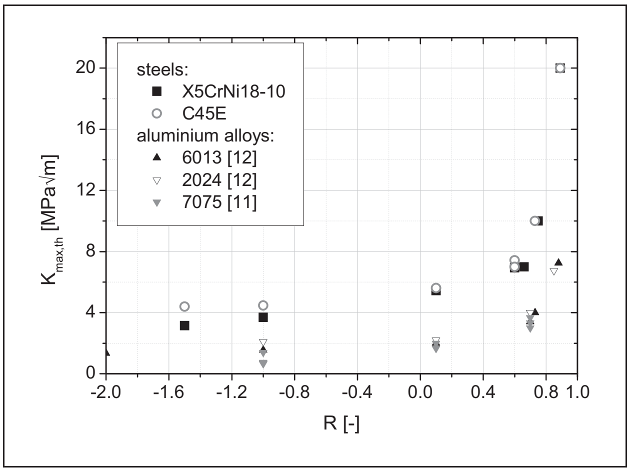

FIG. 3. Crack propagation test under K_{max} control (method B) on C45E da/dN vs. ΔK

Figure 3 shows that the threshold data for both steels lay approximately twice as high as those data received from aluminium alloys, but, nevertheless, the Fe- and Al-alloys show the same behaviour. As in the research studies of Schmidt and McEvily the $K_{max,th}$-values strongly increase for R-ratios greater than 0.5 [13, 14]. For the R-ratios from 0.1 to -2 the $K_{max,th}$–values show a small but continuous decrease. To develop the prediction model for the crack growth behaviour in a range of practical interest $K_{max,th} \leq K_{max} < K_C$ a function for da/dN that depends on K_{max} and R has to be deduced from the experiments. The solution of the author is described within the next chapter.

4. CALCULATING da/dN INDEPENDENCE OF R AND K_{max}

4.1. Prediction model

To describe a single crack propagation curve for a constant R-ratio by a simple power law, equ.1 of Klesnil-Lukáš

$$\text{(1)} \quad da/dN = C \cdot \left(K_{\max}^{m} - K_{\max,th}^{m}\right)$$

represents a good approximation to the experimental results [10, 15, 16]. In this function the C parameter describes the horizontal position of the curve. It is well known and demonstrated by the experiments that C depends on the R-ratio, while exponent m represents the gradient of the da/dN curve which is similar for different R-values. As shown above, the threshold $K_{max,th}$ (da/dN ≈ 10^{-11} m/cycles) depends on the R-ratio, too. In order to improve the crack growth law, the influence of R has to be incorporated into equ. (1). Consequently, C(R) and $K_{max,th}$(R) have to be taken into account. Now, equ.1 can be expressed as follows:

$$\text{(2)} \quad da/dN(K_{\max}, R) = C(R) \cdot \left(K_{\max}^{m} - K_{\max th}^{m}(R)\right).$$

Consequently, to predict the crack propagation behaviour for a material by this function for any K_{max}-value and R-ratio, the quantities m, C(R) and $K_{max,th}$(R) have to be known.

Normally, at first the parameter m is determined. Therefore, by the load shedding method a crack propagation curve is measured. As the threshold measured within this experiment is used to determine $K_{max,th}$(R) the R-ratio, that is kept constant, should be as small as possible. Good results will be received if the R-ratio is ≤ -1. Adjusting equation 1 to the da/dN-data both the exponent m as well as the parameter C(R=-1) can be found. The parameter C(R=-1) will be helpful later on.

Secondly, the characteristic of $K_{max,th}$(R) has to be determined.

4.2. The dependence of threshold $K_{max,th}$ on the R-ratio

Taking the threshold-data of the steels and the aluminium alloys into account, it was found that $K_{max,th}$(R) can be described by the hyperbolic equation

$$\text{(3)} \quad K_{\max,th}(R) = A + \frac{B}{(1-R)}.$$

The parameter A and B can be determined by adjusting the function on the measured threshold $K_{max,th}$-data that are plotted against the R-ratio. Equation 3 correlates very well with the experimental results within R-values from -2 to 0.89. The good correlation (correlation coefficient of 0.99) is confirmed by figure 4, where both, the experimental data and the fit of equation (3) were plotted in the same diagram.

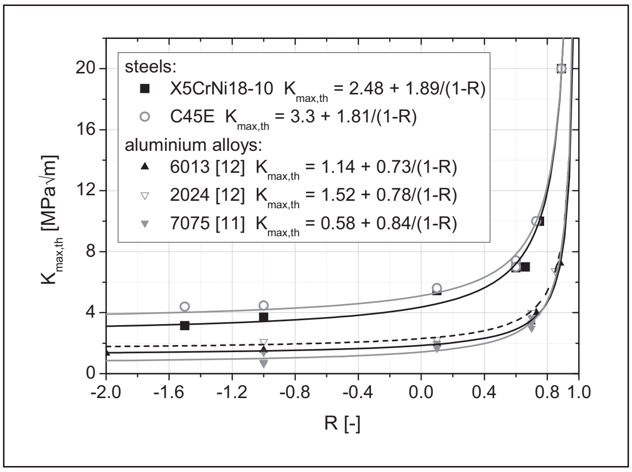

FIG. 4. Crack propagation test under K_{max} control (method B) on C45E da/dN vs. ΔK

The parameters A and B are the asymptotes of the hyperbolic equation (3). Consequently, figure 4 shows that for very low negative R-values $K_{max,th}$ is solely determined by the quantity A. The latter represents the minimum quantity of K_{max} that has to be applied to cause fatigue crack growth and is therefore called $K_{max,th,crit}$. To understand the relevance of the quantity B for the threshold properties the determined thresholds of the steel C45E are displayed in figure 5 as ΔK_{th} vs. $K_{max,th}$. Additionally to the threshold data the adjusted equation with their asymptotes are plotted in this figure, too.

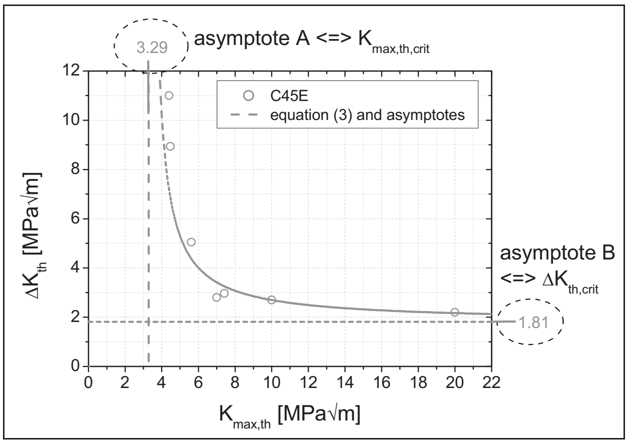

FIG. 5. Experimentally acquired thresholds, adjustment of equ.(3) on experiments and asymptotes A and B (ΔK_{th} vs. $K_{max,th}$)

Now it becomes obvious that the quantity B represents the minimum cyclic loading contribution (the critical value) of ΔK_{th} and it is been called $\Delta K_{th,crit}$. Therefore $K_{max,th,crit}$ and $\Delta K_{th,crit}$ are material conditioned quantities which allow to describe the threshold behaviour of a material by this simple equation

$$(4)\quad K_{\max,th}(R) = K_{\max,th,crit} + \frac{\Delta K_{th,crit}}{(1-R)}\ .$$

With the help of equation (4) the threshold behaviour of a material $K_{max,th}(R)$ can be easily predicted. Besides the one threshold measurement by method A that resulted in a threshold value for R ≤ -1 the threshold has got to be determined once by method B, to get a threshold for a high R-value. The best prediction will be received taking a threshold value for a high R-ratio into account. As a consequence K_{max}, which is kept constant in the experiment, should be as high as possible and lead to a crack growth rate that is greater than 10^{-8}m/cycle at the beginning of the experiment. The crack propagation curve will also be necessary for the determination of C(R).

4.3. Determination of C(R)

As a further step C(R) has to be developed. A method to get a function for C(R) is working as follows. The determined crack propagation curve after method B has got to be described as good as possible by one equation $da/dN_B(R)$. Possibilities how this equation can look like are discussed elsewhere [10]. Taking the determined da/dN-value of the experiment at a R-ratio of -1, $da/dN_B(R=-1)$, and the value C(R=-1) from the load shedding experiment into account, C(R) can be calculated [4], as it is shown in equ.5

$$(5)\quad C(R) = \frac{C(R=-1)\cdot \dfrac{da}{dN}_B(R)}{\dfrac{da}{dN}_B(R=-1)}\ .$$

Now equation (5) and equation (4) can be incorporated into equation (2) and $da/dN(K_{max},R)$ can be predicted.

In figure 6 for example the predicted area for the crack growth behaviour of the steel X5CrNi18-10 can be seen.

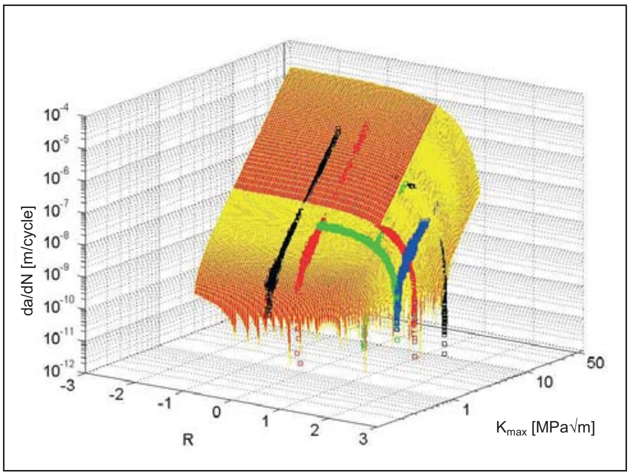

FIG. 6. Predicted crack propagation in comparison with the crack propagation curves for X5CrNi18-10

A rather good correlation between the predicted da/dN-data and the measured da/dN-data has been found for both steels the X5CrNi18-10 and the C45E and the aluminium-based alloy 6013. Comparing the model calculations with the experimental results in a higher resolution, one can find areas where the model underestimates the measured data. Consequently, the aim in near future will be to improve the presented model.

5. SUMMARY

The paper describes the development of a crack propagation model that predicts the crack growth behaviour of steels and aluminium alloys for different loading conditions, different stress intensity factors as well as R-ratios. By using a wide range of experiments that clearly show that da/dN is depending on K_{max} and R, it has been possible to deduce the model. Now, the prediction can be carried out by using only two crack propagation experiments. Thus, the presented model is a helpful tool for an estimation of the crack growth rate for a certain loading condition (a certain R-ratio and K_{max}-value). Of course then the lifetime of a cracked construction under this certain loading condition can be predicted, too.

In future it should be the aim to look for a model for fatigue crack propagation which is no longer based on experimental determined parameters. Going into more micro structural details, additional investigations described in [10] showed that the dislocation interaction at crack tip seams to dominate the fatigue crack growth. Consequently, these aspects have to be incorporated into the model, too.

6. REFERENCES

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