Load history effects on fatigue crack propagation: Its effect on the R-curve for threshold

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ABSTRACT. The study deals with the effect of load history during threshold and fatigue crack propagation measurements in the near threshold regime. The compression pre cracking and the stepwise increasing load amplitude test was applied. The effects of pre-cracking as well as the effect of compression and tension overloads after the pre-cracking on the long crack threshold and on the R-curve of the threshold of stress intensity range are analysed.

KEYWORDS. Threshold of stress intensity range; R-curve; Crack closure; Compression pre-cracking.

INTRODUCTION

The propagation of a fatigue crack in ductile materials is caused by the cyclic plastic deformation at the crack tip, which is governed by the plastic properties of the material and the crack driving force. The discovery of Elber [1] of the premature contact of the crack flanks during the unloading sequence reduces cyclic the plastic deformation, which can be expressed by a reduction of the crack driving force ΔK or the cyclic J integral to an effective crack driving force ΔK_{eff} or ΔJ_{eff}. This phenomenon is usually called crack closure effect.

Both, the cyclic plastic properties of a material and the effect of crack closure can be significantly affected by the loading history. There are a vast number of papers dealing with the effect of loading history during variable amplitude loading for fatigue crack propagation in the Paris regime [2].

This paper will focus the attention to the effect of loading history in the threshold regime and especially to the phenomena occurring it the so-called stepwise increasing load amplitude test, which permits the determination of the crack length dependence of the threshold of stress intensity range ΔK_{th}.
The paper is organized in the following way:
At first, the stepwise increasing load amplitude test is shortly introduced, then the different applied loading procedures and the obtained results are described, and finally a simple estimation of the extension of the crack where the results are affected by the pre-cracking procedure is presented.

THE STEPWISE INCREASING LOAD AMPLITUDE TEST:

The threshold of fatigue crack propagation test is usually measured by a load decreasing technique [3]. In this case a fatigue crack is generated in the Paris regime and then the stress intensity range is slowly reduced till ΔK_{th} is reached. In order to avoid a history effect a very small reduction rate of ΔK should be chosen.
A complete different technique has been proposed by Pippan [3] and later by Newman [5]. The pre-crack in this case is produced in cyclic compression. Such pre-crack is surely open in the unloaded state. The crack closure during cyclic tension loading has to build-up during crack extension in the following fatigue crack experiment.

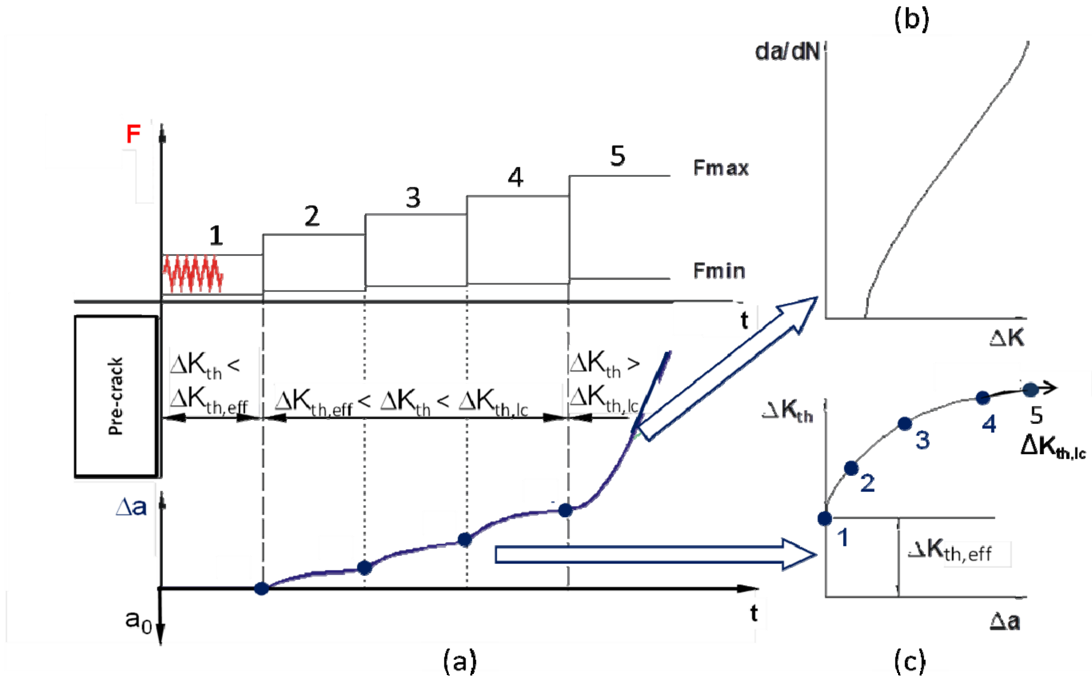

Figure 1: Illustration of the used stepwise increasing constant load amplitude method. The specimens with existing pre-cracks were loaded with a constant amplitude step-by-step. (a) Schematic of the loading procedure. The amplitude was increased to the next step, when the crack stopped to propagate. The final crack extension Δa and the final stress intensity ΔK are plotted in diagram (c) which characteristics the material resistance against crack propagation (the R-curve). For the last step where stable crack extension occurs, the crack growth rate was measured as a function of ΔK depicted in (b). The load at the start of the stable crack growth corresponds to the long crack threshold value in literature.

The loading procedure to determine the threshold ΔK_{th} and fatigue crack propagation behavior is schematically depicted in Fig. 1. After pre-cracking in compression, the load amplitude at the desired stress ratio, R, is increased in steps until the threshold value of the long crack is reached. If no crack extension takes place, the applied ΔK is smaller than the effective threshold (because the crack is open, the closure stress intensity at the beginning is in compression, K_{cl} is smaller than -ΔK_{effth} [6]. If ΔK is larger than ΔK_{effth} a crack extension takes place. If during crack extension sufficient crack closure develops, the crack will stop the propagation. When ΔK is sufficient that the crack closure stress intensity at the threshold is build up, no further stopping of the crack propagation will be observed and the standard long crack growth behavior can be measured.

In addition to the standard fatigue crack propagation behavior of a long crack, also the R-curve [7, 8] for the threshold of stress intensity range ΔK_{th} can be estimated from such experiments, by plotting the stress intensity factor range as a function of the corresponding extension of the crack where stopping takes place. However, this R curve for ΔK_{th} is only an estimation because the residual stresses induced by the pre-cracking can affect the shape of the R-curve.

EFFECT OF COMPRESSIVE OVERLOADS ON THE R-CURVE FOR ΔK_{TH}

In order to visualize the effect of residual stresses in front of the compression pre-cracked samples the R-curve for ΔK_{th} for specimens pre-cracked in cyclic compression with different additional compression overloads at the end of the pre-cracking have been investigated. The material was a quenched and tempered steel with a yield strength of 630MPa. Single edge notch eight point bending specimens (width 20mm, thickness 6mm and a notch depth of 5mm) are used.

To sharpen the notch root, a razorblade polishing technique had been applied. The pre-cracks were generated at a $\Delta K = 18MPa\sqrt{m}$ at R=10 (in pure cyclic compression), 20000 cycles were applied. The length of the pre-cracks was about 30µm, which is significantly larger than the notch root radius. Therefore the standard equations for the determination of the K-values can be used.

On 2 specimens in addition at the end of the cycling compression pre-cracking a single compression overload with a K_{max} of 30 and $40MPa\sqrt{m}$ were applied. On specimens with these additional compression overloads and without the overloads a stepwise increasing load amplitude experiment was performed at a stress ratio R of -1. The resulting R-curve for ΔK_{th} and the observed long crack fatigue crack growth behavior are shown in Fig. 2 and Fig. 3.

From these results it is clearly evident that the fatigue crack growth curves and the long crack threshold are not affected by the pre-cracking procedure and the overloads. However, the R-curve for ΔK_{th} for the samples with overloads is significantly shifted to larger crack extension. This shift increases with increasing overloads.

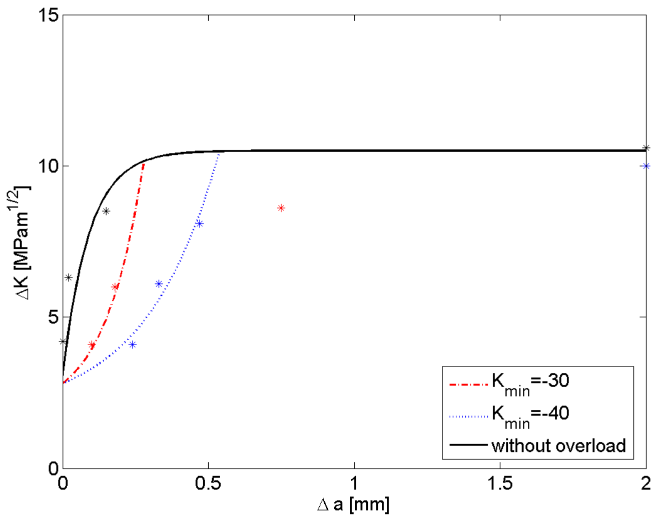

Figure 2: The R-curves for the threshold of stress intensity range at a load ratio of R=-1 for a specimen with pre-cracks generated in cyclic compression and specimens with additional compression overloads.

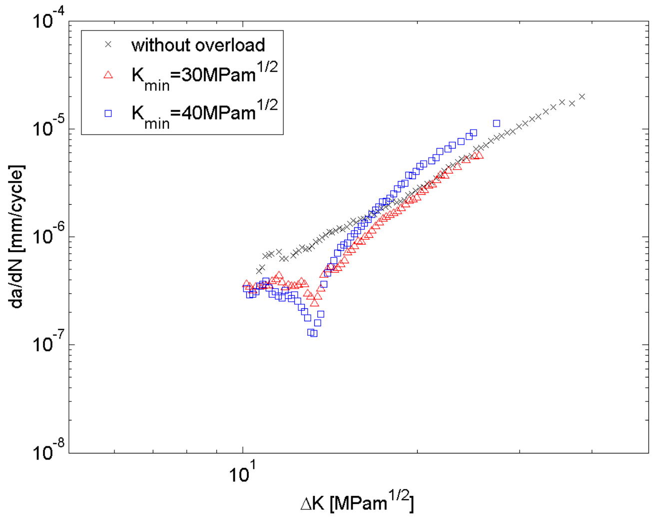

Figure 3: The experimentally obtained long crack fatigue crack growth behavior for a specimen with pre-cracks generated in cyclic compression and specimens with additional compression overloads.

The explanation of this shift of the R-curve is simple. The compressive overloads induce local tensile residual stresses in front of the crack tip. This residual tensile stresses increases the R-ratio locally. The crack can propagate if ΔK is larger than ΔK_{effth} till the residual stresses are not sufficient high enough to compensate the building-up of crack closure. When the crack is grown over the regime of this residual stress zone generated by the compression loading the typical transition to the long crack behavior is observed. This includes also the building-up of the long crack closure contribution, which also takes place on closure free pre-cracks without residual stresses [7]. It should be noted that the sample, which is only compression pre-cracked, contains also residual tensile stresses in front of the pre-crack. They can be reduced if the number of loading cycles is enhanced in order to increase the crack length till the crack stops the propagation. This reduces then the size of zone with residual tensile stress. Another possibility is also to reduce the load amplitude for the compression pre-cracking [6].

ESTIMATION OF AFFECTED ZONE

A finite element analysis can be used to predict the evolution of the effect of the residual stresses induced by the cyclic compression as well as the compression overload on the local stress intensity ratio or the stress intensity factor induced by the residual plastic deformation. A careful analysis of the growing fatigue crack in such a zone is however quite cumbersome.

The concept of dislocation shielding or anti-shielding is a very simple tool to estimate the effect of the wake plasticity induced by such compression overload, especially in the case of plane strain condition which one usually have always in the near threshold regime. Under plane strain condition and small scale yielding the plastic deformation in front of a crack or in front of a very sharp notch is mainly realized by plastic shear inclined between 60° and 100° to the crack plane.

Therefore the effect of an edge dislocation (which is geometrically necessary to realize the mentioned plastic shear deformation) inclined with 70° and 90° as a function of the distance behind the crack will be discussed in the following. Fig. 4 shows a geometrical arrangement of a single dislocation generated during the compression loading of a very sharp notch. Such notch can be considered as a crack which does not come into contact during compression loading.

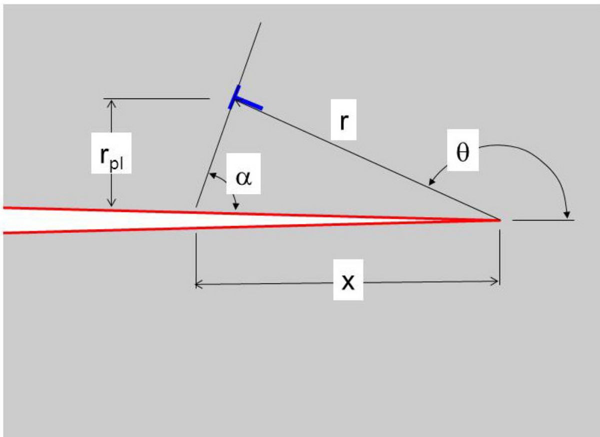

Figure 4: Schematic representation of the geometrical arrangement of a single dislocation generated during the compression loading.

The real effect of the compression loading can be calculated by a simple linear superposition of all geometrically necessary dislocation to realize the necessary plastic deformation. Since all the geometrically necessary dislocations have similar Burgers' vectors and the mentioned linear superposition, it is sufficient to show the effect of a single dislocation. The mode I shielding (if K is negative) or anti-shielding (if the resulting K is positive) stress intensity for the arrangement of the edge dislocation as depicted in Fig. 4 can be calculated by:

Parallel to the crack propagation direction: $$b_x = b \cdot \cos(\alpha) \qquad (1)$$

Perpendicular to the crack propagation direction: $$b_y = b \cdot \sin(\alpha) \qquad (2)$$

$$K = -\frac{b_x G}{2(1-\nu)\sqrt{\pi}}\sqrt{\frac{1}{2r}}\sin\theta\cos\frac{3}{2}\theta - \frac{b_y G}{2(1-\nu)\sqrt{\pi}}\sqrt{\frac{1}{2r}}(2\cos\frac{1}{2}\theta + \sin\theta\sin\frac{3}{2}\theta) \qquad (3)$$

where G is the shear modulus, r is the distance from crack tip to the dislocation [9]. The Burgers vector b is separated into two parts which are parallel (b_x) and perpendicular (b_y) to the crack propagation direction, respectively. ν is the Poisson's ratio, Θ is the angle between the connection line from crack tip to the position of dislocation and the crack plan.

This expression is identical also with the solution presented in [10].

In Fig. 5 and 6 the anti-shielding effect of a single dislocation generated during the compression overload as a function of its distance in the wake of the crack x is shown. The anti-shielding stress intensity is displayed for two inclination angles of the edge dislocation, 70°and 90°. The values are calculated for a shear modulus of 80000MPa, a Burgers' vector b = 0.3nm, a distance of the dislocation r_{pl} = 1μm.

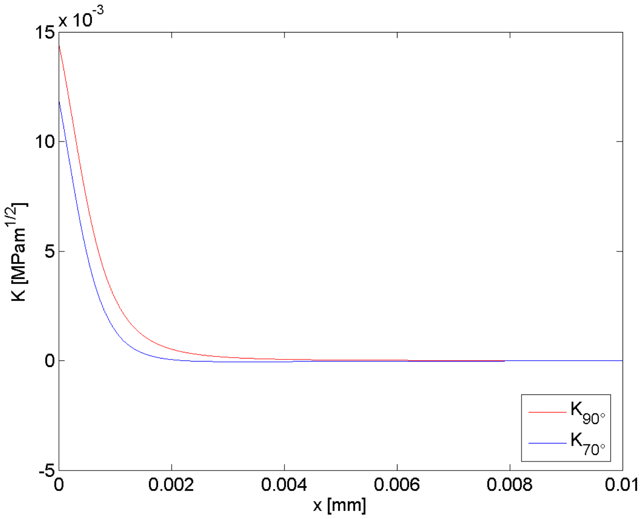

Figure 5: The stress intensity factors induced for 70° and 90° inclined dislocations as a function of the distance to the crack tip in the wake.

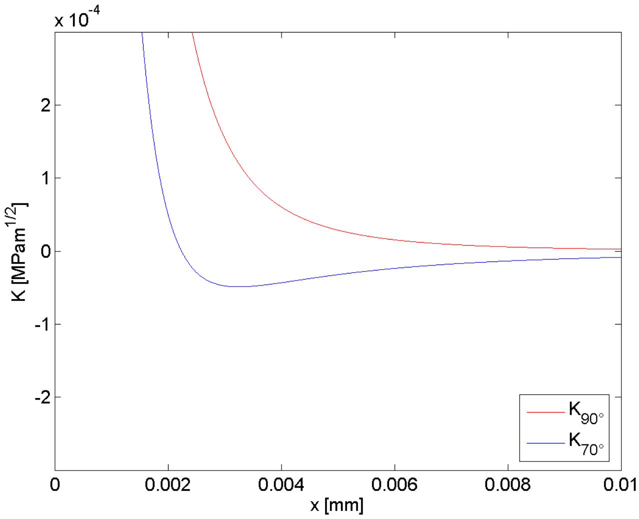

Figure 6: Magnified stress intensity factors induced for 70° and 90° inclined dislocations as a function of the distance to the crack tip in the wake. For x larger than $2r_{pl}$, the stress intensity of the 70° inclined dislocation becomes somewhat shielding compares to the 90° inclined dislocation which remains anti-shielding.

From Fig. 5 it is clearly evident that for crack extensions Δa or x smaller than r the dislocation generated during the compression loading induces a significant anti-shielding, this is the reason that cracks can propagate under pure cyclic compression. However, for x larger than r the K values becomes very small, they remain anti-shielding for the inclination angle 90° and becomes shielding for inclination angle 70°, but the values are very small and disappear relatively fast.
The consequence of this estimation is that the increase of the local R-ratio induced by the compression overload should be significant only for crack extensions comparable to the size of the generated plastic zone. Using the estimation of Irwin for the size of the plastic zone under plane strain condition

$$r_{pl} = \frac{K^2}{3\pi\sigma_y^2}$$

gives a plastic zone size of 0.241mm and 0.428 mm for the 30 and 40MPa√m overload, respectively.
A comparison of the R-curves for ΔK_{th} in Fig. 2 shows that the shift of the R-curves for the 30 and 40MPa√m compression overloads agree quite well with the estimation of the size of the plastic zone. Hence as a simple estimation of the pre-cracking affected zone is the size of the plastic zone.

CONCLUSION

- Compression overloads of pre-cracks can significantly affect the fatigue crack propagation behavior of short fatigue cracks.
- Such compressive overloads can shift the R-curve for ΔK_{th} to large crack extension. This is also important for practical application, because each crack or flaw has load history.
- The shift can be explained by the anti-shielding induced by the plastic deformation generated during the compression overload.
- The crack propagation rate is affected over a distance comparable to the size of the plastic zone.

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