Fatigue Crack Propagation in Aluminium Alloys Subjected to Block Loading

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

[1] Department of Mechanical Engineering, ISEC, Rua Pedro Nunes, Quinta da Nora, 3030-199 Coimbra, Portugal, e-mail: luis.borrego@dem.uc.pt
[2] Department of Mechanical Engineering, University of Coimbra, Polo II, Pinhal de Marrocos, 3030-201 Coimbra, Portugal, e-mail: geral@dem.uc.pt

ABSTRACT. *Fatigue crack propagation tests with high-low and low-high blocks have been performed in 6082-T6 aluminium alloy at several baseline ΔK levels. The tests were carried out at constant ΔK conditions. Two stress ratios were analysed: R=0.05 and R=0.4. Crack closure was monitored in all tests by the compliance technique using a pin microgauge. The observed transient post load step behaviour is discussed in terms of the load change magnitude, ΔK baseline levels and stress ratio. The crack closure parameter U was obtained and compared with the crack growth transients. The experimental crack growth rate transients are compared with crack growth rates inferred from the experimental closure measurements and the characteristic da/dN versus ΔK_{eff} relation of the material. A good agreement between experimental and predicted crack growth rates is obtained when the phenomenon of partial closure is properly taken into account. Therefore, plasticity induced crack closure plays an important role on the load interaction effects observed in aluminium alloys.*

INTRODUCTION

For many fatigue critical parts of structures, vehicles and machines, fatigue crack propagation under service conditions generally involves random or variable amplitude, rather than constant amplitude loading conditions. Significant accelerations and/or retardations in crack growth rate can occur as a result of these load variations. Thus, an accurate prediction of fatigue life requires an adequate evaluation of these load interaction effects.

The majority of the work carried out in this field has been on the effects of single peak tensile overloads [1,2] simply because this type of loading can lead to significant load interaction effects. However, the precise micromechanisms responsible for these effects are not fully understood.

Generally, closure measurements produce a good correlation between low stress ratio and high stress ratio crack growth rate data [3]. However, at the near-threshold regime the measured opening loads are some times excessively high [4]. Among other observations, this behavior has contributed for some of the controversy around the phenomenon of crack closure. Recently, Paris et al. [4] introduced the new concept of *partial crack closure*, suggesting that a significant contribution to fatigue damage occurs in the load range below the opening load as measured by the compliance technique. Accordingly to the Partial Closure Model the conventional Elber's definition of the effective range of K ($\Delta K_{eff}=K_{max}-K_{op}$) should be rewritten as

$$\Delta K_{eff} = K_{max} - \frac{2}{\pi} K_{op} \tag{1}$$

where K_{op} is the stress intensity factor at opening load. For aluminium alloys, this new concept demonstrates a significant improvement in the correlation of R-ratio effects at the near-threshold regime [4].

In a recent paper, the authors have applied and enhanced the Partial Closure Model to loadings containing overloads [5] using the following expression :

$$\Delta K_{eff} = K_{max} - \frac{2}{\pi} F^{*} K_{op} \tag{2}$$

where F^{*} is a correction factor, function of the crack length after the load variation event, $a-a_O$, to account for the transition period from full closure to partial closure [5]. This correction function is given by the following expressions,

$$F^{*} = 1 + \left(\frac{\pi}{2} - 1 \right) e^{-\pi\xi} \tag{3}$$

$$\xi = \frac{2(a - a_o) - r_p}{r_p(\pi - 1)} \tag{4}$$

where a_O is the crack length at which the change in load is applied and r_p the monotonic plastic zone established by the load step.

Previous work [6,7] has confirmed that load step-down in a high-low block can also cause crack growth retardation. Therefore, the present work intends to analyse the fatigue crack growth on aluminium alloy specimens subjected to high-low blocks and also low-high blocks, and evaluate if the observed transient crack growth behaviour can be correlated with the crack closure phenomenon.

EXPERIMENTAL DETAILS

This research was conduced using an AlMgSi1 (6082) aluminium alloy with a T6 heat treatment has received. The main chemical composition (wt.%) of this alloy was 1.05 Si, 0.8 Mg, 0.68 Mn and 0.26 Fe. The mechanical properties of the 6082-T6 aluminium alloy were as follows: 300 MPa tensile strength, 245 MPa yield strength and 9% elongation.

Fatigue tests were conducted, in agreement with the ASTM E647 standard, using Middle-Tension, M(T), 3 mm thick specimens with 200 mm and 50 mm length and width, respectively. The specimens were obtained in the longitudinal transverse (LT) direction from a laminated plate. All experiments were performed in a servohydraulic, closed-loop mechanical test machine with 100 kN capacity, interfaced to a computer for machine control and data acquisition. All tests were conducted in air and room temperature, at a frequency of 20 Hz and a stress ratio of 0.05 or 0.4. The specimens were clamped by hydraulic gripes. The crack length was measured using a travelling microscope (45X) with an accuracy of 10 μm.

The tests were performed under constant DK 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 crack growth rates were determined by the secant method.

Load-displacement behaviour was monitored at specific intervals throughout each of the tests using a pin microgauge. The gauge pins were placed in the centre of the notch. In order to collect as many load-displacement data 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. The fraction of the load cycle for which the crack remains fully open, parameter U, was calculated by the following equation:

$$U = \frac{P_{max} - P_{op}}{P_{max} - P_{min}} \tag{5}$$

RESULTS AND DISCUSSION

Transient Crack Growth Behaviour

Figure 1 presents the transient crack growth behaviour obtained when a specimen is subjected to a high-low or a low-high block in a constant ΔK test. In this Figure the crack length from the step load event, a-a_O, is plotted against the number of cycles from the point of load variation, N-N_O, where N_O is the number of cycles at which the change in load is applied.

The magnitude and extent of retardation are quantified by the crack growth increment affected by the step in load, Da_O, and by the delay cycles, N_D. The parameter Da_O is the crack growth distance between the point of load variation and the one at which the crack growth rate reaches the steady-state level corresponding to the second DK level, DK_2. N_D is the difference between the number of cycles at which growth to steady-state DK_2 level is achieved and the number of cycles that would occur, for the same loading conditions and crack length, if no load variation was applied.

After the load step-down there is an immediate retardation of the crack growth rate followed by a gradual approach to the level of the baseline steady-state corresponding to the lower block . The effect of the high-low blocks is similar to that observed for peak overloads. However, for a peak overload the retardation is not always immediate and generally is preceded by a brief initial acceleration of crack growth. [1,2,5]. The low-high sequences produce an acceleration of crack growth rate, above the steady state level expected for the higher block, followed by a gradual reduction to the corresponding steady-state DK_2 level. These trends are consistent with the behaviour normally reported in the literature [6,7].

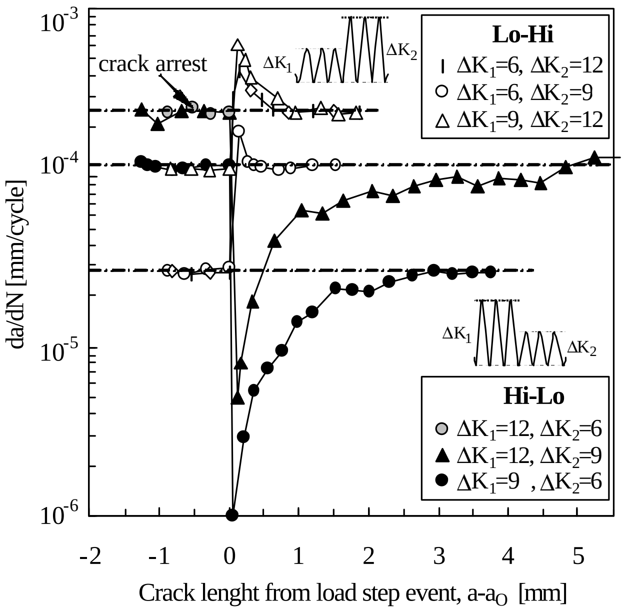

Figure 1. Influence of the magnitude and position of the load step in block loading.

Figure 1 shows that for the step load from ΔK_1=12 to ΔK_1=6 MPa $m^{1/2}$ the crack was arrested. Therefore, crack growth retardation is enhanced by increasing the initial stress intensity relative to the final stress intensity range, *i.e.*, the magnitude of the load step-down. The behaviour observed for this high-low block ($\Delta K_2/\Delta K_1$=0.5) is in agreement with the experimental results of Sehitoglu and McDiarmid [6], where non-propagating cracks occurred in mild steel for load step ratios, DK_2/DK_1, less than 0.6. For the blocks with the same increase in load (3 MPa $m^{1/2}$), N_D decreased from 179 733 to 41 055 cycles when DK_2/DK_1 increased from 0.67 (ΔK_1=9 and ΔK_2=6 MPa $m^{1/2}$) to 0.75 (ΔK_1=12 and ΔK_2 =9 MPa $m^{1/2}$). However, the affected crack length increased with DK_2/DK_1 (Δa_O=2.95 mm for $\Delta K_2/\Delta K_1$=0.67 and Δa_O=4.83 mm for $\Delta K_2/\Delta K_1$=0.75). Therefore, in spite of the larger plastic zone established by the higher DK_1, the crack growth rate is slower for the lower DK_2, namely the minimum da/dN achieved during the transition period, resulting in the increase of retardation with the load step ratio decrease.

Similarly, Figure 1 shows that for low-high sequences the acceleration during the crack growth transition phase increased with the DK of the higher block. Furthermore, a smaller acceleration of the crack is observed for $\Delta K_2/\Delta K_1$=2 (ΔK_1=6 and

ΔK_2=12 MPa m$^{1/2}$) than for $\Delta K_2/\Delta K_1$=1.3 (ΔK_1= 9 and ΔK_2 =12 MPa m$^{1/2}$) indicating also an increase of the acceleration with DK_1. In any case, the initial acceleration due to the low-high sequences (<800 cycles) is much lower than the retardation induced by the high-low blocks analysed (>40 000 cycles).

Stress Ratio Effect

The influence of the stress ratio on the transient crack growth behaviour following a load step in high-low and low-high blocks can be seen in Fig. 2.

This Figure shows that the crack growth increment affected by the step in load is increased, although only slightly, when the stress ratio increases from 0.05 to 0.4 (from Δa_O=2.95 mm to Δa_O=3.49 mm). However, a significant reduction of the delay cycles with increasing R is observed (from N_D=179 733 to N_D=60 302). Therefore, similar to the generally observed behaviour in tensile overloads [1,2], the retardation effect is reduced with increasing stress ratio. A similar trend is observed for the low-high blocks.

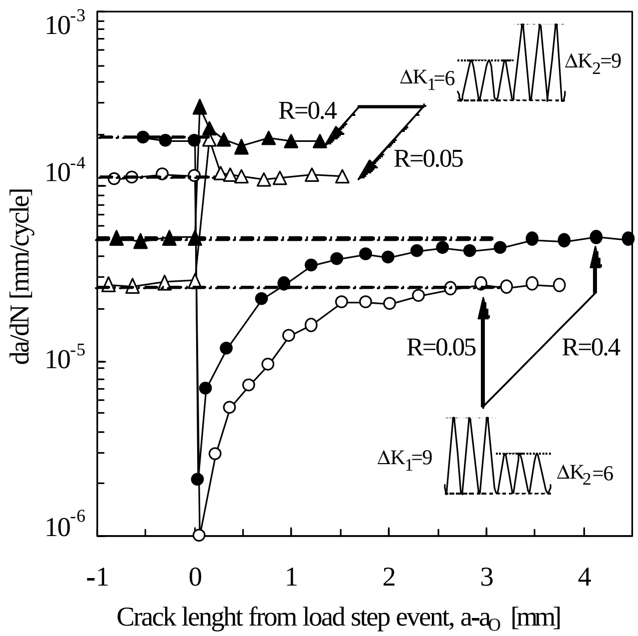

Figure 2. Influence of the stress ratio in block loading.

Crack Closure

Figure 3 illustrates the typical crack closure response obtained following high-low and low-high block sequences in 6082-T6 aluminium alloy. The obtained data are plotted in terms of the normalized load ratio parameter U, calculated by Eq. 5, against a-a_O. This Figure presents crack closure data corresponding to crack growth rates presented in Fig.1, showing, in this way, the crack closure variation due to the magnitude and position of the load step.

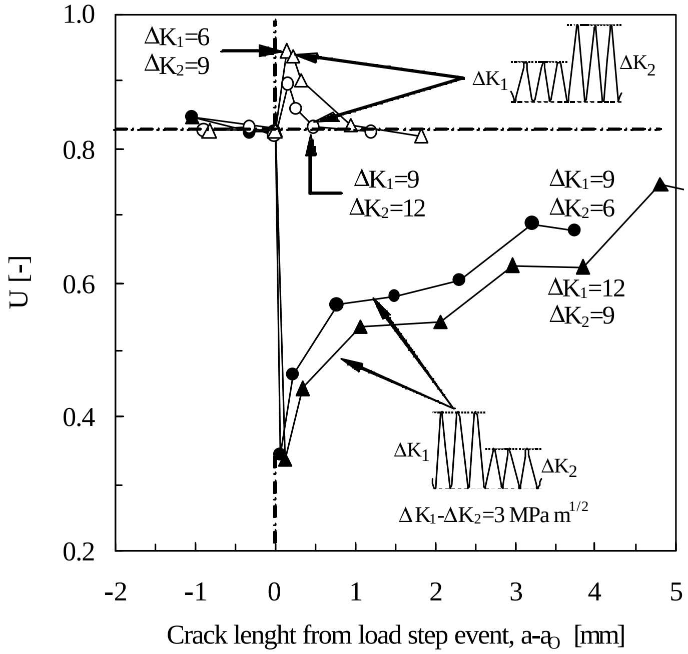

Figure 3. Typical crack closure response following in block loading.

It is clear that the crack closure data presented show basically the same trend as the corresponding experimentally observed crack growth rate response. For the high-low blocks, the reduction in load leads to increased closure levels due to the larger plastic zone induced by the high block, which causes a decrease of the crack growth rates to values well below the steady-state level expected for the lower block. This effect is similar to that observed in single peak overloads in the analysed alloy [5] as well as in steels [1,2]. However, for a high-low block, the load step-down plastic zone and hence the near tip crack closure are imposed at the values corresponding to the higher block, the retardation is therefore always immediate. For a low-high block, as evident from the crack closure measurements, the initial acceleration of crack growth is due to removal of near tip closure by the load step itself.

Figure 4 shows some typical features of the fatigue fracture surfaces. The crack direction is from bottom to top. The images presented were obtained close to the centre of the specimens. Figure 4(a) shows a typical dark band observed following the load step-down in a high-low block. This band could be followed continuously over the full thickness of the specimen. Generally the crack front corresponding to the load step-down cycle was slightly bowed (<0.3 mm in all cases). Curved crack fronts following a peak overload were also observed for this alloy [5]. Figure 4b presents a high magnification image of the dark band. Typical fatigue fracture surfaces of 6082-T6 alloy have a chaotic wavy appearance exhibited relatively smooth areas separated by tear ridges [5]. However, Figure 4b shows a smeared fracture zone in the whole crack front, denoting premature contact of the crack faces. This observation provides good evidence for the enhancement of crack closure following the load step-down.

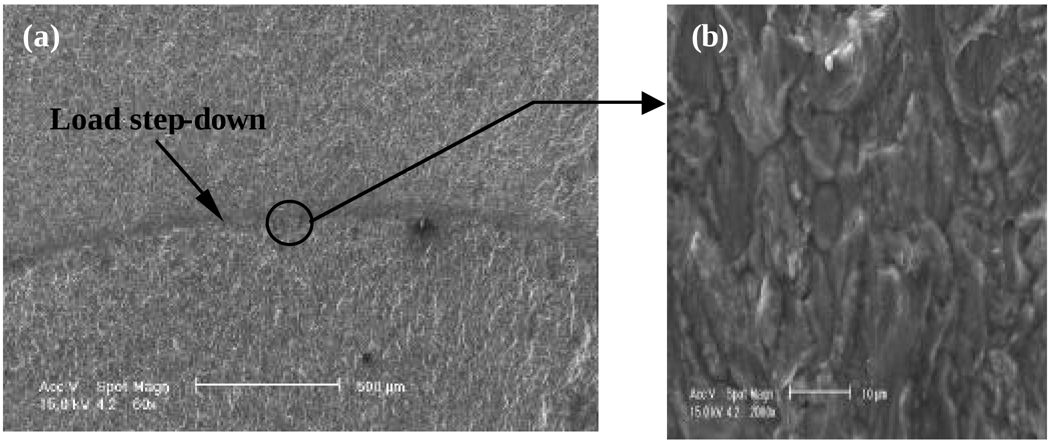

Figure 4. SEM images of fracture surfaces, ΔK_1= 9, ΔK_2 =12 MPa $m^{1/2}$ and R=0.05: (a) typical dark band observed following load step-down, (b) high magnification image.

The crack growth rates inferred directly from the closure measurements, using Elber´s approach and the characteristic *da/dN versus* DK_{eff} relation of the material obtained in previous work [3], are compared with the experimental da/dN in Fig. 5. The crack growth rates inferred using Eq. 2 for crack lengths higher than half the monotonic plastic zone established by the high block are also superimposed in such a Figure.

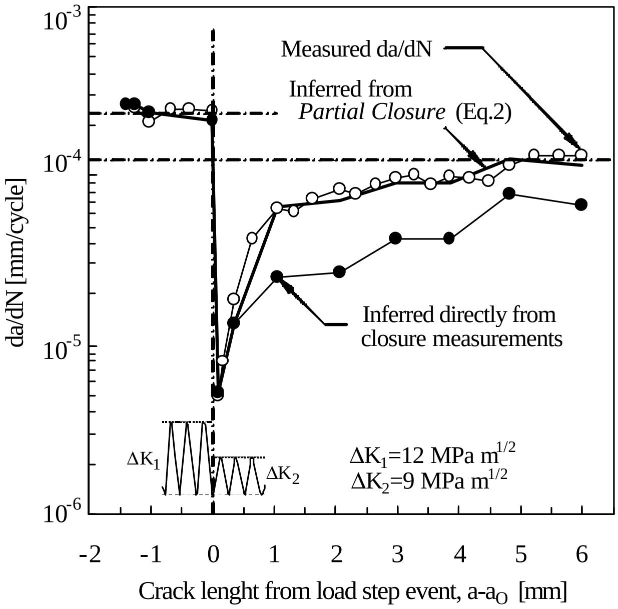

Figure 5. Comparison of predicted from closure measurements and observed crack growth rates, $\Delta K_2/\Delta K_1$=0.75.

The inferred directly from closure measurements and experimental crack growth rates show good agreement only until the crack growth rate is recovering from the minimum value. Beyond this point predicted values tend to be lower than the experimental ones. Thus, similar to peak overloads [5,8], the phenomenon of discontinuous or partial closure is observed for high-low blocks. This behaviour is due to the crack surface contact at some distance from the crack tip, namely near the load step-down location. However, it is clear that the Enhanced Partial Closure Model (Eqs 2, 3 and 4) is able to correctly account for the discontinuous closure phenomenon observed for the high-low blocks.

CONCLUSIONS

1. The effect of block loading is similar to that observed for peak overloads. However, for this load sequence the retardation is always immediate. High-low sequences produce crack acceleration.
2. For high-low blocks, increasing the difference between the initial stress intensity and the final stress intensity range increases crack growth retardation. Furthermore, for equal step-down in loads, retardation increases with the decrease of the lower ΔK. For low-high blocks acceleration increases with the final ΔK.
3. The retardation and acceleration effects observed in high-low and low-high blocks, respectively, are reduced with increasing stress ratio.
4. There is a good correlation between crack closure and crack growth transients in block loading when the partial closure phenomenon is correctly account for. Therefore, plasticity induced crack closure plays an important role on the load interaction effects observed in aluminium alloys.

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