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FATIGUE CRACK GROWTH UNDER SIMPLE VARIABLE AMPLITUDE LOAD SEQUENCES

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ABSTRACT

Fatigue crack propagation tests with single tensile peak and periodic overloads, Hi-Lo blocks and Lo-Hi blocks have been performed in 6082-T6 aluminium alloy, either in load control or in constant ΔK conditions. The tests were carried out using Middle-Tension specimens in a servo-hydraulic machine at R=0.05 and a frequency of 20 Hz. 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 overload ratio, ΔK baseline levels and number of intermediate baseline cycles. The crack closure parameter U was obtained and compared with the crack growth transients. Plasticity induced closure seems to be the main mechanism in determining the transient crack growth behaviour in 6082-T6 aluminium alloy following the simple variable amplitude load sequences analysed.

KEYWORDS

aluminium alloys, fatigue crack propagation, overloads, crack closure

INTRODUCTION

The 6000 aluminium alloys series are very frequently used in structural applications under service conditions that involve random or variable amplitude rather than constant amplitude loading conditions, mainly due to the fact of allying a relatively high strength, good corrosion resistance and high toughness to a good formability and weldability. An accurate prediction of fatigue life requires an adequate evaluation of load interaction effects. However, fatigue crack growth under variable load amplitudes in this series of aluminium alloys is not as well understood as in the 7000 and 2000 series. Furthermore, the amount of data available for the material studied in this work is reduced.

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 [1-8]. Several mechanisms have been proposed to explain crack growth retardation, which include models based on residual stress [9], crack closure [10], crack tip blunting [11], strain hardening [12], crack branching [13] and reversed yielding [14]. The precise micromechanisms responsible for these phenomena are not fully understood. In spite of some controversy, the effect of plasticity induced crack closure, has been identified as the main variable in explaining, fairly reasonably, the variation of the characteristic features of post-overload transients [1-5].

In recent work, the authors [15] concluded that crack closure was able to explain the influence of the stress ratio on the fatigue crack growth rate in 6082-T6 aluminium alloy, in both regimes I and II of crack propagation. Furthermore, for overload conditions, the influence of several load parameters could be correlated with the variation of crack closure. The present work intends to analyse the transient behaviour observed on crack growth rate following block loading and periodic overloads and to clarify if the observed behaviour can also be correlated with the crack closure phenomenon.

EXPERIMENTAL DETAILS

The material used in this research was an AlMgSi1 (6082) aluminium alloy with T6 heat treatment. The chemical composition (wt.%) of this alloy was 0.7-1.3 Si, 0.6-1.2 Mg, 0.4-1 Mn, 0.5 Fe, 0.25 Cr, 0.2 Zn, 0.1 Cu, 0.1 Ti, 0.05 other. 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. The geometry of the M(T) specimen used in this study was presented elsewhere [15]. The notch preparation was made by electrical-discharge machining. After that, the specimen surfaces were polished mechanically.

All experiments were performed in a servo-hydraulic, 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.

Four different types of simple variable amplitude fatigue loading conditions were applied in this study, as shown schematically in Figure 1.

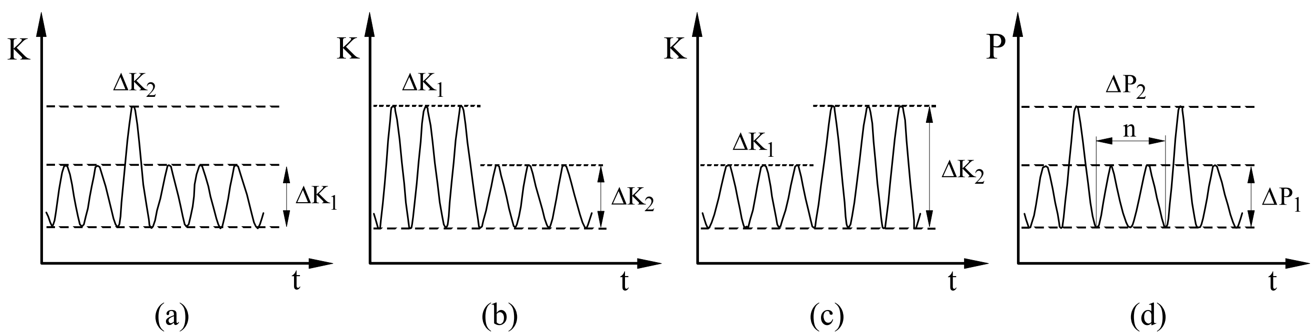

Figure 1: Applied simple variable amplitude loading sequences: (a) single peak overload; (b) Hi-Lo block; (c) Lo-Hi block; (d) periodic single overloads.

The single overload and the block loading tests where 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 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 the change of load, the associated transient crack growth behaviour was carefully observed. All loading conditions were investigated at R=0.05. The periodic overload tests were performed under load control and the intermediate baseline cycles were previously programmed for each test. The crack growth rates were determined by the secant method.

Load-displacement behaviour was monitored at all crack measurements for each of the tests using a pin microgauge. The gauge pines were placed in the two drilled holes of 0.5 mm diameter located above and below the centre of the notch. The distance between these points was 3.5 mm. In order to collect as much 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 can 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:

$$U = \frac{P_{max} - P_{op}}{P_{max} - P_{min}} \tag{2}$$

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

$$\Delta K_{eff} = K_{max} - K_{op} = U\,\Delta K \tag{3}$$

RESULTS AND DISCUSSION

Figure 2(a) illustrates the typical transient crack growth behaviour obtained when a specimen is subjected to a single tensile overload, a high-low block and 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 a_O and N_O are the crack length and the number of cycles at which the change in load is applied, respectively. Generally, the magnitude and extent of retardation are quantified by the crack growth increment affected by the step in load, Δa_O, and by the delay cycles, N_D. Δa_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 ΔK_2. N_D is the difference between the number of cycles at which growth to steady state level ΔK_2 is achieved and the number of cycles that would occur for the same loading conditions and crack length if no load variation was applied.

Figure 2(a) shows that 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. The observed behaviour is usually referred to as delayed retardation of crack growth. The effect of the high-low block is similar to that observed for the peak overload. However, for this load sequence, the retardation is always immediate and not preceded by the acceleration phase. The low-high sequence produces an acceleration of crack growth rate, above the steady state level expected for the high block, followed by a gradual reduction to the corresponding steady-state level ΔK_2. These trends are consistent with the behaviour normally reported in the literature [3,5,17].

As expected, the magnitude and extent of crack retardation are higher for the high-low block than for an equivalent single tensile overload. For the overload Δa_O=0.65 mm and N_D=12900, while for the high-low block Δa_O=2.64 mm and N_D=277500, representing an increase in life of approximately fourteen times. Also, the minimum value of da/dN reached during the retardation phase decreases from 0.32 to 0.009 relative to the constant amplitude da/dN baseline level. Moreover, the crack retardation is even higher for the high-low sequence with ΔK_1=9 MPa $m^{1/2}$ and ΔK_2=6 MPa $m^{1/2}$, than for a 100% overload (Δa_O=2.52

mm and N_D=87400 cycles). The accelerated da/dN produced by the low-high block persisted for several thousands of cycles (approximately 2500 cycles and 0.35 mm affected crack increment).

The corresponding crack closure data are presented in figure 2(b), plotted in terms of the normalised load ratio parameter U, calculated by (4), against the crack growth increment from the point of the step in load. This plot presents the typical crack closure response, in 6082-T6 aluminium alloy, obtained following the load sequences (a) to (c) represented in figure 1.

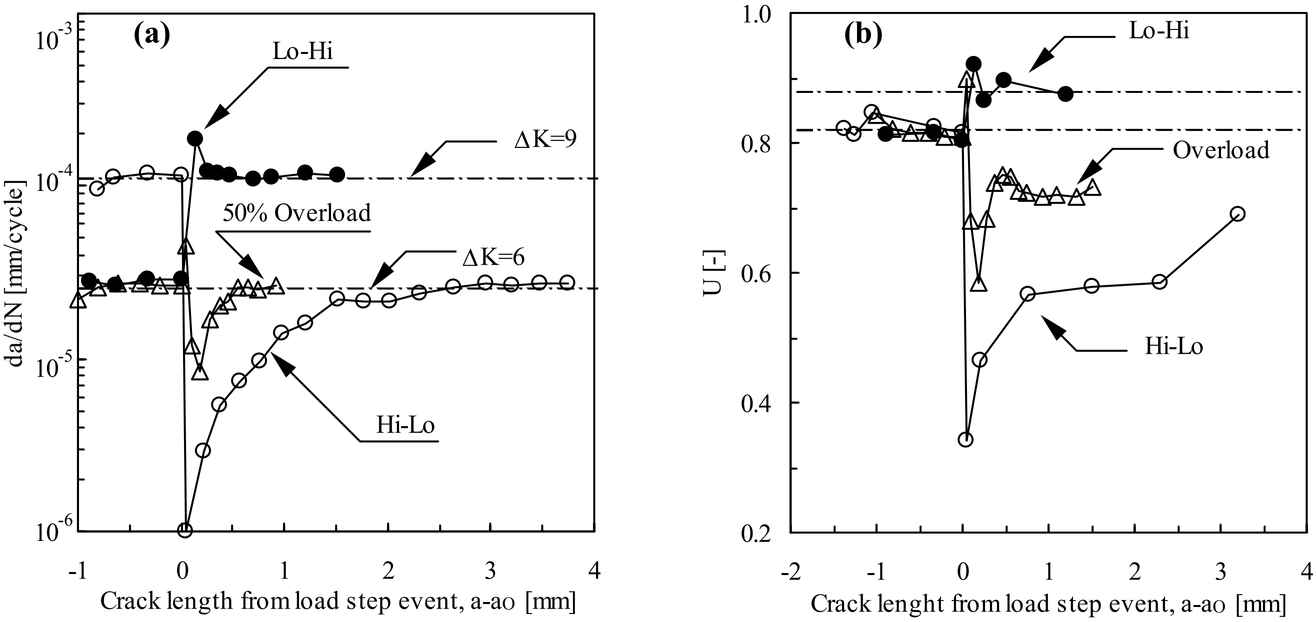

Figure 2: Transient behaviour following a single tensile overload, a high-low block and a low-high block. (a) crack growth rate response, (b) crack closure response.

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. For load step-down, the decrease in parameter U is immediate after the change in load and for low-high blocks there is a decrease of U until some crack length after load change. In general the minimum U value occurs at the same crack increment after load variation, where the minimum value of the crack growth rate is reached. Thus, the phenomenon of plasticity-induced closure seems to be the dominant cause of the post-overload crack growth transients in 6082-T6 aluminium alloy.

Figures 3(a) and 3(b) present the influence of the magnitude and position of the load step in block loading for high-low and low-high sequences, respectively. Figure 3(a) shows that increasing the initial stress intensity relative to the final stress intensity range increases crack growth retardation. For the step load from ΔK_1=12 MPa $m^{1/2}$ to ΔK_1=6 MPa $m^{1/2}$ the crack was arrested. This behaviour is in agreement with the experimental results of Sehitoglu and McDiarmid [17], where non-propagating cracks occurred for $\Delta K_1/\Delta K_2$ ratios less than 0.6. For the blocks with the same increase in load (3 MPa $m^{1/2}$), affected crack length increases from Δa_O=2.64 mm to Δa_O=5.23 mm when ΔK_1 and ΔK_2 increase from 9 to 12 MPa $m^{1/2}$ and 6 to 9 MPa $m^{1/2}$, respectively. However, N_D decreases from 277500 to 86100 cycles for the same loading conditions, indicating that fatigue live is enhanced by the decrease in the final ΔK, ΔK_2. Similarly Figure 3(b) shows that for low-high sequences, crack growth acceleration increases with the final ΔK.

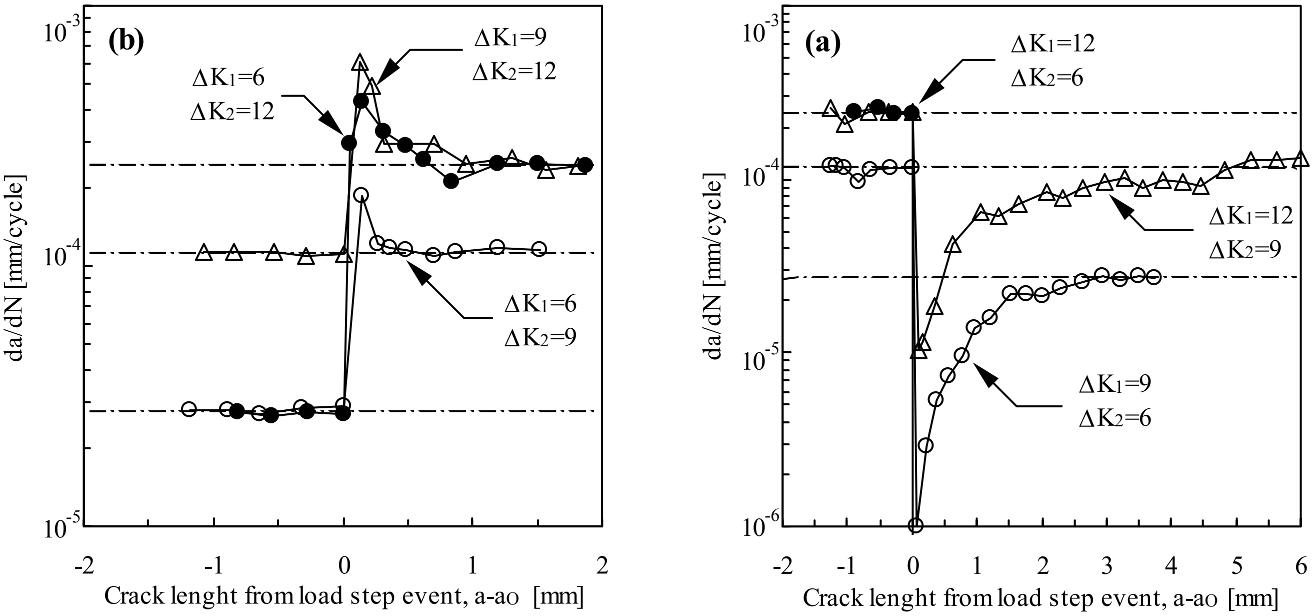

Figure 3: Influence of the magnitude and position of the load step in block loading.
(a) high-low block, (b) low-high block.

The effect of periodically applied overloads after ΔK=6 MPa $m^{1/2}$ for several numbers of intermediate baseline cycles n can be seen in Figures 4(a) and 4(b). In Figure 6(a), the crack length is plotted against the number of cycles, and Figure 4(a) presents the correspondent crack growth response as a function of ΔK. For less frequently applied overloads (n>10) crack retardation is observed, while the results for overloads applied after 10 baseline cycles present crack acceleration. For a crack length of 10 mm N_D are 216282, 419308 and 475538 cycles for n=100, n=1000 and n=10000, respectively. The crack retardation represents a fatigue life increase of approximately 1.8 to 4, in comparison to constant amplitude loading, when n increases from 100 to 10000. For overloads applied after 10 baseline cycles the crack reach 10 mm at 94777 cycles, corresponding to a decrease in fatigue life of approximately 20%.

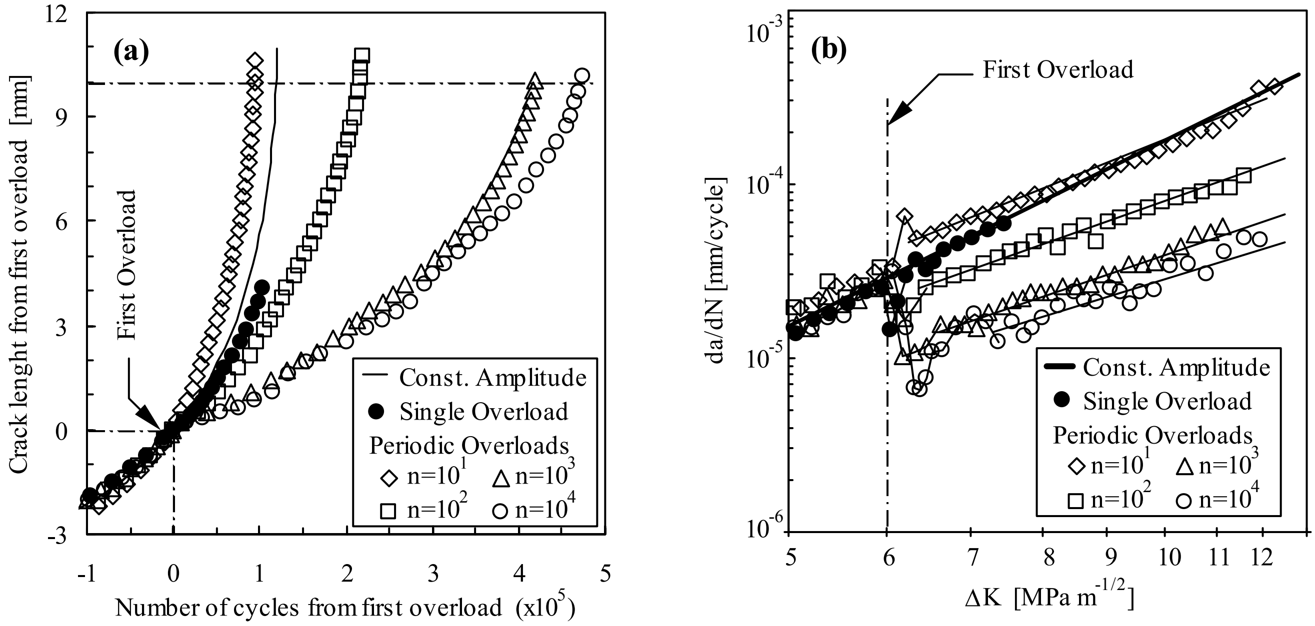

Figure 4: Transient fatigue crack growth behaviour following periodically applied single tensile overloads. (a) crack length versus cycles, (b) crack growth rate response.

It can be seen in figure 4(b) that the retardation in crack growth rate increases with ΔK for overloads applied after baseline cycles higher than 10. For overloads applied with 10 intermediate baseline cycles the acceleration in crack growth rate decreases with ΔK and for ΔK values above 10 MPa $m^{1/2}$ there is even a small crack growth retardation. Similar experimental results were reported in [8]. This is not surprising because the monotonic plastic zone produced by the overloads increases with ΔK. An interesting feature that can be seen in figure 4 (b) is that after application of the first overload there was a delay retardation period that persisted for several thousands of cycles. During this period, the minimum crack growth rate was attained only after approximately 29000, 38000 and 55000 cycles for n=100, n=1000 and n=10000, respectively. Furthermore, crack growth rates lower than the following ones persisted for approximately 52000, 112000 and 125000 cycles for n=100, n=1000 and n=10000, respectively.

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. Load step-down leads to a greater increase in fatigue life than overloads. High-low sequences produce crack acceleration.

2. The phenomenon of plasticity-induced closure seems to be the dominant cause of the post-load variation crack growth transients in 6082-T6 aluminium alloy.

3. Increasing the difference between the initial stress intensity and the final stress intensity range, for high-low blocks, 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.

4. For less frequently applied overloads (n>10) crack retardation is observed, while the results for overloads applied after 10 baseline cycles present crack acceleration.

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