# EXPERIMENTAL DETERMINATION OF $\Delta K_{eff}$

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An experimental method for determination of the partitioning point $K_{op}$ is described which partitions $\Delta K$ into an effective and an ineffective part as far as fatigue crack propagation (FCP) is concerned. The experimental method relies only on the FCP behavior itself. $K_{op}$ data as a function of fatigue loading conditions ($K_{max}$,R) are presented for Al7475-T7351 and a Ni-base alloy Nicrofer 5219 Nb.

## INTRODUCTION

There are numerous investigations which lead to doubts Elber's concept (1) that closure be the physical cause for the existence of $\Delta K_{eff}$, namely the reduction of the applied $\Delta K$ to an effective one in respect to fatige crack propagation (FCP). For clarification, closure comprises all phenomena associated with the fracture surfaces of a propagating fatigue crack which in concert act as a wedge between the fracture surfaces. Closure thereby modifies the loading conditions. On the assumption that a fatigue crack propagates only if tensile stresses act on the crack front, Elber postulated that the end of the wedging action of closure be the start of the effective part of the loading cycle $\Delta K$. This partitioning point of $\Delta K$ is commonly denoted as $K_{op}$.

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$$\Delta K = K_{max} - K_{min} \qquad (1)$$

$$\Delta K_{eff} = K_{max} - K_{op} \quad \text{if } K_{op} > K_{min} \qquad (2)$$

$$\Delta K_{eff} = K_{max} - K_{min} \quad \text{if } K_{min} > K_{op} \qquad (3)$$

Equations (2) and (3) are not quite correct, if Elbers preposition

$$\Delta K_{eff} = 0 \quad \text{no FCP} \qquad (4)$$

$$\Delta K_{eff} > 0 \quad \text{FCP} \qquad (5)$$

is accepted. This is due to the existence of a closure-free threshold $\Delta K_T$ (2) in the stress intensity range $K_{max}$ - $K_{op}$ (3). Then, Eqs. (2) and (3) have to be written as:

$$\Delta K_{eff} = (K_{max} - K_{op}) - \Delta K_T \qquad (6)$$

$$\Delta K_{eff} = (K_{max} - K_{min}) - \Delta K_T \qquad (7)$$

In the scientific literature, the compressive stress field in the cyclic plastic zone and associated phenomena are often referred to as closure, too. Schijve and Broek (4) explained their results from overload experiments on Alclad 2024-T3 by compressive stress fields produced in the plastic zone. Yet, it is not clear by which phenomena cyclic plastic deformations should be prevented from producing additional damage during the lower part of a loading cycle.

Doubts about the closure concept as cause for the existence of $\Delta K_{eff}$ by Hertzberg et al. (5) were based on the fact that "artificial" closure was not reflected in the appropriate way by the respective FCP-rates. Similarly, determination of the partitioning point $K_{op}$ by means of a "growth versus no-growth" criterion (6,7) furnished values agreeing with semi-empirically determined values, but not with measured closure values.

## THEORY OF $K_{op}$ TESTING

The $K_{op}$ test method determines $K_{op}$ for a certain cyclic loading condition characterized by $K_{max,i}$ and $K_{min,i}$ (Fig. 1). The fatigue crack is initiated from the tip of a notch under the cyclic loading conditions selected for the first $K_{op}$ test. This initial crack is propagated under the same cyclic loading conditions up to a preselected crack length, i.e., a preselected $\Delta a$. If the crack reaches the preselected crack length, the actual $K_{op}$ test starts as graphically shown in Fig. 1. The $K_{op}$ test relies on the criterion "FCP versus No FCP". The test procedure is based on the idea:

$$\text{if } \Delta K_{eff} = 0 \qquad \text{no FCP can occur} \tag{4}$$

$$\text{if } \Delta K_{eff} > 0 \qquad \text{FCP must occur in every cycle} \tag{5}$$

The theoretical basis is the modified (3) Elber-equations (6) and (7) and a closure-free FCP threshold $\Delta K_T$ as shown in Figs. 2 and 3 for Al7475-T7351 and the Ni-base alloy Nicrofer 5219 Nb. It should be noted that the small amplitude in Fig. 1 acts only as a probe. The test procedure uses a $\Delta Kj$ for the small amplitude of

$$\Delta Kj = Z \circ \Delta K_T \tag{8}$$

Depending on the material, "Z" may be chosen 1.1 to 1.5, i.e., such that $\Delta Kj$ is equal to $\Delta K_T$ plus (0.1 to 0.5 $MPa\sqrt{m}$). The big advantage of using such a small amplitude as probe consists in the small FCP rates ($10^{-7}$ < da/dN < $5 \circ 10^{-6}$ [mm/cycle]) once the fatigue crack starts to propagate. This allows to obtain up to 10 determinations of $K_{op}$ on a C(T) specimen with W = 50 mm.

Theory and practice are not always identical, as is valid for statements (4) and (5). While in theory simple and plausible, in practice one has to define "No FCP" as all FCP-rates equal to and below 6.6 $10^{-8}$ mm/cycle. But, due to experimental limitations, even this definition is not sufficient. In addition the FCP-rate 6.6 $10^{-8}$mm/cycle has to be averaged over a crack growth interval of 0.1 mm; this corresponds to averaging over 1.5 Mill cycles or more. If FCP is detected at a fatigue loading condition $\Delta Kj = K_{max,j} - K_{min,j}$ then the $K_{max,j}$ of the previous loading condition is determined at which no FCP occured.

Via Eq. (6), $K_{op}$ is determined

$$\Delta K_{eff} = 0 = (K_{max,j} - K_{op}) - \Delta K_T \tag{9}$$

$$K_{op} = K_{max,j} - \Delta K_T \tag{10}$$

where $\Delta K_T$ corresponds to $K_{max,j}$ (see Figs. 2 and 3).

## EXPERIMENTAL RESULTS AND DISCUSSION

The results of the $K_{op}$ determinations on Al7475-T7351 are shown in Figs. 4 and 5 plotted versus $K_{max}$ and plotted versus $\Delta K$, respectively. In each figure, the $K_{op}$ data for different R-ratios (from 0.1 to 0.75) have a linear relation to $K_{max}$ and to $\Delta K$; the slope of the lines increase with increasing R-ratio. The lines pass through the origin. Similarly, the $K_{op}$ data for Nicrofer 5210 Nb are plotted versus $K_{max}$ in Fig. 6. Here again, the $K_{op}$ data for each R-ratio have linear relationships to $K_{max}$ which pass through the origin. The $K_{op}$ data normalized by division through $K_{max}$ are plotted versus R-ratio in Fig. 7. In addition to the materials investigated, the $K_{op}/K_{max}$ data for Inconel 617 and Ti 6Al 4V are shown which were investigated previously. It can be seen from Fig. 7, that the experimentally determined $K_{op}$ values agree quite well with values determined semiempirically via da/dN - $\Delta K$ data. The assumption is made in such semi-empirical analyses that above R-ratios of approximately 0.7 to 0.75 the $\Delta K$ becomes effective in its total range, i.e., $\Delta K = \Delta K_{eff}$.

By analysis of the $K_{op}$ data presented, it can be seen that a partitioning point $K_{op}$ exists up to very high R-ratios and very high $K_{max}$ values. This fact can not be reconciled with Elber's original closure idea as reason for the existence of such a partitioning point in $\Delta K$. Therefore, the author proposes not to use the descriptor "$K_{op}$" in connection with $\Delta K_{eff}$ and investigate the influence of closure on FCP and the partitioning of $\Delta K$ independent of each other. The author proposes to use $K_G$ as descriptor of the partitioning point which is the lower limit (Grenz-) point for the $\Delta K_{eff}$ range. In this way, no definitive physical model is attached to the partitioning point; any model could be wrong at the present state of knowledge.

## SUMMARY

An experimental method is presented which allows determination of the partitioning point $K_G$ ($K_{op}$) which divides $\Delta K$ into a $\Delta K_{eff}$.

The $K_G$ ($K_{op}$) results found for Al7475-T7351 and Nicrofer 5219 Nb agree quite well with data determined semi-empirically via da/dN - $\Delta K$ curves.

The $K_G$ ($K_{op}$) values determined do not agree with closure data measured via COD (CMOD) or back-face strain signals.



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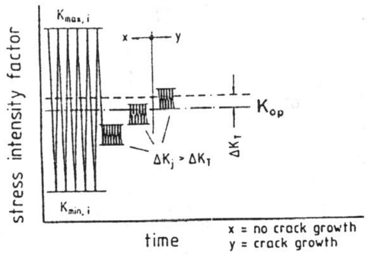


Fig. 1: Test method for $K_{op}$ determination

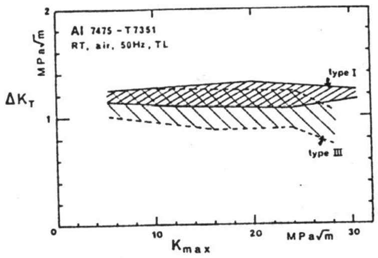


Fig. 2: Closure-free threshold $\Delta K_T$ for Al7475-T7351

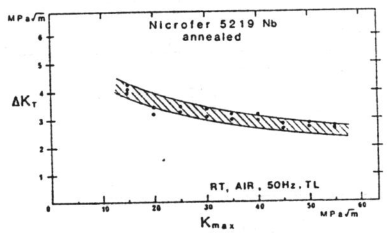


Fig. 3: Closure-free threshold $\Delta K_T$ for Ni-base alloy Nicrofer 5219 Nb

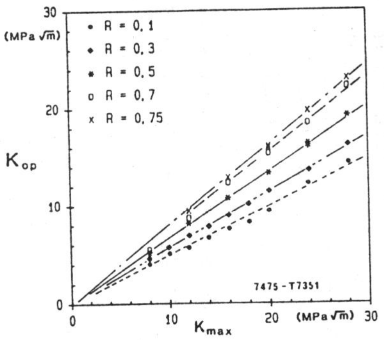


Fig. 4 : Measured $K_{op}$ values as function of $K_{max}$ for Al7475-T7351

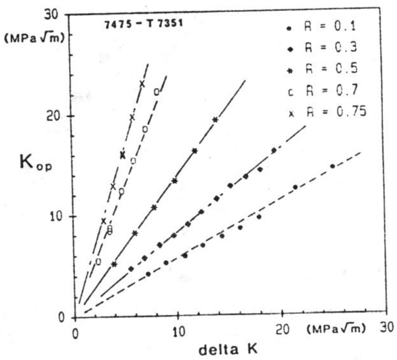


Fig. 5 : Measured $K_{op}$ values as function of delta K for Al7475-T7351

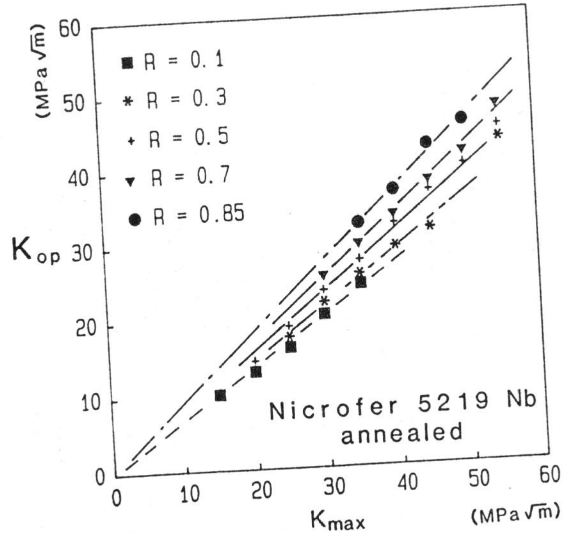


Fig. 6: Measured $K_{op}$ values as function of $K_{max}$ for Nicrofer 5219 Nb

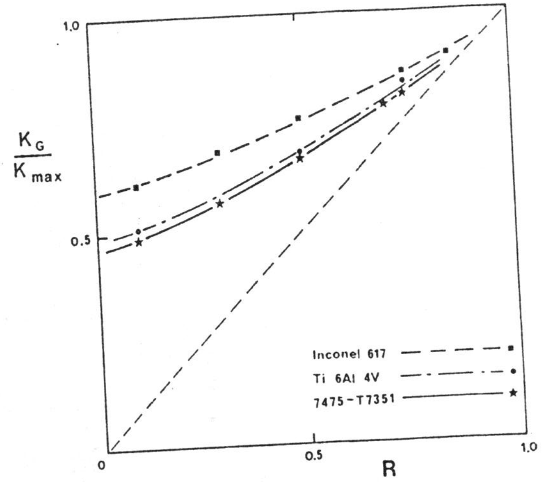


Fig. 7: $K_{op}/K_{max}$ as function of R for several materials investigated by the test method