Crack Closure Effect on Two Aluminum Alloys in Relation to Short Fatigue Crack Growth Behavior — Comparison Between Various Measurement Techniques

A. LEFRANÇOIS* and A. PINEAU

Centre des Matériaux, Ecole des Mines BP 87, 91003 Evry Cedex, UA CNRS N° 866, France

ABSTRACT

Various techniques were used to measure crack closure effect in 2124-T351 and 7475-T7351 aluminum alloys. These measurements were made both on long (~ 10 mm) and short (~ 0.2 - 1 mm) cracks obtained by machining off the wake of long fatigue cracks. In both alloys it is shown that the opening stress intensity factor, Kop is an increasing function of crack length before reaching a plateau corresponding to the value associated with long cracks. The short crack transient effect in Kop extends over larger distances in 7475 alloy compared to 2124 alloy while the plateau Kop is dependent not only on the material but also on crack growth rate. The variations of Kop with crack length are compared to other results published in the literature.

INTRODUCTION

Many studies have been devoted to crack closure phenomenom since the pioneer work by Elber [1971]. These studies showed that crack closure effect is a useful concept to explain a number of behaviors observed on long fatigue cracks ($\simeq$ 10 mm), especially the effect of stress ratio, R. More recently it was shown that closure effect was crack size dependent. This property was used by a number of investigators (see eg [Breat *et al.*, (1984), Mc Evily and Minakawa, (1984), Ritchie and Yu, (1986), Lefrançois *et al.*, (1986)]) to rationalize the behavior of the so-called physically-short cracks (<< 1 mm). The anomalous fatigue behavior of these short cracks is now well documented (see eg [Pearson, (1975), Lankford, (1982), Miller, (1987), Suresh and Ritchie (1984)]). At equivalent ΔK values, the short cracks tend to propagate faster than the long ones. They also grow below the thresholds commonly observed for long cracks. Depending on different parameters, such as local plasticity, crack length, crack geometry, environment, crack closure and microstructure, a wide range of possible behavior patterns is observed. Eventually the growing short crack behavior merges with that of long cracks at some particular small crack length. There is a need to unify different aspects of the short crack problem in terms of few and simple concepts. As stated previously an effort is currently placed to characterize, to some extent, the short crack

* Now at FRAMATOME, Tour Fiat, 1 Pl. de la coupole, 92084 PARIS LA DEFENSE

behavior in relation to crack closure effect. This is the main object of the present study. For this purpose measurements of crack closure effect as a function of crack length have to be carried out. The results of such measurements are still very scarce in the literature, except those obtained on a low alloy steel [Breat *et al.*, (1984), Journet *et al.*, (1988)], nodular cast iron [Clément *et al.*, (1984)], a 9 Cr-1 Mo steel [Minakawa *et al.*, (1984)] and Al alloys [Zaiken and Ritchie, (1985), Journet *et al.*, (1988), Morris, (1973)].
Several techniques are commonly used to measure crack closure effect. Most of them were essentially applied to long fatigue cracks. They can be classified as follows : (1) physical measurements, such as the compliance technique or the potential drop technique (2) Direct methods based on the observation of the crack mouth displacement (3) Indirect methods based on the postulated existence of an effective stress intensity factor, ΔK_{eff} to measure the efficient crack driving force.
The object of the present study is first to compare the results of crack closure measurements on long cracks obtained by several techniques. Then the results of crack closure measurements as a function of crack length are reported. These results are used to show the influence of the crack closure transient effect observed on small cracks on the fatigue life corresponding to the propagation of a small crack initiated from a notch. The techniques used for crack closure measurements included : (1) Crack mouth displacement measurements achieved with a front clip gauge, (2) observation of the surface crack lip displacement, (3) front strain gauge extensometer measurements, (4) indirect method based on the concept of effective stress intensity factor.

MATERIALS AND EXPERIMENTAL PROCEDURES

The composition of the investigated materials was (weight percent) : 2124 (4.37 Cu - 1.46 Mg - 0.63 Mn) - 7475 (5.5 Zn - 1.55 Cu - 2.35 Mg). The grain size was 600 µm, (800 µm) in the longitudinal direction, 200 µm (500 µm) in the transverse direction, and 60 µm, (80 µm), in the short transverse direction in 2124 and (7475), respectively. The yield strength measured in the longitudinal direction was 375 MPa (2124) and 425 MPa (7475). Conventional CT specimens (W = 75 mm, thickness = 8mm) and four point bend specimens (W = 30 mm, thickness = 15 mm) were tested in the LT direction at a frequency of 30Hz. Two types of test were run on CT specimens : (i) constant amplitude (CA) tests at R ratio of 0.1 and 0.50; (ii) variable amplitude (VA) loading corresponding to CA test at R = 0.10 including one overload ($\tau = P_{overload}/P_{max} = 1.70$) every 1000 cycles. Crack closure loads were measured directly using a clip gauge extensometer mounted on the front face of the specimens, only for CA tests.
Bend specimens were used to measure the variation of the opening stress intensity factor, Kop as a function of crack length. 2D short cracks (a = 0.050 - 0.25 mm) were obtained by machining off the wake of the long fatigue precracks.The tests for measuring Kop = f(a) were carried out on an electromechanical Schenck bending machine. Crack closure was measured with a clip gauge extensometer or strain gauges mounted on the front surface of the specimens. In a number of specimens a longer crack (a $\simeq$ 3 mm) was left. These specimens were used to compare the results of Kop measurements obtained by using either the compliance technique (CT specimens) or a direct method based on the observation of the crack lip displacement. The crack lips were observed with an optical microscope (X 1000) under increasing bending moment which was applied by a small mechanical bending machine.

RESULTS

The results of fatigue crack growth rates (FCGR) measurements on CT specimens containing long cracks are reported in Fig.1a et b. For CA loading it is usually assumed that the R ratio effect observed on these curves is related to crack closure effect. In the medium range of FCGR (10^{-8} to 10^{-6} m/cycle) it is convenient to assume that the U ratio ($U = \Delta K_{eff}/\Delta K = (K_{max} - K_{op})/(K_{max} - K_{min})$) follows a linear relation with R ratio, as originally proposed by Elber [(1971)], i.e.

$$U = AR + B$$

Similarly to account for the retardation effect observed under VA loading conditions, DAVY et al [(1985)] assumed that the crack closure stress intensity factor associated with long cracks, Kop remained constant during the 1000 cycles following one overload and that Kop could also be calculated from Elber expression, written as :

$$\left(K^P_{max} - K^{\cdot}_{op}\right) \Big/ \left(K^P_{max} - K_{min}\right) = AR_P + B = A\left(K_{min} \Big/ K^P_{max}\right) + B$$

The coefficients A and B can therefore be determined from both CA and VA tests. It was found that A = 0.39,(0.29), B = 0.61,(0.71) in 2124 and (7475) alloy, respectively. The values of Kop calculated from Elber expression are given in Table 1. These values are in good agreement with those obtained both on CT and on 3 point bend specimens by using the deviation of the linearity of the crack mouth displacement measured with a clip gauge mounted on the front surface of the specimens.
The results of crack lip displacements ($\delta - \delta r$) are given in Fig.2a and 2b. The displacements were measured at various distances a^*i , behind the crack tip. δr (~ 1µm) is the residual displacement measured in the absence of any applied load. Two methods were used to assess the value of Kop . Full details are given elsewhere [Lefrançois, (1987)]. Here it is enough to say that in the first method, Kop was obtained by extrapolating, as a function of K applied, the length (Δas) over which an interference of the crack lips was observed up to zero. The values determined from this method are referred in Table 1 as "displacement extrapolation". The second method relies upon the theoretical value of the displacement determined from LEFM. For a Mode I crack the crack lip displacement is theoretically given by :

$$2u_y = (\delta - \delta_r) = k\ (8\ K_I/E)\ \left(a^*_i\ /2\pi\right)^{1/2}$$

where E is Young modulus, while k = 1 or $(1 - \upsilon^2)$ in plane stress or plain strain condition, respectively. This expression, which is valid only for an opened crack, was used to calculate the value of Kop . by plotting the varation of ($\delta - \delta r$) as a function of $(a^*i)^{0.5}$. A straight line with a slope verifying the above equation is obtained as soon as K applied is larger than Kop. The values of Kop inferred from this method, assuming that k = 1 are given in Table 1. They are referred as $(a^*i)^{0.5}$ displacement values.
Table 1 shows that the value of Kop obtained by various techniques are very consistent. Similar results have been reported on Al 2124 alloy [6]. At low ΔK values, both materials lead to similar results (Kop ~ 2.7MPa m) . At higher ΔK the values of Kop measured in 2124 alloy (~ 6.4MPa m) are significantly larger than those determined in 7475 alloy (~ 5.2MPa m). This difference might be related to the fact that the plasticity induced

crack closure component is lower in 7475 alloy than in 2124 alloy because of the difference in yield strength between both materials.
The results of measurements of Kop as a function of crack length are given in Fig. 3 for both materials. These results were obtained by using the front clip gauge technique, except otherwise stated. The measurements were made for two values of the precracking stress intensity factor, ΔK = 5.5 and 15MPa m . In 2124 alloy it is observed that the short crack effect extends over rather small distances ($\simeq$ 0.3mm). This result is consistent with those obtained by Ritchie and Yu [(1986)] on the same material. On the other hand in 7475 alloy the short crack effect extends over larger distances ($\sim$ 1 to 2mm). It is also worth noting that the value of Kop determined with a strain gauge mounted on the front surface of the specimens in 7475 are consistent with those obtained with a clip gauge extensometer.
The shape of the Kop curves can be fitted by a simple expression proposed originally by Mc Evily et al [(1984)] as :

$$K_{op} = K^{*}_{op} \; [1 - \exp - ka]$$

where Kop is the opening stress intensity factor for long cracks. The k factor is a material constant, expressed in reciprocal millimeters units which characterizes the length over which the short crack transient effect occurs. For the materials investigated in the present study large differences are noticed since k $\simeq$ 10mm^{-1} and 2mm^{-1} for both values of ΔK in 2124 and 7475 alloy, respectively. In Table 2 we have also reported the results obtained on other materials in which similar measurements were made. It is observed that K depends on both the microstructure and on the mechanical properties of the materials. It is not possible to derive from Table 2 a one-to-one relationship between k and the yield strength although in ferritic materials k increases with the yield strength. However in Al alloys the opposite is observed. This suggests that in these materials the grain size which controls the fracture surface roughness plays also a predominant role.

APPLICATION OF CRACK CLOSURE TRANSIENT EFFECT TO FATIGUE LIFE

As stated in the introduction the crack closure transient effect has already been largely used to explain the behavior of short cracks initiated from smooth specimens. The introduction of this effect into the analysis of the growth of cracks initiated from notches leads also to a better understanding of matters, such as the non-propagating cracks. In the following an attempt is made to illustrate how this concept can be used to calculate the fatigue life of a notched component containing a small crack. The component is a simple plate with a hole of diameter, 2ρ (Fig. 4a). For a constant value of $\Delta\sigma$ the curves shown in Fig. 4b represent the variation of ΔK as a function of crack length. Curves (1) and (2) are only approximations while curve (3) is the analytical expression derived by Schijve [(1982)] which can be used for $a^{*}/\rho \leqslant 1$. Above this value the long crack approximation (curve 1) must be used. It is well to remember that these values of K do not take into account the plasticity associated with the notch.
The use of long crack data to predict the fatigue life spent in crack propagation (N) is not conservative since it includes the upper limit of crack closure effect measured by Kop . Those data can easily be converted into da/dN - ΔKeff curves when the variation of Kop with crack growth rate is known. ΔKeff = Kmax - Kop is the effective stress intensity factor. The da/dN- ΔKeff curve for 2124 alloy is shown in Fig.5. The use of this curve

leads to a life prediction which is too conservative. On the other hand a better assessment of the fatigue life (Neff) is obtained by using the Kop-a curves similar to those shown in Fig.3 in addition with the da/dN - ΔKeff data. The calculations were made for 2124 alloy, with various initial crack lengths ($a^{*}o$) and various hole radii, ρ.
The variations of the Neff/N ratio are reported in Fig.6 for two initial values of the stress intensity factor ΔKi = 4.05 and 6.05MPa which are above the theshold measured on long cracks. It is observed that the long crack data (da/dN-ΔK curve) are the less conservative as the initial radius ρ is large and as the initial crack length $a^{*}o$ is small, as expected. Fig.7 shows the calculated crack length as a function of number of cycles. It is noticed that the acceleration in crack growth rate due to the short crack effect occurs only over a small distance. From these calculations it is observed that the fatigue live inferred from the long crack data can be overestimated by a factor of about 2. Larger effects would have been obtained if similar calculations had been made for 7174 alloy since in this material the short effect extends over larger distances.

CONCLUSIONS

1 - Consistent results of crack closure measurements carried out on long cracks by using various techniques were obtained.
2 - The shape of the experimental curve Kop = f(a) determined on short cracks in Al 2124 and Al 7475 alloys can be described by a simple expression Kop/Kop = 1 - exp(-ka). The parameter k denotes the distance over which the short crack transient effect is operating, while Kop is the crack closure associated with long cracks.
3 - Larger differences in the value of k parameter are noticed when comparing not only these two Al alloys but also the results published on other materials in the literature. There is not a straightforward relation between k parameter and metallurgical factors or mechanical properties.
4 - Kop = f(a) curves can be used to correlate the growth behavior of cracks initiated from notches. In 2124 alloy it is shown that, above the threshold, the fatigue life calculated by using the crack closure transient effect associated with short cracks is significantly lower than the life predicted by using the long crack data.

REFERENCES

BREAT J.L., MUDRY F. and PINEAU A. (1984) Short crack propagation and closure effect in A 508 steel. *Fat. of Engng. Mat. Struct.*, 6, 349-358.
CLEMENT P., ANGELI J.P. and PINEAU A. (1984). Short crack behaviour in nodular cast iron; *Fatigue of Engineering Materials and Structures*, 7, 251-265.
DAVY A., ALIAGA D. and SCHAFF H. (1985) A simple crack closure model for predicting fatigue crack growth under flight simulation loading. Proc. of the 13th *Symp. Int. Commitee on Aeronautical Fatigue*, PISE, (ITALY) 22-24 May, 605-630.
ELBER W. (1971) The significance of fatigue crack closure. *ASTM STP* 486, 230-242.
JOURNET B.S., LEFRANCOIS A. and PINEAU A., (1988), A crack closure study to predict the threshold of 2D short cracks. To appear in *Fatigue and Fracture of Engineering Materials and Structures*.
LANKFORD, J. (1982) : The growth of small fatigue cracks in 7075-T6 aluminium. *Fatigue of Engineering Materials and Structures*, 5, 233-248.
LEFRANCOIS A., CLEMENT P. and PINEAU A., (1986) The growth of short fatigue cracks in an aluminium alloy in relation to crack closure effect. *Proceed of the I. MECH E. conf, SHEFFIELD*, 15-19 Septembre, 59-65.

LEFRANCOIS A., (1987) Propagation of 2D and 3D, short and long cracks under constant and variable amplitude fatigue loading in two aluminium alloys. Thesis Ecole des Mines de Paris.

Mc EVILY A.I. and MINAKAWA K.N. (1984) Crack closure and the growth of short and long fatigue cracks. *Scripta Met.*, <u>18</u>, 71-76.

Mc EVILY A.J., MINAKAWA K. and NAKAMURA H., (1984). Fracture Mechanics, Microstructure, and the growth of short and long fatigue cracks. Fracture : "*Interactions of Microstructures, Mechanisms and Mechanics*, Wells, J., Stoltz, T. and Landes, J. Eds. Proc. of a AIME Symp. Warrendale (USA), 215-233.

MILLER, K.J. (1987) : The behaviour of short fatigue cracks and their initiation Part I : A review of two recent books; Part II : A general summary. *Fatigue and Fracture of Engineering Materials and Structures*, <u>10</u>, 75-91 and <u>10</u>, 93-113.

MINAKAWA K., NAKAMURA H. and Mc EVILY A.J. (1984) On the development of crack closure with crack advance in a ferritic steel. *Scripta Met.*, <u>18</u>, 1371-1374.

PEARSON S., (1975) : Initiation of fatigue cracks in commercial aluminium alloy and the subsequent propagation of very short cracks. *Engineering Fracture Mechanics*, <u>7</u>, 235-247.

RITCHIE R.O. and YU W. (1986) Short crack effect in fatigue : a consequence of crack tip shielding. *Proceed of 2nd Eng. Found. Internat. Conf, Santa Barbara*, 5-10 January, 167-189.

SCHIJVE J. (1982). The stress intensity factor of small cracks at notches. *Fat of Eng. Materials and Structures*, <u>5</u>, 77-90.

SURESH S. and RITCHIE R.O., (1984) : Propagation of short fatigue cracks. *International Metals Reviews*, <u>29</u>, 445.

ZAIKEN E. and RITCHIE R.O. (1985) On the development of crack closure and the threshold conditions for short and long fatigue cracks in 7150 aluminium alloy. *Met. Trans.* <u>16A</u>, 1476-1477.

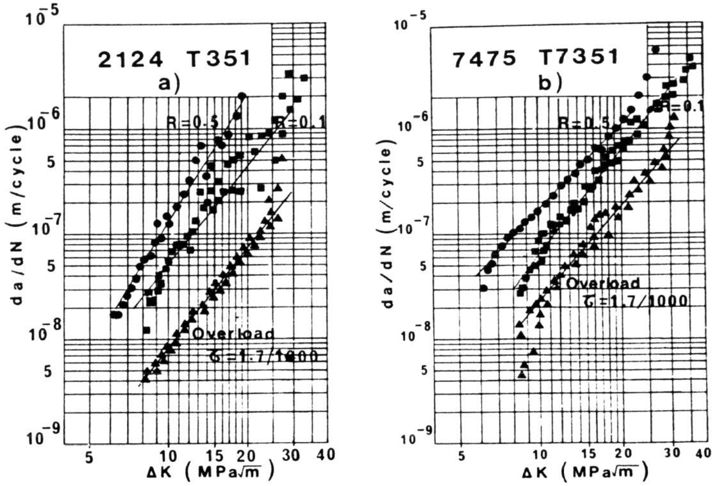
MATERIAL	2154	T351	7475 -	T7351
Precracking ΔK (MPa $\sqrt{m}$)	5.5	15	5.5	15
U model CT specimens	2.54	6.9	2.05	5.6
Front clip gauge CT specimens	2.8 ± 0.3	5 ± 0.3	ND	ND
Front clip gauge Bend specimens	2.9 ± 0.2	6 ± 0.5	2.6 ± 0.3	4.5 ± 0.3
Displacement Extrapolation	ND	7	ND	6
$\left(a_i^*\right)^{0.5}$ Displacement	ND	6 - 8	ND	4 - 5

ND : Not Determined

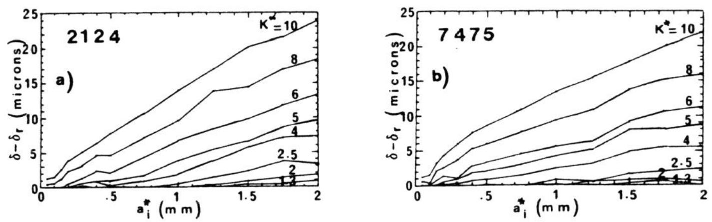
<u>Table 1</u> : Results of crack closure measurements Kop. On long cracks using different techniques.

MATERIAL	YIELD STRENGTH (MPa)	k (mm^{-1})
2124 7475	375 425	10 2
Nodular Cast Iron	270	1.5
A 508 Steel	419	3
9Cr - 1Mo Steel	531	13

<u>Table 2</u> : Values of the k parameter describing the short crack closure transient effect in various materials.



<u>Fig.1</u> - Fatigue crack growth rates as a function of ΔK measured at R = 0.10 and 0.50 under constant amplitude loading. Effect on an overload (τ = 1.70) applied every 1000 cycles, a) 2124 Alloy; b) 7475 Alloy.



<u>Fig.2</u> - Crack lip displacement at various distances, a_i^*, behind the crack tip, as a function of applied K*.
a) 2124 Alloy; b) 7475 Alloy.

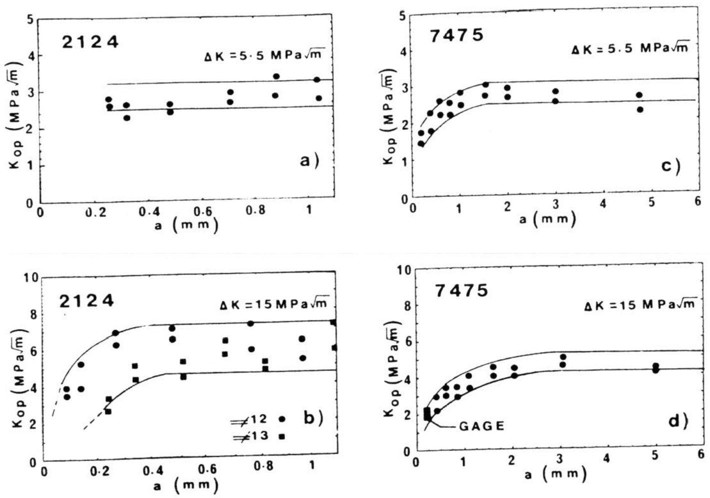


Fig.3 - Measurements of K_{op} as a function of crack length for two precracking conditions (ΔK_i = 5.5 and 15 MPa$\sqrt{m}$). a) and b) 2124 Alloy; c) and d) 7475 Alloy.

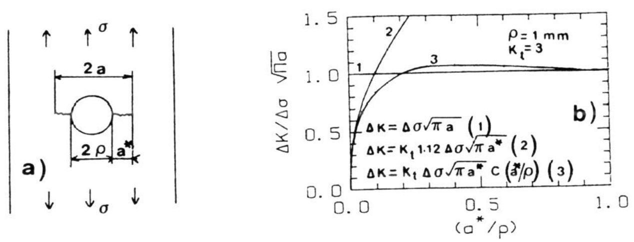


Fig.4 - a) Propagation of a fatigue crack from a hole; b) Relations used to calculate ΔK.

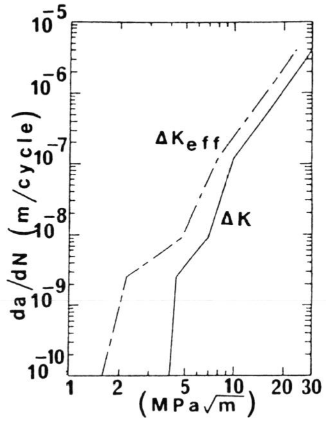


Fig.5
Crack growth rate as a function of applied ΔK and the effective stress intensity factor, ΔK_{eff} - 2124 Alloy.

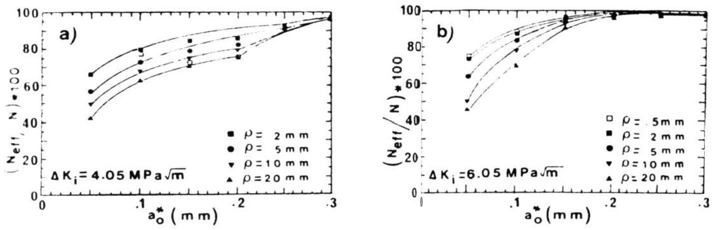


Fig.6 - Number of cycles to propagate a short crack (a_o) from a notch (radius ρ), calculated by using the long crack data (N) or the transient effect associated with short cracks (N_{eff}). Calculations for two initial values of ΔK_i.

a) ΔK_I = 4.05 MPa$\sqrt{m}$; b) ΔK_i = 6.05 MPa$\sqrt{m}$.

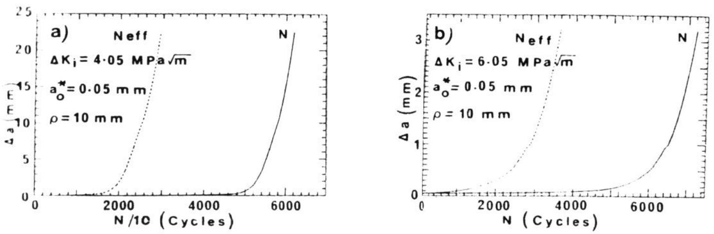


Fig.7 - Calculated crack length as a function of number of cycles for two values of ΔK_i :

a) ΔK_i = 4.05 MPa $\sqrt{m}$; b) ΔK_i = 6,05 MPa$\sqrt{m}$.