RESISTANCE CURVES FOR THE THRESHOLD OF FATIGUE CRACK PROPAGATION

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The threshold of stress intensity range increases with increasing crack extension and reaches a constant value (the long crack threshold stress intensity range). Such curves can be interpreted as an *R*-curve for the threshold of stress intensity range. Using the conventional *R*-curve method one can estimate the fatigue limit for components containing small defects and small cracks. A very simple method to measure such *R*-curves in conventional fracture mechanics specimens will be presented. Different examples for steels and Al-alloys, and the influence of the stress ratio will be shown and the consequences for the fatigue limit vs. defect size diagram are discussed.

INTRODUCTION

What is an *R*-curve?

The *R*-curve is defined as a plot of the resistance to fracture versus crack extension. If the *R*-curve is independent of the geometry – it should be noted that this is often very questionable – one can easily determine the critical load of a component which contains a defect. The application of this concept for static loading is described in many text books for fracture mechanics. If one defines the threshold of stress intensity range, ΔK_{th}, as the resistance of a material against fatigue crack propagation it is also possible to use this *R*-curve method for fatigue problems (Pook (1), Tanaka and Akinawa (2) and Pippan and Stüwe (3)).

Threshold of short cracks

Fatigue cracks should not grow at stress intensity ranges smaller than the threshold of stress intensity range. But this is correct only for long cracks. Many studies show that short cracks grow also at stress intensity ranges which

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are much smaller than the threshold determined according to the ASTM E 647 procedure.

Romaniv et al. (4), Pippan et al. (5), Pineau (6) and (2) show that the threshold of stress intensity range increases with increasing crack length and reaches a constant value at a certain extension of crack. This value is called the long crack threshold. The increase of ΔK_{th} with increasing crack extension can be interpreted as an R-curve (2), (3) and can be used to calculate the fatigue limit of a specimen containing small defects, notches or short cracks. Many authors (2, 3, 4, 5, 6, 7, 8) explained this increase of the threshold by an increase of "crack tip shielding" (Ritchie (9)) especially by an increase the crack closure stress intensity.

Tanaka and Akinawa measured the increase of the crack closure stress intensity – which should be equal to the change of ΔK_{th} – as a function of the crack extension for short cracks. But the measurement of the crack closure load is associated with a relative large uncertainty, especially in the short crack region. Therefore it is still the question, how should one measure the R-curve for ΔK_{th}?

Suresh (7), Pippan (10) and Novack and Marissen (11) proposed a new method to measure ΔK_{th} and the crack growth curve on specimens pre-cracked in cylic compression. This method also permits to determine an R-curve for ΔK_{th} in addition (Pippan et al. (12)).

This paper presents this simple method to measure such R-curves and shows some examples and some applications in the short crack region.

A SIMPLE TECHNIQUE TO DETERMINE THE R-CURVE

In cyclic compression a crack emanates from the notch – similar to the crack initiation in cyclic tension – but then the growth rate decreases progressively until the crack stops to propagate completely. The advantage of pre-cracking the specimen in cyclic compression is that the stress intensity where the crack closes is below zero at the beginning of the fatigue crack growth test. One can perform the threshold test by increasing the load amplitude in steps until the threshold value of a long crack is reached (7, 10, 12). Fig. 1 shows schematically how the experiments are done. The specimen pre-cracked in compression is first tested at small constant load amplitudes. If the load amplitude corresponds to a ΔK which is smaller than the effective threshold $\Delta K_{\mathrm{eff\,th}}$ the crack does not grow. The first propagation is observed if ΔK is larger than $\Delta K_{\mathrm{eff\,th}}$. Therefore, this technique permits to determine an upper and a lower bound for $\Delta K_{\mathrm{eff\,th}}$.

If the load amplitude corresponds to a ΔK which is larger than $\Delta K_{\mathrm{eff\,th}}$ and smaller than the long crack threshold, at each load step the crack starts to grow and stops where $\Delta K_{\mathrm{eff}} = \Delta K_{\mathrm{eff\,th}}$. Finally there is a step where the crack does not stop, from there on the test can be continued to measure the da/dN vs. ΔK diagram for long cracks. Thus, we have also an upper and a lower bound for the long crack threshold of stress intensity range. In addition, a plot of the extension of the crack where the crack stops to grow versus the corresponding ΔK gives an R-curve for the threshold of stress intensity range. Different examples of such measured R-curves are presented in Fig. 2 – 4.

EXAMPLES

ARMCO-iron

The fatigue crack growth behavior was studied in ARMCO-iron with different grain sizes as a function of the stress ratio R. The mechanical properties, the pre-cracking procedure and the long crack behavior of this study was presented elsewhere (Pippan (13)). The R-curve for $R = 0.1$ and 0.7 is shown in Fig. 2 (grain size 70 μm). No increase in the crack length was observed till $\Delta K = 2.5\,\mathrm{MPa}\sqrt{\mathrm{m}}$ at both R-ratios. The first propagation of the crack was observed at a $\Delta K = 2.8\,\mathrm{MPa}\sqrt{\mathrm{m}}$. Therefore, $\Delta K_{\mathrm{eff\,th}}$ at both R-ratios lies in the same interval.

At $R = 0.7$ no arrest of the crack was determined after this first extension. Hence, $\Delta K_{\mathrm{eff\,th}} = \Delta K_{\mathrm{th}}$ and we received a very simple R-curve – the resistance against fatigue crack growth ΔK_{th} is independent of the extension of the crack. At $\Delta K = 3.0$ and $3.5\,\mathrm{MPa}\sqrt{\mathrm{m}}$ at $R = 0.1$ the crack stopped to grow after a small extension of about 10 and 30 μm, respectively. At larger ΔK the extension of the crack where it stopped to propagate was relative large. The long crack ΔK_{th} was reached at an extension of the crack of a few mm contrary to $R = 0.7$ where no difference between the "short" and long crack threshold was observed.

Fig. 3 shows the influence of the grain size at $R = 0.1$. The effective threshold is equal for both grain sizes. In the fine grained material the R-curve increases faster than in the coarse grained material. But the long crack threshold in the coarse grained material is significantly larger and the extension of the crack where the long crack threshold was reached is in the coarse grained material also much larger than in the fine grained material.

Aluminum alloys

Threshold tests on specimens pre-cracked in cyclic compression were also performed in a modified 7075 aluminum alloy (yield stress 624 MPa and fracture stress 650 MPa; details of this experiments were shown by Pippan et al. (12)). Fig. 4 presents the R-curves for the threshold at $R = 0.1$ and $R = 0.7$. The effective threshold lies between 0.8 and $1\,\mathrm{MPa}\sqrt{\mathrm{m}}$ at both R-ratios. Contrary to the results in ARMCO at $R = 0.7$ the threshold increases with the extension of the crack. However, the contribution of the effect of crack closure (crack tip shielding) is much larger at $R = 0.1$ than at $R = 0.7$ and the extension of the crack, where the long crack threshold is reached, is significantly larger at $R = 0.1$ than at $R = 0.7$.

APPLICATION

If one assumes that the shape of the R-curve is independent of the initial crack length, one can determine (estimate) the fatigue limit as a function of defect size:

- We can apply the R-curve concept to fatigue loading in analogy to static loading.
- A variation of the defect size (initial crack length) gives the fatigue limit versus defect size diagram ("Kitagawa diagram") of a material for a certain load ratio.

An example for the application of the R-curve concept is shown in Fig. 5. The resistance curve (R-curve, Fig. 4) is drawn into a driving force diagram (ΔK vs. a). The difference between the origin of the R-curve and the origin of the driving force diagram is set equal to the chosen defect size. The different driving force curves (ΔK vs. a for constant stress amplitudes) are drawn in Fig. 5.

- The ΔK vs. a curve which is tangential to the R-curve gives the fatigue limit for the chosen defect size.
- At smaller stress amplitudes the crack may propagate at first but it should stop to grow after a certain extension (which is determined by the intersection of the two curves).
- At larger load amplitudes the driving force curve is always larger than the resistance (threshold) curve. Hence, such a component should fail.

Fig. 6 presents a typical result of the application of the R-curve concept to the 7075 alloy. We assumed crack like defects (so we can ignore the effect of notch geometry on ΔK) and a component width or specimen width which is much larger than the crack length. Thus the driving force is given by $\Delta K = \Delta\sigma \cdot \sqrt{\pi a}$.

The different limit curves are indicated in this Figure:

- the limit curve obtained from the R-curve (Fig. 4)
- the limit curve calculated from the long crack threshold of stress intensity range
- the lower bound determined from the effective threshold of stress intensity range
- the upper bound for very small defects – the fatigue limit of a smooth specimen

The dramatic influence of the R-curve of threshold on this fatigue limit vs. initial crack size curve is evident, especially at $R = 0.1$.

Limitation

The limitations of the application of the R-curve concept is similar to the limitations of the application of constant load amplitude data for long cracks:

- Since ΔK is a linear elastic fracture mechanics parameter the small scale yielding conditions should be fulfilled. Therefore, we believe that in most metallic materials the fatigue limit of smooth specimens and the behavior of the Kitagawa diagram very near to this limit can not be described by the R-curve.
- Large overloads should influence the increase of the crack closure stress intensity. The R-curve concept should be conservative in the case of tension overloads and nonconservative in the case of compression overload.
- Residual stresses should also influence the shape of the R-curve.

CONCLUSIONS

The step-wise increase of the load amplitude on specimens pre-cracked in cyclic compression permits to measure:

- the effective threshold of stress intensity range
- the minimum length where one can expect a long crack behavior
- the threshold of stress intensity range for long cracks
- the increase of the threshold as a function of the crack extension (R-curve for threshold).

This R-curve can be used to estimate the transition from short to the long crack behavior in a Kitagawa diagram.

It was shown that the shape of the R-curve depends on the microstructure of a material and the stress ratio.

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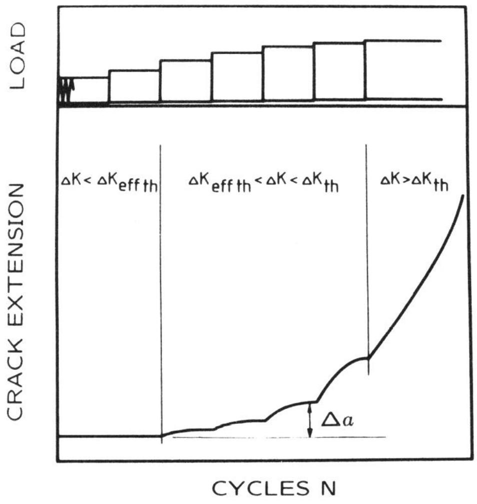

Figure 1: Schematic illustration of the loading procedure of an *R*-curve, threshold and fatigue crack growth test on specimens pre-cracked in cyclic compression

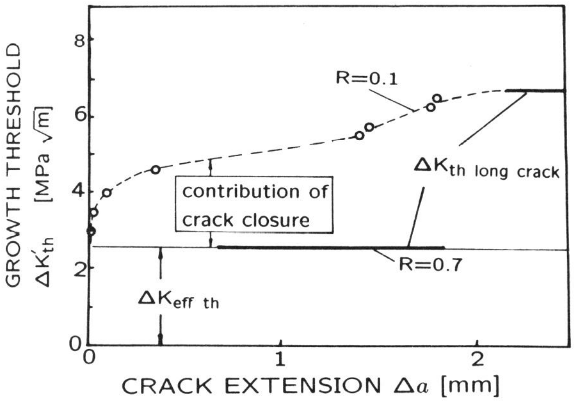

Figure 2: *R*-curve for fatigue growth threshold of ARMCO-iron (grain size 70 μm) at $R = 0.1$ and 0.7

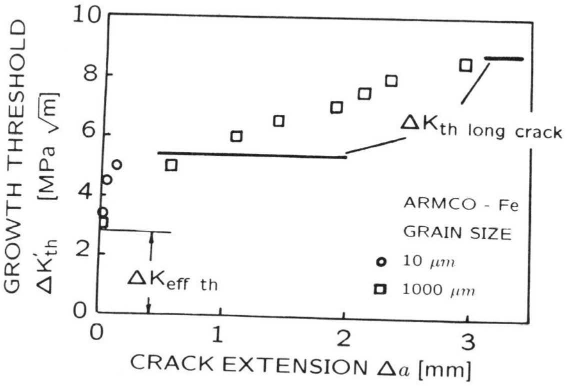

Figure 3: R-curve for fatigue growth threshold of ARMCO-iron for different grain sizes at $R = 0.1$

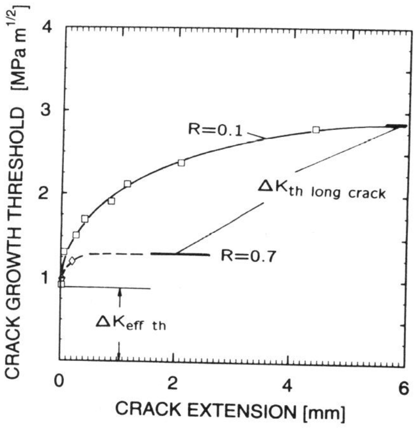

Figure 4: R-curve for fatigue growth threshold of a 7075 alloy at $R = 0.1$ and 0.7

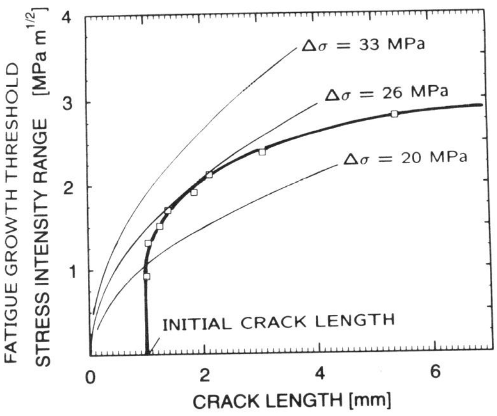

Figure 5: R-curve concept applied to the 7075 alloy

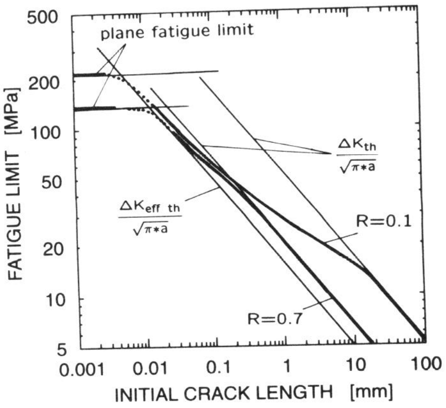

Figure 6: Fatige limit versus initial crack length (defect size) for the 7075 alloy obtained from the R-curves of Fig. 4