CRACK CLOSURE ANALYSIS AFTER PEAK OVERLOADS

L.P. Borrego[1], J.M. Ferreira[2], J.M. Costa[2]

[1]**Department of Mechanical Engineering, ISEC/IPC, 3030 Coimbra, Portugal**
[2]**Department of Mechanical Engineering/FCT, University of Coimbra**
Polo II, Pinhal de Marrocos, 3030 Coimbra, Portugal

Abstract. Fatigue crack propagation tests with single tensile peak overloads have been performed in 6082-T6 aluminium alloy at several baseline ΔK levels, ranging from 4 to 10 MPa $m^{1/2}$, and at stress ratios of 0.05 and 0.25. The tests were carried out at constant ΔK conditions, using MT specimens in a servohydraulic machine at a frequency of 20 Hz. Crack closure was monitored in all tests by the compliance technique using a pin microgauge. The observed transient post overload behaviour is discussed in terms of overload ratio and baseline ΔK level. The crack closure parameter U was obtained and compared with the crack growth transients. Plasticity induced closure seems to be the main mechanism determining the transient crack growth behaviour following overloads on 6082-T6 alloy. Predictions based on crack closure measurements show good correlation with the observed crack growth rates for all the post-overload transients when discontinuous closure is accounted for.

1. INTRODUCTION

The effects of crack growth retardation following single or multiple peak tensile overloads have been reported in many investigations simply because this type of loading can lead to significant load interaction effects [1-10]. Several mechanisms have been proposed to explain crack growth retardation, which includes models based on residual stress, crack closure, crack tip blunting, strain hardening, crack branching and reversed yielding. The precise micromechanisms responsible for these phenomena are not fully understood. In spite of some controversy, the effect of residual plastic deformation, which leads to compressive stresses before the crack-tip and raises the crack opening load on subsequent crack growth (crack closure), has been identified as the most important variable in explaining, fairly reasonably, the variation of the characteristic features of post-overload transients [2-8].

However, some discrepancies appear when the experimental post-overload transients are compared with the crack growth rates inferred from remote closure measurements and the da/dN versus ΔK_{eff} relation for the material [5-8]. Typically, the inferred and measured crack growth rates show good agreement only until the maximum retardation point or when crack growth rates are already recovering from the minimum value. Beyond this point predicted values tend to be lower than the experimental ones. Such behaviour has been attributed to the phenomenon of discontinuous closure [6-9] first identified experimentally by Fleck [6], *i.e.*, the crack is open near the tip, but still shut near the overload location at loads below the crack opening load, inducing measurements of crack opening loads that are excessively high. Finite element analyses have shown that this phenomenon can occur depending on the loading variables [7,10].

Recently, Donald and Paris [11], using a remote displacement gage, observed that for aluminium alloys in the near-threshold regime, with crack growth data obtained by load-reduction, the measured opening loads were excessively high. To take this effect in consideration, Paris *et al* [12] proposed a “partial closure model”, suggesting that the effective range of K, between its real minimum and maximum is:

$$\Delta K_{eff} = K_{max} - \frac{2}{\pi} K_{op} - \sigma_{nom} \sqrt{\frac{\pi d}{2}} \qquad (1)$$

where K_{op} is the stress intensity factor at opening load, σ_{nom} is the nominal uniform stress that would be present at minimum load if the crack were absent and d is the distance between the crack tip and the contact zone behind the crack.

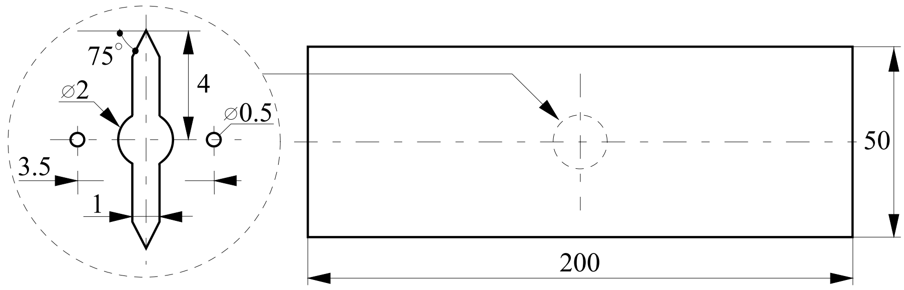

Fig. 1 Geometry of the M(T) specimen used in this work (dimensions in mm).

They further suggested that an approximate result could be given by the following simple expression:

$$\Delta K_{eff} = K_{max} - \frac{2}{\pi} K_{op} \quad (2)$$

Experimental evidence was presented [11,12] suggesting that, for several aluminium alloys, this equation produced very good correlation of fatigue crack growth data under load-reduction (threshold) simulations. Incidentally, Newman [13] has also indicated that under conditions of remote (partial) closure the appropriate opening stress to calculate the effective stress is 0.62 σ_{op}, very close to $2/\pi$.

It is important to notice that the partial closure model was physically established assuming that, under ΔK reduction simulations, the crack is open at tip and closed near the load reduction location, at loads below the crack opening load [12]. This is similar to the hypothesis of the discontinuous closure phenomenon for overload situations [6]. Thus, it seems adequate to use this model to predict post-overload transients from far field closure measurements.

In recent work the authors [14] concluded that crack closure was able to explain the influence of stress ratio on the fatigue crack growth rate in 6082-T6 aluminium alloy in both regimes I and II of crack propagation. The present work intends to analyse if the transient behaviour observed on crack growth due to single tensile overloads for several loading conditions can be correlated with the crack closure phenomenon. The use of the partial closure model to predict the post-overload transients will also be evaluated.

2. EXPERIMENTAL DETAILS

The material used for this research was the 6082 (AlMgSi1) aluminium alloy with T6 heat treatment. The chemical composition and the mechanical properties are shown in tables 1 and 2, respectively.

Table 1. Chemical composition of the 6082-T6 aluminium alloy [% Weight].

Si (%)	Mg (%)	Mn (%)	Fe (%)	Cr (%)
0.7-1.3	0.6-1.2	0.4-1	0.5	0.25

Table 2. Mechanical properties of the 6082-T6 aluminium alloy.

Tensile strength, σ_{UTS} [MPa]	300±2.5
Yield strength, σ_{YS} [MPa]	245±2.7
Elongation, ε_r [%]	9
Cyclic hardening exponent, n'	0.064
Cyclic hardening coefficient, K' [MPa]	443
Fatigue strength exponent, b	-0.0695
Fatigue strength coefficient, σ'_f [MPa]	485
Fatigue ductility exponent, c	-0.827
Fatigue ductility coefficient, ε'_f	0.773

Fatigue tests were conducted using (MT) specimens with a thickness of 3 mm, in agreement with the ASTM E647 standard [15]. The specimens were obtained in the longitudinal transverse (LT) direction from a laminated plate. Figure 1 illustrates the major dimensions of the samples used in the tests. The notch preparation was made by electrical-discharge machining. After that, the specimens surfaces were polished mechanically.

All experiments were performed in a servohydraulic, closed-loop mechanical test machine with 100 kN load capacity, interfaced to a computer for machine control and data acquisition. All tests were conducted in air, at room temperature and with a frequency of 20 Hz. The specimens were clamped by hydraulic grips. The crack length was measured using a travelling microscope (30X) with a resolution of 10 μm. Collection of data was initiated after achieving an initial crack length $2a_0$ of approximately 12 mm.

The tests were performed under constant ΔK and stress ratio R conditions, by manually shedding the load with crack growth. The load shedding intervals were chosen so that the maximum ΔK_{BL} variation was smaller than 2%. The overloads were applied under load control during one cycle by programming the increase in load to the designated overload value. After overloading, the baseline loading was resumed and the transient crack growth behaviour associated with the overload was carefully observed. The influence of a single tensile overload was investigated at R=0.05 and R=0.25. The crack growth rates were determined by the secant method [15].

Single tensile overload tests were performed at several ΔK baseline levels ranging from 4 to 10 MPa $m^{1/2}$. Overload ratios OLR were kept constant at 1.5 and 2, which were defined as:

$$OLR = \frac{\Delta K_{OL}}{\Delta K_{BL}} = \frac{K_{OL} - K_{min}}{K_{max} - K_{min}} \qquad (3)$$

where K_{max}, K_{min}, and K_{OL} are the maximum, minimum and peak overload intensity factors, respectively.

Load-displacement behaviour was monitored at all crack measurements for each of the tests using a pin microgauge. The gauge pins were placed in the two drilled holes of 0.5 mm diameter located above and below the centre of the notch (figure 1). The distance between these points was 3.5 mm. In order to collect as many load-displacement data points as possible during a particular cycle, the frequency was reduced to 0.5 Hz.

From the load-displacement records, variations of the opening load P_{op}, were derived using the technique known as maximisation of the correlation coefficient [16]. This technique involves taking the upper 10% of the P-ε data and calculating the least squares correlation coefficient. The next data pair is then added and the correlation coefficient is again computed. This procedure is repeated for the whole data set. The point at which the correlation coefficient reaches a maximum could then be defined as P_{op}.

The fraction of the load cycle for which the crack remains fully open, parameter U, was calculated by the following equation:

$$U = \frac{P_{max} - P_{op}}{P_{max} - P_{min}} \qquad (4)$$

The values of the effective stress intensity factor range, ΔK_{eff}, are given by the expression:

$$\Delta K_{eff} = K_{max} - K_{op} = U\Delta K \qquad (5)$$

3. RESULTS AND DISCUSSION

3.1 Typical transient behaviour and OLR influence

Figure 2 illustrates the typical transient crack growth behaviour obtained when a specimen is subjected to a single tensile overload in a constant ΔK test. In this figure the crack length from the overload event, $a-a_{OL}$, is plotted against the number of cycles from the point of overload application, $N-N_{OL}$, where a_{OL} and N_{OL} are the crack length and the number of cycles at which the overload is applied, respectively.

There is a brief initial acceleration of crack growth rate immediately after the overload. The subsequent crack growth rate decreases until its minimum value is reached, followed by a gradual approach to the level of the baseline steady state. This trend is consistent with the behaviour normally reported in the literature [1-10]. The observed behaviour is usually referred to as delayed retardation of crack growth.

Generally the magnitude and extent of retardation is quantified by the crack growth increment affected by the overload, Δa_{OL}, and by the delay cycles, N_D. Δa_{OL} is the crack growth distance between the point of overload application and the point at which the crack growth rate recovers its initial value. N_D is the difference between the number of cycles at which growth to steady state is achieved and the number of cycles that would occur for the same loading conditions and the same crack length in constant amplitude loading, N_{CA}.

The influence of the overload ratio can also be seen in Figure 2. This figure presents the results obtained from single tensile peak overloads in the Paris regime with OLR=2 and OLR=1.5 at ΔK_{BL}=6 MPa $m^{1/2}$ and R=0.05. It is clear that the amount of crack growth retardation increases with the level of the overload ratio.

The minimum value of the fatigue crack growth rate reached during the delayed retardation phase decreases from 0.32 to 0.09 of the constant amplitude baseline level crack growth rate, $(da/dN)_{CA}$, and the distance to the point at which this minimum occurs increases from 180 μm to 200 μm when OLR increases from 1.5 to 2. The crack growth increment affected by the overload, Δa_{OL}, and the delay cycles, N_D, increase with OLR from 0.65 mm to 2.72 mm and from 12900 to 87400 cycles, respectively, representing an increase in life of about seven times. The described trends were observed for all the ΔK_{BL} analysed in this work at both R-ratios of 0.05 and 0.25. Therefore, the magnitude and extent of crack retardation increases with the overload ratio, in agreement with many other studies [5-8].

It is worthwhile to notice that the maximum fatigue crack growth rate achieved during the initial period of acceleration increases only slightly with OLR, from 1.69 to 1.89 of $(da/dN)_{CA}$. For all the analysed conditions the increase in crack growth rate takes place only in the first 60-100 μm after application of the overload, representing a very small part of the overload affected crack increment. For the tests conducted for OLR=1.5 at ΔK_{BL}=4 the period of initial acceleration was not detected.

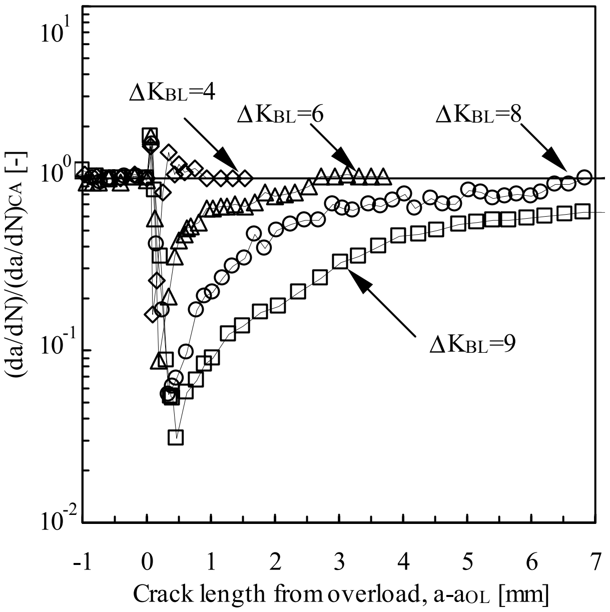

Fig 4. Effect of ΔK_{BL} on the normalised crack growth rate. OLR=2 at R=0.05.

The corresponding crack closure data are presented in figure 3, plotted in terms of the normalised load ratio parameter U, calculated by (4), against the crack growth increment from the point of overload application. This plot presents the typical crack closure response obtained following tensile peak overloads in 6082-T6 aluminium alloy.

It is clear from this figure that the crack closure data show basically the same trend as the corresponding experimentally observed crack growth rate response. Prior to the overload the U parameter for the baseline loading level is relatively stable. Upon application of the overload, U rapidly increases followed by a decrease to a minimum value and then increases gradually towards the baseline level**.** It is important to notice that the decrease in U is not immediate after the overload application, but on the contrary decreases slowly towards the minimum value. This is in accordance with delayed retardation behaviour observed on the crack growth rate transients. In general the minimum U value occurs at the same crack increment after the overload, were the minimum value of the crack growth rate is reached.

Figure 3 shows that prior to the overload the U value is approximately 0.82. The maximum value of U attained increases form 0.9 to 0.95 and the minimum U value decreases from 0.58 to 0.45 when OLR increases from 1.5 to 2. This corresponds to a decrease of 30% and 45% of the baseline U level, respectively. The minimum value of U occurs at the same $a\text{-}a_{OL}$ where the minimum da/dN is reached, *i.e.*, at 180 μm for OLR=1.5 and at 200 μm for OLR=2. The results presented in figure 2 show that generally crack closure increases with OLR.

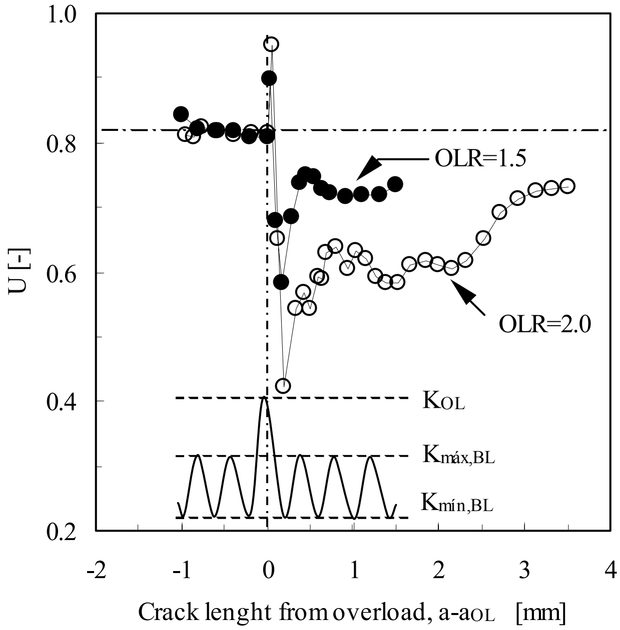

Fig 3. Crack closure response after single tensile peak overloads. ΔK_{BL}=6 MPa $m^{1/2}$ and R=0.05.

3.2 Influence of ΔK baseline level

The influence of the ΔK baseline level, ΔK_{BL}, at which the overload is applied, can be seen in figure 4 in terms of the normalised crack growth ratio, $(da/dN)/(da/dN)_{CA}$, against the crack growth increment from the point of overload application, $a\text{-}a_{OL}$. The respective crack closure measurements are compared in figure 5.

Figure 4 shows that the amount and extent of crack growth retardation increases significantly with ΔK_{BL}. When ΔK_{BL} increases from 4 to 9 MPa $m^{1/2}$ the overload affected crack growth increment highly increases from Δa_{OL}=0.43 mm to Δa_{OL}=12.57 mm. Also the maximum and minimum values of the crack growth rate achieved during the corresponding transient period increase and decrease, respectively. The minimum value of the fatigue crack growth rate reached during the delayed retardation phase decreases from 0.16 to 0.03 of $(da/dN)_{CA}$. The distance to the point at which this minimum occurs increases with ΔK_{BL}, being 100 μm and 480 μm for ΔK_{BL}=4 and ΔK_{BL}=9, respectively. The maximum fatigue crack growth rate achieved during the initial period of acceleration increases only slightly with ΔK_{BL} and is approximately 1.5 to 1.8 of $(da/dN)_{CA}$ for all the ΔK_{BL} analysed. N_D increases from 64300 to 238000 cycles. Thus when ΔK_{BL} changes from 4 to 9 MPa $m^{1/2}$ there is a life increase of approximately four times.

The results presented in figure 5 indicate that the normalised load parameter U also decreases (crack closure increases) with ΔK_{BL}. Therefore, the influence of the ΔK baseline level on the crack retardation behaviour is in agreement with the variation of crack closure. The minimum U attained during the test for OLR=2 at ΔK_{BL}=4 MPa $m^{1/2}$ was 0.55 while at ΔK_{BL}=9 MPa $m^{1/2}$ was 0.27 implying a reduction of the minimum U value of approximately 50%. As expected, the respective crack length increases with ΔK_{BL} from 0.1 mm at ΔK_{BL}=4 MPa $m^{1/2}$ to 0.42 mm at ΔK_{BL}=9 MPa $m^{1/2}$ corresponding approximately to the crack length where the minimum value of the crack growth rate is reached.

3.3 Influence of stress ratio

The influence of the stress ratio on the transient crack growth behaviour following a single tensile overload can be seen in figure 6 for OLR=1.5 at ΔK_{BL}=6 MPa $m^{1/2}$. From these data it is apparent that as the stress ratio is increased from R=0.05 to R=0.25 the magnitude and extent of crack growth retardation is decreased. The same behaviour has been reported in the literature for steels [4,8] and for aluminium alloys [10].

The crack growth increment Δa_{OL} and N_D decrease with R from 2.72 mm to 1.58 mm and from 87400 to 42800 cycles, respectively, representing a decrease in life of approximately 50% when R increases from 0.05 to 0.25. The maximum da/dN achieved during the initial period of acceleration also decreases. It is worthwhile to notice that, despite the described trends, the minimum value of the fatigue crack growth rate reached during the delayed retardation phase is lower for R=0.25 than for R=0.05. However, the distance to the point for which this minimum happens decreases from 160 μm to 200 μm.

The respective crack closure measurements are compared in figure 7. As expected crack closure decrease with the increase in R. Prior to the overload the parameter U increases approximately 20% but after overloading this increase is slightly higher, typically 25%.

The results presented in figures 3, 5 and 7 show that in general the normalised load parameter U decreases (crack closure increases) when the overload ratio and ΔK baseline level increase and, also, when the stress ratio decreases. When U decreases the minimum effective driving force behind the crack is also decreased. The corresponding crack growth rates must therefore be lower. Thus, the observed effect of OLR, ΔK_{BL} and R on the crack retardation behaviour is in accordance with the variation of crack closure. An increase in OLR or ΔK_{BL} increases crack closure, and, therefore, the retardation effect should be more pronounced. On the contrary, an increase in R, decreases the crack closure phenomenon and, consequently weakens the transient crack growth.

The observed effect of OLR, ΔK_{BL} and R on the post-overload crack growth is in agreement with the hypothesis that the plasticity-induced closure is the main mechanism causing retardation in 6082-T6 aluminium alloy. The higher the OLR and ΔK_{BL} values the more wake plasticity is generated and, consequently, the features of the post-overload crack growth transients, namely the minimum and maximum da/dN, the crack length where the minimum da/dN occurs and Δa_{OL}, increase. On the contrary, an increase in R reduces the plasticity-induced crack closure mechanism, thus, the retardation effect should be less pronounced. Therefore, the phenomenon of plasticity-induced closure seems to be the dominant cause of the post-overload crack growth transients.

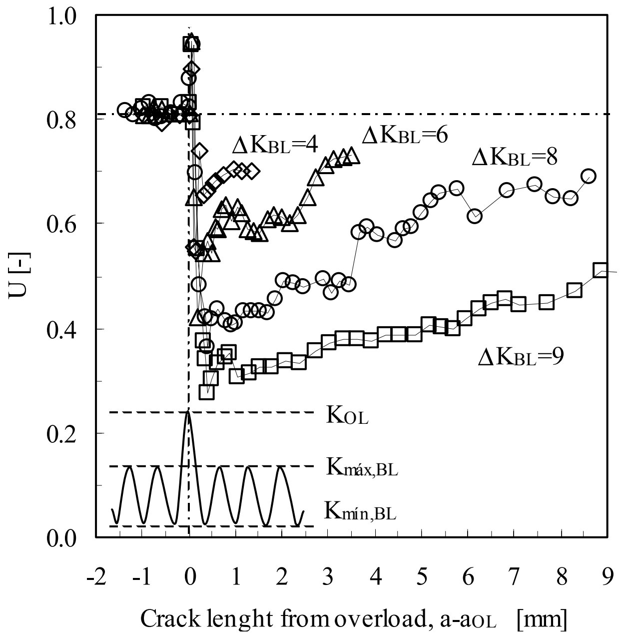

Fig 5. Correspondent closure response. OLR=2 at R=0.05.

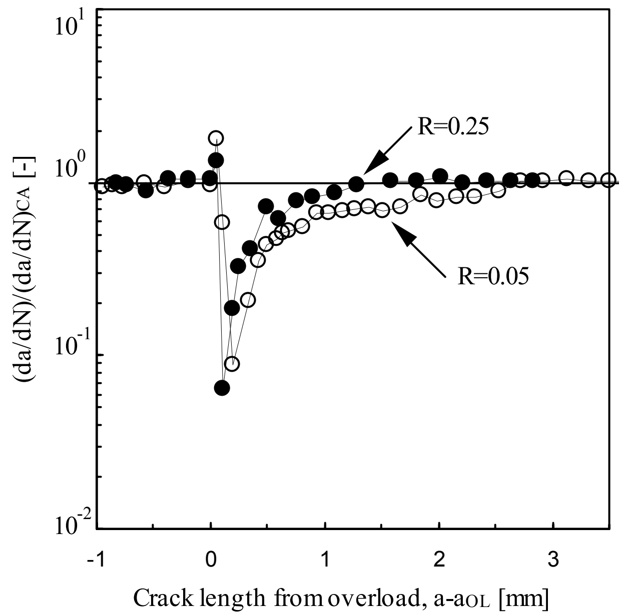

Fig 6. Effect of the stress ratio on the transient behaviour. OLR=2 at ΔK_{BL}=6 MPa $m^{1/2}$.

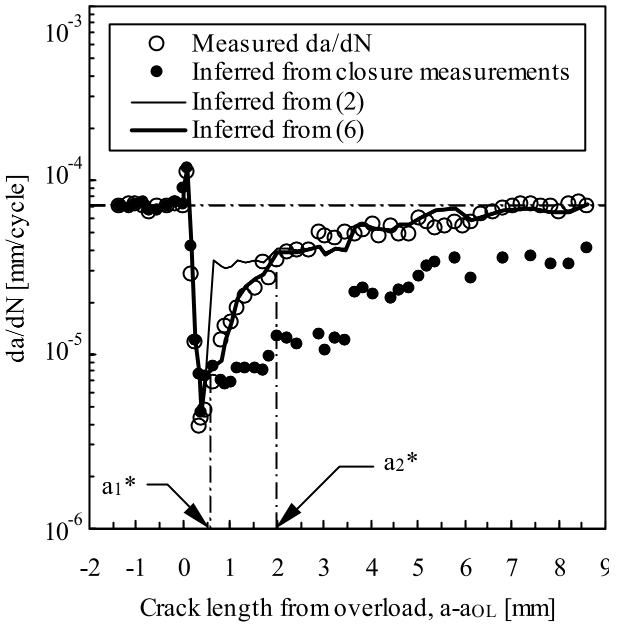

Fig. 8. Comparison of predicted from closure measurements and observed crack growth rates. OLR=2 at ΔK_{BL}=8 MPa $m^{1/2}$ and R=0.05.

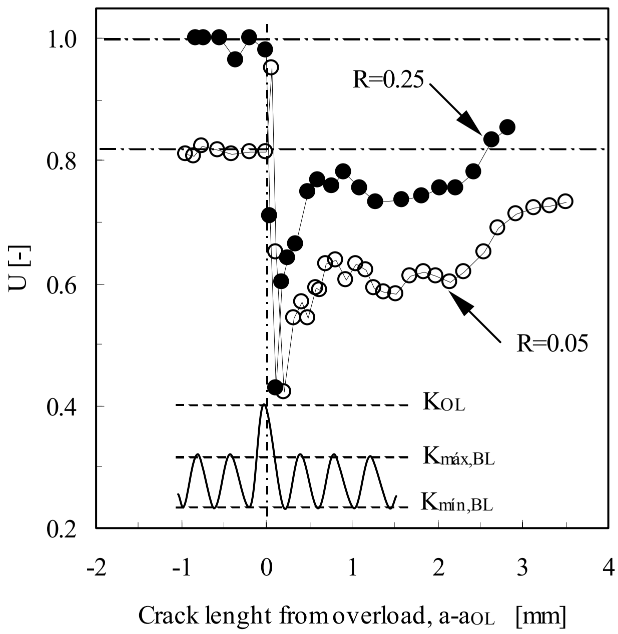

Fig 7. Correspondent closure response. OLR=2 at ΔK_{BL}=6 MPa $m^{1/2}$.

3.4 Prediction from crack closure measurements

The crack growth rates inferred directly from the closure measurements and the characteristic da/dN versus ΔK_{eff} relation of the material, which was determined in previous work [14], are compared with the experimental da/dN in figures 8 and 9.

The inferred and measured crack growth rates show good agreement, except for the period when crack growth rates are already recovering from the minimum value. Beyond this point predicted values tend to be lower than the experimental ones. Similar discrepancies have been reported for the same alloy [7], and for steels [5-8]. This behaviour is attributed to the phenomenon of discontinuous or partial closure.

The appearance of the discrepancy some time after the application of the overload was also observed by Shercliff and Fleck [7] for the same alloy and for steel and is consistent with the plasticity-induced crack closure argument. After the overload the crack must growth an initial distance before the overload plastic zone starts to become a part of the plastic wake leading to the delayed retardation phase [1,8]. It is suggested that an additional increase in crack length is necessary after the minimum value of the fatigue crack growth rate is reached, so that the deformation mismatch between the plastically stretched material and the surrounding elastic material can be less severe at the crack tip than at the overload location. Only then can the crack be open at the tip and closed at the overload location.

It can be seen in figures 8 and 9 that the crack growth rates inferred using (2), for crack lengths higher than the crack increment after overloading where discontinuous closure starts, show better agreement with measured values than those inferred directly from the closure measurements. However, it is clear from the figures that after a_1* there is a transition period from full closure to partial closure for crack tip advance from the overload event between a_1* and a_2*, respectively. Thus, a correction factor is needed in (2) to account for this transition period.

Therefore, it is suggested that (2) can be rewritten as

$$\Delta K_{eff} = K_{max} - \frac{2}{\pi} F^*(a - a_{OL})\, K_{op} \qquad (6)$$

where $F^*(a-a_{OL})$ is a correction factor, function of the crack length after overloading. This function has to be equal to $\pi/2$ for $(a-a_{OL})=a_1^*$, 1 for $(a-a_{OL})\geq a_2^*$ and to decay from $\pi/2$ to 1 when $(a-a_{OL})$ increases from a_1^* to a_2^*.

Thus, considering a parabolic decay, the following expression is proposed for $F^*(a-a_{OL})$

$$F^*(a - a_{OL}) = \left(1 - e^{-\pi\xi}\right) + \frac{2}{\pi} e^{-\pi\xi} \qquad (7)$$

where ξ is

$$\xi = \frac{(a - a_{OL}) - a_1^*}{a_2^* - a_1^*} \qquad (8)$$

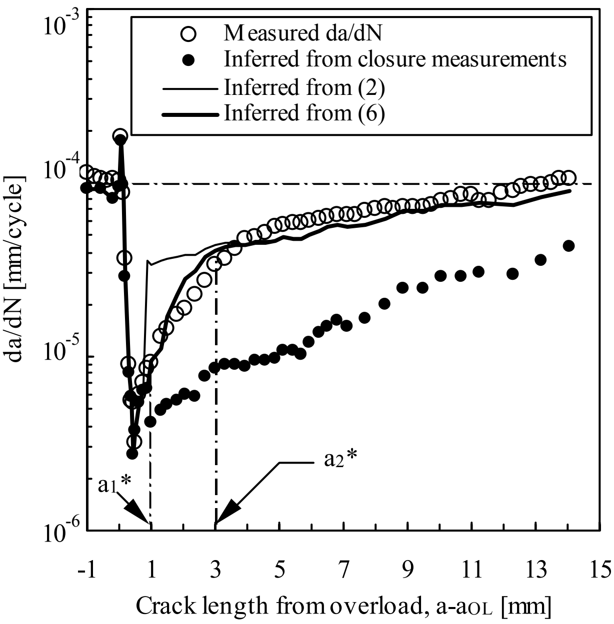

Fig. 9. Comparison of predicted from closure measurements and observed crack growth rates. OLR=2 at ΔK_{BL}=9 MPa $m^{1/2}$ and R=0.05.

representing the fraction between the crack length after the appearance of discontinuous closure and the length of the transition period.

From the crack closure data analysis, the point where discontinuous closure starts appears to correspond to a crack tip advance from the overload event, a_1*, of about 1/2 of the size of the overload plastic zone evaluated, for a plane stress condition, from the following equation:

$$R_{OL} = \frac{1}{\pi}\left(\frac{K_{OL}}{\sigma_{YS}}\right)^2 \qquad (9)$$

where K_{OL} is the stress intensity factor at peak load during the overload cycle and σ_{YS} is the yield stress. Also, the transition period occurs until a crack increment after overloading of approximately $a_2^*=2/\pi\ R_{OL}$ is reached.

Thus, (8) can be approximated by

$$\xi = \frac{2(a - a_{OL}) - R_{OL}}{R_{OL}(\pi - 1)} \qquad (10)$$

The crack growth rates inferred using (6) for crack lengths higher than a_1* are superimposed in figures 8 and 9. It is clear that (6) is able to correctly account for the partial closure phenomenon inclusively during the transition period. However, it must be emphasised that (7), (8) and (10) were based on the limited data presented in this study.

4. CONCLUSIONS

From the experimental study on crack growth behaviour in 6082-T6 aluminium alloy under single tensile overload conditions at various ΔK_{BL} levels, the following conclusions can be drawn:

1. As expected, strong influence of the overload ratio and the baseline ΔK level on the crack growth transients was observed. The magnitude and extent of crack retardation increases with OLR and ΔK_{BL}. On the contrary, decreases with the stress ratio.

2. The observed effect of OLR, ΔK_{BL} and R on the crack retardation behaviour is in accordance with the variation of crack closure.

3. The crack growth rates inferred considering the phenomenon of discontinuous closure are in better agreement with measured values than the inferred directly from the closure measurements. Therefore, it seems relevant to include the effect of discontinuous closure in predictions based in far field closure measurements.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge POCTI programme, project 1999/EME/32984, for funding the work reported.

6. REFERENCES

[1] Ward-Close C.M., Blom A.F. and Richie R.O., "Mechanisms associated with transient fatigue crack growth under variable amplitude loading: an experimental and numerical study", Engng Fract. Mech., **32**, 613-638 (1989).

[2] Damri D. and Knott J.F., "Fracture modes encountered following the application of a major tensile overload cycle", Int. J. Fatigue, **15**, 53-60 (1993).

[3] Ng'Ang' A.S.P. and James M.N., "Variable amplitude loading in En8 (080M40) steel: a detailed experimental study of crack growth", Fatigue Fract. Engng Mater. Struct., **19**, 217-216 (1996).

[4] Shuter D.M. and Geary W., "The influence of specimen thickness on fatigue crack growth retardation following an overload", Int. J. Fatigue, **17**, 111-119 (1995).

[5] Robin C., Louah M. and Pluvinage G., "Influence of the overload on the fatigue crack growth in steels", Fatigue Fract. Engng Mater. Struct., **6**, 1-13 (1983).

[6] Fleck N.A., "Influence of stress state on crack growth retardation", in Basic Questions in Fatigue: Volume 1 (Ed. Fong J.T. and Fields R.J.) pp. 157-183, ASTM STP **924**, American Society for Testing and Materials, Philadelphia (1988).

[7] Shercliff H.R. and Fleck N.A., "Effect of specimen geometry on fatigue crack growth in plane strain – II. Overload response", Fatigue Fract. Engng Mater. Struct., **13**, 297-310 (1990).

[8] Shin C.S. and Hsu S.H., "On the mechanisms and behaviour of overload retardation in AISI 304 stainless steel", Int. J. Fatigue, **15**, 181-192 (1993).

[9] Brahma K.K., Dash P.K. and Dattaguru B., "Observations of crack closure using a crack mouth opening displacement gauge", Int. J. Fatigue, **11,** 37-41 (1989).

[10] Tsukuda H., Ogiyama H. and Shiraishi T. "Transient fatigue crack growth behaviour following single overloads at high stress ratios", Fatigue Fract. Engng Mater. Struct., **19**, 879-891 (1996).

[11] Donald K. and Paris P.C., "An evaluation of ΔK_{eff} estimation procedures on 6061-T6 and 2024-T3 aluminium alloys", Int. J. Fatigue, **21** (Supplement), S47-S57 (1999).

[12] Paris P.C, Tada H. and Donald J.K., "Service load fatigue damage – a historical perspective", Int. J. Fatigue, **21** (Supplement), S35-S46 (1999).

[13] Newman Jr. J.C, "Analysis of fatigue crack growth and closure near threshold conditions for large-crack behavior", in Fatigue Crack Growth Thresholds, Endurance Limits, and Design (Ed. Newman Jr. J.C. and Piascik R.S.) pp. 1-25, ASTM STP **1372**, American Society for Testing and Materials, West Conshohocken (1999).

[14] Borrego L.P., Ferreira J.M., Costa J.M., "Fatigue crack growth and crack closure in an AlMgSi alloy", Fatigue Fract. Engng Mater. Struct., in publication (2001).

[15] American Society for Testing and Materials, "Standard test method for measurements of fatigue crack growth rates", Annual Book of ASTM Standards: Volume 03.01, ASTM E 647, 562-598 (1995).

[16] Allison J. E., Ku R. C. and Pompetzki M. A., "A comparison of measurement methods and numerical procedures for the experimental characterization of fatigue crack closure", in Mechanics of Fatigue Crack Closure (Ed. Newman Jr. J.C and Elber W.) pp. 171-185, ASTM STP **982**, American Society for Testing and Materials, Philadelphia (1988).