INFLUENCE OF CRACK CLOSURE ON FATIGUE CRACK PROPAGATION

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ABSTRACT

The crack opening stress intensity factor, K_{op}, was evaluated as a function of ΔK, R and test frequency. It was found that at intermediate growth rate regime of the Paris plot, K_{op} is independent of ΔK, R and test frequency. The effective stress intensity range ratio $U = \frac{\Delta K_{eff}}{\Delta K}$ can be described as a function of ΔK and R by the equation :

$$U = \frac{1}{1-R} - \frac{K_{op}}{\Delta K} \quad \text{with } K_{op} = \text{constant}$$

This equation accounts well for the influence of R and ΔK on crack closure. K_{op} data in the near-threshold region, are found to be consistent with the oxide-induced closure model and the roughness-induced closure model. K_{op} and ΔK are remarkably sensitive to test frequency when oxide-induced closure arises. If the fracture surface roughness is important K_{op} and ΔK_{th} are independent of R and test frequency. Comparison between the fatigue crack threshold and the crack closure data has allowed a conservative estimation of the threshold values from the crack opening stress intensity level :

$$\Delta K_{th} = (1-R).K_{op} \quad \text{with } K_{op} = \text{constant}$$

KEYWORDS

Fatigue Mechanisms, Crack Growth, Crack Closure, Threshold, Crack Oxidation.

INTRODUCTION

The tensile residual strains left in the wake of a fatigue crack tip lead to crack closure at tensile loads. Elber (1971) introduced the hypothesis that crack propagation can occur only during that portion of the loading cycle in which the crack is fully open at the crack tip ; Elber defined the effective stress intensity range, $\Delta K_{eff} = K_{max} - K_{op}$, where K_{max} and K_{op} are the maximum and crack opening stress intensities respectively. Subsequently, several studies were made in order to evaluate the changes in magnitude of crack closure during the fatigue test. These studies are generally based on different experimental methods and lead to contradictory results. In particular, there are some conflicting results in the literature about the effect of the load ratio R ($= \frac{\text{minimum load}}{\text{maximum load}}$) and stress intensity range, ΔK, on K_{op}.

In this paper we analyse experimental data obtained with a large range of metallic materials in tests performed at R = 0. The crack opening load was detected for all tests using the elastic compliance method. The crack closure effect was evaluated as a function of ΔK, R and test frequency. Furthermore, attempts were made to correlate the threshold value ($K_{max(th)}$) with K_{op} measurements corresponding to the linear regime of the Paris plot.

MATERIALS

A wide range of steels, one Al alloy and one α-brass have been investigated. Chemical composition and mechanical properties are listed in Table 1.

TABLE 1 Chemical analysis, heat treatment and mechanical properties of the materials

Material	Heat Treatment	Chemical composition (weight %)									Mechanical properties σ_y (MPa)	UTS (MPa)	A % (MPa)	σ'_y (MPa)	n'
		C	Mn	Si	S	P	Ni	Cr	Mo	Al_t					
Steels															
E 36 Z	Annealed	0,145	1,40	0,29	0,003	0,006	0,42	0,075	0,031		380	555	33	300	0,21
E 550	Quench-and Temp. 625°	0,145	1,41	0,36	0,001	0,020					640	720	20	430	0,10
Rail St. gr. 70		0,481	1,10	0,26	0,022	0,009	0,044	0,028		0,012	406	766	20	(410)	(0,26)
Rail St. gr. 90		0,622	1,39	0,33	0,019	0,038	0,043	0,021		0,012	489	928	14,4	(400)	(0,21)
35 NCD 16 (A)		0,36	0,23	0,34	0,001	0,006	3,98	2,05	0,43		630	1040	13,6		
35 NCD 16 (B)	Q + T. 200	-	-	-	-	-	-	-	-		1515	1915	9	(1400)	0,14
35 CD 4	Q + T. 500	0,35	0,67	0,21	0,030	0,016		0,91	0,21		1180	1270	12,9		0,15
80 C 4	Q + T. 575	0,80	0,8	0,4	0,015	0,011	0,7	1,0	0,3		860	1200	14	660	0,19
160 C 4	Annealed	1,6	1,3	0,4	0,013	0,003	0,7	1,2	0,3		470	500	1	450	0,26
		Cu	Mg	Mn	Fe	Si	Ti								
Aluminium alloy															
Al-Cu 2024	T 351	4,81	1,51	0,7	0,29	0,23	0,014				319	458	21,9		
		Zn	Pb	Fe	Ni										
Brass															
α-brass 70-30	Annealed 450°	28,88	0,007	0,006	0,005						103	330	66		

EXPERIMENTAL PROCEDURES

Crack growth tests were conducted in laboratory air using constant amplitude loading, with different R values and frequencies (R = 0.1-0.7 ; f = 5-65 Hz). Compact tension and three point bending specimens were employed. Crack opening measurements were performed using a crack mouth displacement gauge and back face strain gauges. The load-displacement (or load-back face strain) signals were recorded either conventionally by reducing the test frequency to f = 0.1 Hz, or at the test frequency by using a digital storage oscilloscope with a 16 K word (16 bit), buffer memory. Electric interferences were reduced by active filters and care was taken to ensure no attenuation of the original load signal. When necessary, the output signals was smoothed by numerical averaging over a few cycles. To get an accurate detection of the opening load, an offset system was used (Ohta and Sasaki, 1975).
The determination of the ΔK threshold was made in this study by the decreasing ΔK technique. ΔK was reduced slowly so that $dK/da \leq -1$ MPa $\sqrt{m}$/mm and $(1/\Delta K).(dK/da) \sim 0.1$ mm until a growth rate less than 10^{-10} m/c was reached. ΔK was then allowed to increase under constant load amplitude to confirm that the da/dN - ΔK relation followed under decreasing ΔK was re-traced. ΔK_{th} was taken, as the value of ΔK at which $da/dN = 10^{-10}$ m/c.

RESULTS AND DISCUSSION

Crack closure in linear regime of Paris plot

Experimental data are presented in figure 1 for three different materials : 35 NCD 16, 2024 T351 and 160 C4. This figure shows the variation of K_{op} with ΔK : K_{op} is roughly independent of both ΔK and R. All the materials studied have shown similar behaviour and a detailed list of K_{op} values is given in Table 2. Figure 2 shows the variation of the effective stress intensity range ratio, $U = \frac{\Delta K_{eff}}{\Delta K}$, as a function of ΔK for different R ratios.

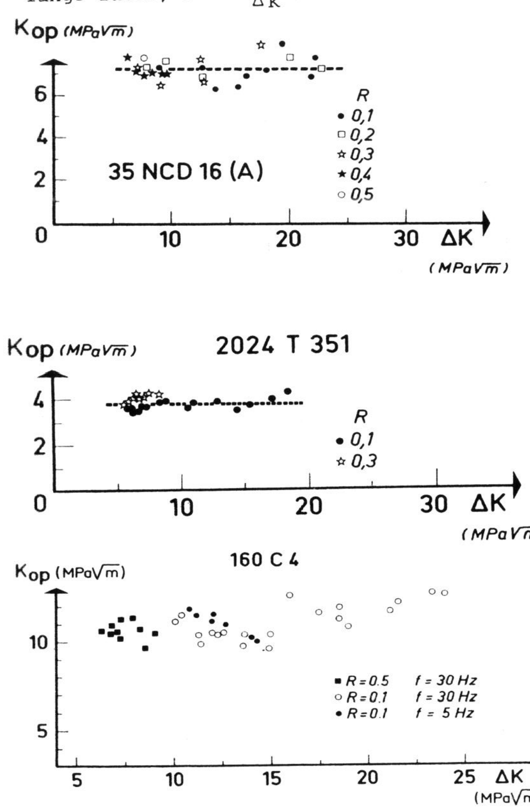

Fig. 1. Crack opening stress intensity factor versus stress intensity range for different materials

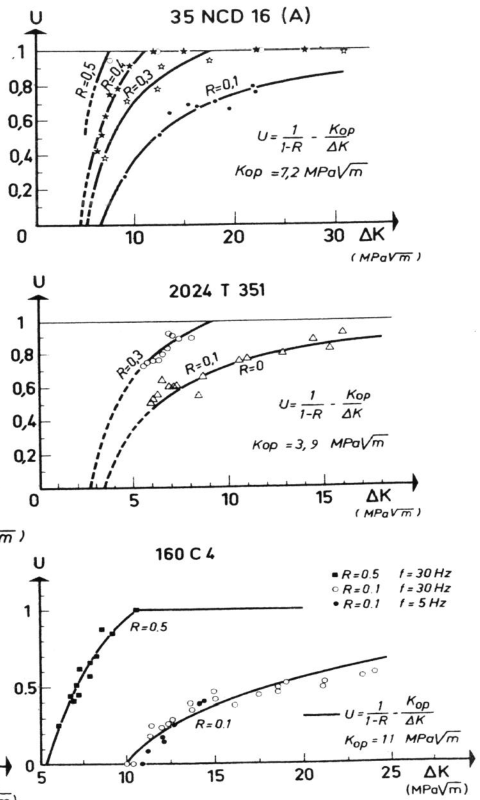

Fig. 2. Comparison of actual effective stress intensity ratio obtained from experimental measurements with curves calculated from eq. (1).

The experimental results fit a sample relationship :

$$U = \frac{\Delta K_{eff}}{\Delta K} = \frac{K_{max} - K_{op}}{\Delta K} = \frac{\Delta K}{1-R} - K_{op} \cdot \frac{1}{\Delta K}$$

$$\text{i.e. } U = \frac{1}{1-R} - \frac{K_{op}}{\Delta K} \qquad \text{with } K_{op} = \text{constant} \qquad (1)$$

The curves calculated from equation (1) are plotted in figure 2. It should be pointed out that the variation of U predicted by equation (1) rather well the fact that usually no closure is detected for high R ratio or high ΔK. For high R ratios, closure can exist only for very low ΔK.

TABLE 2 Crack opening stress intensity factor values for various materials in different experimental conditions

Material	Test frequency (Hz)	K_{op} (MPa $\sqrt{m}$) R = 0.1	R = 0.2	R = 0.3	R = 0.4	R = 0.5	$\bar{K}_{op}$ (MPa $\sqrt{m}$)
E 36 Z	40	$4.6^{\pm 0.6}$					$4.6^{\pm 0.6}$
E 550	65	$4.1^{\pm 0.3}$					$4.1^{\pm 0.1}$
35 NCD 16 (A)	40	$6.9^{\pm 0.5}$	$7.4^{\pm 0.3}$	$7.3^{\pm 0.8}$	$7.3^{\pm 0.3}$		$7.2^{\pm 0.5}$
35 NCD 16 (B)	40	$2.9^{\pm 0.6}$	$2.9^{\pm 0.2}$	2.9			$2.9^{\pm 0.6}$
35 CD4	40	$3.4^{\pm 0.6}$	$3^{\pm 0.5}$				$3.2^{\pm 0.8}$
Rail St. gr. 70	40	$6.3^{\pm 0.8}$					$6.3^{\pm 0.8}$
Rail St. gr. 90	40	$6.1^{\pm 0.7}$					$6.1^{\pm 0.7}$
80 C 4	30	$4^{\pm 0.2}$					$3.6^{\pm 0.6}$
	0.2	$3.5^{\pm 0.5}$					
160 C 4	30	$11.2^{\pm 1}$				$10.7^{\pm 0.5}$	$11^{\pm 1}$
	5	$11^{\pm 0.7}$					
2024 T 351	30	$3.8^{\pm 0.2}$		$4^{\pm 0.2}$			$3.9^{\pm 0.3}$
α-brass 70-30	30	$4.1^{\pm 0.3}$		$4^{\pm 0.2}$			$4.1^{\pm 0.3}$

A crack opening stress intensity factor, K_{op}, independent of load ratio, R, and of stress intensity range, ΔK, suggests to consider a standard curve which represents ΔK_{eff} as a function of K_{max} for a given material. Our experimental results are in good agreement with the results of Vazquez, Morrone, and Ernst (1979) obtained for aluminium alloys.

Crack closure at low fatigue crack growth rate

In addition to the plasticity-induced closure proposed by Elber (1971), two other closure mechanisms for plane strain conditions have been suggested to explain near-threshold crack growth behaviour. These proposed mechanisms are based on the role of crack surface corrosion deposits, "oxide-induced closure" (Ritchie, Suresh and Moss, 1980 ; Benoit, Namdar-Irani and Tixier, 1980 ; Freeman, Smith and Stewart 1982), and fracture surface roughness or morphology, "roughness-induced crack closure" (Suresh, Zamiski and Ritchie, 1981 ; Walker and Beevers, 1979 ; Mayes and Baker, 1981 ; Minakawa and Mc Evilly, 1981). Two steels, 80 C4 and 160C 4, of composition and properties listed in Table 1, with very different fracture surface morphology (see table 3) were chosen in order to investigate the relative influence of the two closure mechanisms. The results obtained are shown in figures 3 and 1-c where opening stress intensity factors, K_{op}, are plotted versus stress intensity range, ΔK.

For steel 80 C4, figure 3, K_{op} remains roughly constant for high ΔK values and the two different test frequencies (0.2 Hz and 30 Hz). Below a ΔK of 12 MPa $\sqrt{m}$ the closure behaviour depends on test frequency : at low frequency test (5 Hz) K_{op} follows the results obtained at high ΔK level ; for higher frequency (30 Hz) K_{op} does not follow this trend but begins to increase for ΔK values smaller than 12 MPa$\sqrt{m}$.

This latter behaviour is in close agreement with the oxide-induced closure model and the test frequency dependent fracture surface oxide thickening observed by Bignonnet, Namdar-Irani and Truchon (1982) and shown in fig. 4.

As a consequence of the variation of the crack closure behaviour, fatigue threshold values change in the same way as K_{op} , fig. 5. Table 3 shows the values of K_{op}, $K_{op(th)}$, $K_{max(th)}$ and fracture surface roughness for the different test conditions. The $K_{op(th)}$ values are very close to the $K_{max(th)}$ values and differences between these values and K_{op}, measured in the linear region of Paris plot, are due to wedge effect of corrosion deposit as discussed above.

For steel 160 C4, a high value of K_{op} was found independent of R, ΔK and test frequency, even for near-threshold level (figure 1-c).

The values of K_{op}, $K_{op(th)}$ and K_{max} are very close for all test conditions This behaviour can be related to the marked roughness of the fracture surface which dominates the crack closure. In this case, the influence of oxide-induced closure is negligible in comparison with roughness-induced closure, althought oxide debris also exist on the fracture surface

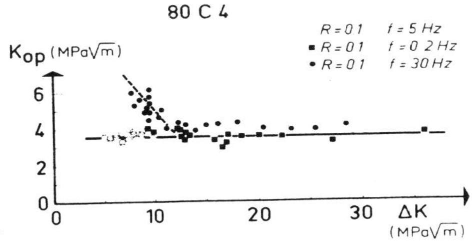

Fig. 3 Opening stress intensity factor versus stress intensity range for steel 80 C4.

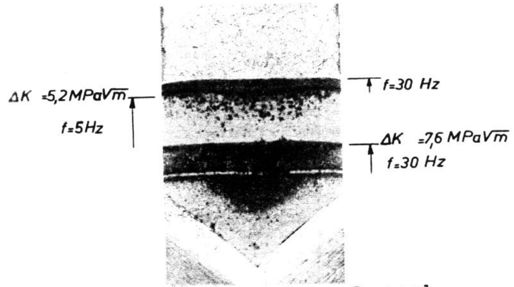

Fig. 4. Fracture surface of steel 80 C4 produced by fatigue in moist air enviroment at 30 Hz, then at 5 Hz, finally at 30 Hz.

From these consideration, K_{op} at low fatigue crack growth rate does not have a universal behaviour but depends on the fracture surface roughness of the material and the test frequency, as well as test environment and load ratio (Bignonnet and Colleagues, 1982, 1983). According, the fatigue threshold value also depends on the same parameters.

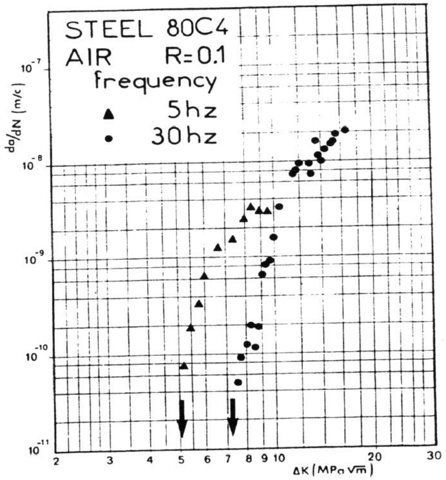

Fig. 5 Variation of crack growth rate with amplitude of stress intensity factor for steel 80 C4 in laboratory air

In summary :

- K_{op} and $K_{max(th)}$ are remarkably sensitive to test frequency when closure is oxide-induced ;
- K_{op} and $K_{max(th)}$ do not depend on R ratio or test frequency when closure is roughness-induced.

It is evident that in the case of oxide-induced closure the increase of K_{op} created by oxide deposits invalidates equation (1) (see figure 6). In this case relation (1) is valid for tests where K_{op} is constant, i.e., tests performed at high load ratio or at low test frequency, where fracture surface corrosion debris is insignificant.

TABLE 3 Comparison between K_{op}, $K_{op(th)}$ and $K_{max(th)}$

Material	Test frequency	R	K_{op} (MPa$\sqrt{m}$)	Threshold $K_{op(th)}$ (MPa$\sqrt{m}$)	Threshold $K_{max(th)}$ (MPa$\sqrt{m}$)	Ra (μm)	Rma (μm)
Rail St. gr. 70	40 Hz	0.1	$6.3^{\pm 0.8}$	-	8 (ref. Cooke and Beevers, 1974)	-	-
Rail St. gr. 90	40 Hz	0.1	$6.1^{\pm 0.7}$	-	8	-	-
80 C 4	30 Hz	0.1	$4^{\pm 0.2}$	$6^{\pm 1}$	7	5	43
	5 Hz	0.1	$3.6^{\pm 0.6}$	$3.5^{\pm 0.5}$	5	2.5	19
160 C 4	30 Hz	0.1	$11.2^{\pm 1}$	$11.2^{\pm 1}$	12.2	>25	-
	5 Hz	0.1	$11^{\pm 0.7}$	$11^{\pm 0.7}$	12.2	>25	-
	30 Hz	0.5	$10.7^{\pm 0.5}$	$10.7^{\pm 0.5}$	12.4	>25	-
2024 T 351	30 Hz	0.1	$3.8^{\pm 0.2}$ (ref. Bignonnet, 1979)	-	4.4 (ref. Baïlon and colleagues, 1982)	-	-
α-brass 70-30	30 Hz	0.1	$4.1^{\pm 0.3}$ (ref. Bignonnet, 1979)	-	4.7 (ref. Lanteigne and Baïlon, 1981)	-	-

USE OF K_{op} AS A LOWER BOUND OF THE THRESHOLD VALUE

The fatigue crack growth threshold may be interpreted in terms of fatigue crack closure. The idea of the interpretation of fatigue threshold by a crack closure concept was first suggested by Schmidt and Paris (1973). This model suggests that the stress intensity for crack closure, K_{op}, is constant and ΔK must exceed a limiting value above K_{op}, insensitive to stress ratio variation, to cause crack growth at threshold.

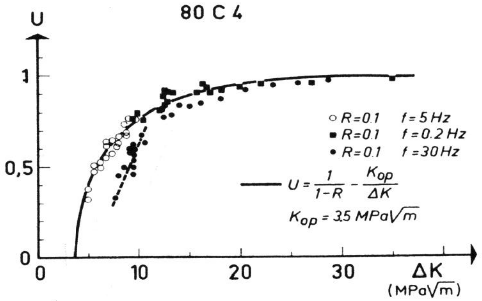

Fig. 6 comparison of actual effective stress intensity ratio.

Afterwards, several studies were made in order to evaluate the effective stress intensity range at the threshold, $\Delta K_{eff(th)}$, with contradictory results. Kikuwa, Jono and Tanaka (1976) have found significant values of ΔK_{eff} at threshold, with different $\Delta K_{eff(th)}$ values for different materials. On the other hand Ohta and Sasaki (1975) observed a fully closed crack at the threshold. Minakawa and Mc Evily (1982) found a partially closed crack at threshold for steels and a fully closed crack for an aluminium alloy and their results on steels show $\Delta K_{eff(th)}$ insensitive to yield strength and heat-treatment. Lin and Fine (1982) showed that for iron $\Delta K_{eff(th)}$ increases with grain size and decreases with cold working. Bignonnet and Colleagues (1983), for one steel and several environments, found $K_{max(th)}$ always slightly higher than K_{op} at threshold, and a comparison of crack surface oxide thickness with crack tip opening displacement range near-threshold showed that the oxide was thick enough to fully wedge-close the crack. Finally, the results of the present study show a fully closed crack at fatigue threshold.

In summary, it is generally accepted that in the near-threshold region the crack remains closed over most of the load cycle, but an objective understanding of $\Delta K_{eff(th)}$ is not available at present.

In spite of the uncertainties about $\Delta K_{eff(th)}$, it seems reasonable to consider that ΔK_{eff} approaches zero at threshold. In such an analysis, we can use equation (1) :

$$U = \frac{\Delta K_{eff}}{\Delta K} = \frac{1}{1-R} - \frac{K_{op}}{\Delta K} \approx 0 \quad \text{at } \Delta K = \Delta K_{th}$$

$$\text{i.e.} \quad \Delta K_{th} \approx (1-R) \cdot K_{op} \quad \text{or} \quad K_{max(th)} \approx K_{op} \qquad (2)$$

As shown above, K_{op} (measured in the linear region of the Paris plot) is constant and independent of R. Figure 7 illustrates this hypothesis and shows why K_{op} can be taken as an estimate of $K_{max(th)}$

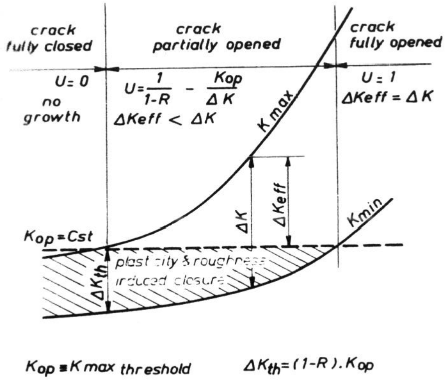

Fig. 7. Significance of crack opening stress intensity

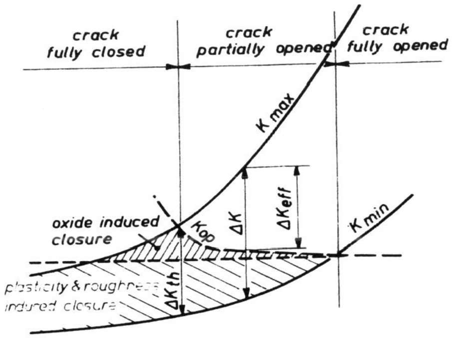

Fig. 8. Crack opening stress intensity for oxide-induced clossure

Equation (2) can be compared with the empirical relationship proposed by Masounave and Baïlon (1975) for ferritic-pearlitic steels :

$$\Delta K_{th} = (1-R) \cdot K_{max(th)}$$

Where $K_{max(th)}$ is a material property independent of R. Equation (2) also agrees with results of several authors (Schmidt and Paris, 1973 ; Cooke and Beevers, 1974) who have shown that for a given material the maximum threshold stress intensity factor ($K_{max(th)}$), under constant amplitude loading, is nearly constant over a large range of the load ratio R.

Table 3 gives a comparison between K_{op} measured in the linear regime of the Paris plot and $K_{max(th)}$ for some of the materials studied. As discussed above, when oxide-induced closure is significant, the effect of an oxide deposit developed at low fatigue crack growth rates cannot be estimated from K_{op} data measured for growth rates well above threshold. Figure 8 shows the expected behaviour of K_{op} for oxide-induced closure. In this case, the threshold ΔK_{th} estimated from equation (2) must then be interpreted as a lower bound.

CONCLUSION

Fatigue crack propagation in wide range of alloys has been studied in a moist air environment for different R ratio and test frequencies. Crack closure was monitored in all tests using the elastic compliance method, from which the following conclusions may be drawn :

- in the linear region of the Paris plot
  - . K_{op} is roughly constant, independent of ΔK, R and test frequency ;

. the variation of $U = \frac{\Delta K_{eff}}{\Delta K}$ can be described by the equation :

$$U = \frac{1}{1-R} - \frac{K_{op}}{\Delta K} \quad \text{with } K_{op} = \text{constant}$$

This equation accounts well for the influence of R and ΔK on crack closure.

- at low fatigue crack growth rate
  . K_{op} data are found consistent with either oxide-induced closure or roughness induced closure, depending on the material ;
  . ΔK_{th} and K_{op} are sensitive to frequency when oxide-induced closure dominates ;
  . if roughness-induced closure dominates, K_{op} and ΔK_{th} are independent of R and test frequency.
- a comparison between fatigue crack growth threshold and crack closure data has allowed a conservative estimate of ΔK_{th} :

$$\Delta K_{th} = (1-R).K_{op} \quad \text{with } K_{op} = \text{constant}$$

where K_{op} is the crack opening stress intensity factor measured in the linear regime of the Paris plot.

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