FATIGUE CRACK GROWTH OF A*l* 7475 T761 UNDER CONSTANT AND VARIABLE AMPLITUDE LOADING

Celso Pinto Morais Pereira[1]
Herman Jacobus Cornelis Voorwald[2]

(1) Department of Mechanics - UNESP/FEG
(2) Department of Materials and Technology - UNESP/FEG
Av. Ariberto Pereira da Cunha, 333 - Guaratinguetá - SP - Brasil

ABSTRACT

Experimental programs in constant and variable amplitude loading were performed to obtain a x N curves and to study retardation in fatigue crack growth due to overloads. The main aim of this research program was to analyse the effect of overload ratio and number of overload peaks. The effect of underloads, before and after the overload blocks was also studied. The generalised equation of Paris-Erdogan type was used for modelling of obtained data on crack propagation under constant amplitude load.

KEYWORDS

Fatigue crack growth, aluminium, retardation, variable amplitude loading, a x N curves.

INTRODUCTION

The 7xxx series of A*l* alloys are widely used in structural engineering applications where high strength and low density characteristics are fundamental design requirements. Under constant amplitude loading, the crack growth behaviour of metallic materials, can be characterized by plotting the crack propagation rate (da/dN) as a function of the stress intensity range (ΔK). Fatigue crack growth can be affected by numerous variables, such as crack size, metallurgical parameters, load level, spectrum loading, and environment. Recent results (Chubb et al, 1995) indicate that, for A*l* 7178-T6, the presence of exfoliation corrosion enhances the fatigue crack growth rate at intermediate ΔK values. Under variable amplitude loading crack growth retardations and accelerations can occur, as a function of load level and sequences of load history. Some interesting results were obtained by (Mayer et al, 1992; Pantelakis et al, 1995; Tokaji and Ogawa, 1990; Sanctis and Lazzeri, 1992), analysing the response of different A*l* alloys to constant and variable amplitude loading. The retarded crack growth after a load amplitude reduction is related to the occurrence of plasticity-induced crack closure. According to this model introduced by Elber (1970), crack closure is a result of plastic deformation in the wake of the crack, due to crack tip plasticity of previous cycles. The aim of the present investigation is to study fatigue crack growth behaviour of A*l* 7475 T761 under constant and variable amplitude loading.

TESTING MATERIAL, EXPERIMENTAL PROCEDURES

The material used is Al 7475 T761, an age hardened aluminium alloy, used in fatigue-critical aircraft structural components. The chemical composition is (in ωt%) : Ti 0.03%, Zn 5.76%, Mg 2.05%, Fe 0.10%, Cu 1.35%, Mn 0.02%, Cr 0.24%. The static properties of the material are 0.2% yield stress 433 MPa, tensile strength 496 MPa. Fatigue crack growth tests were carried out on centre-cracked tension (CCT) specimens according to ASTM E 647 with length, width and thickness egual to 300mm, 75mm and 4.17mm, respectively. The tests were conducted in air at room temperature on a closed loop servo-electrohydraulic MTS system having a load capacity of ± 10 tons operating under a load control sinusoidal cyclic load of constant amplitude range, applied at a frequency of 10Hz. During cyclic loading, the crack length was measured with 7x microscope using stroboscopic for clear visibility at the test light frequency. Constant amplitude loading tests occured at: (9.45 ± 3.15) KN, (14.7 ±3.15)KN, (19.2 ± 3.15)KN, (35.9 ± 3.15)KN and (56.7 ± 3.15)KN, with R egual to 0.50; 0.65; 0.72; 0.84 and 0.89, respectively. In variable amplitude loading, 1,10, 100 and 1000 blocks of overload were applied during fatigue crack growth to study the influence on retarded crack growth after descendent sequence loading. Two values of the ratio between the overload maximum stress intensity factor ($K_{max\ OL}$) divided by the reference loading maximum stress intensity factor (K_{RL}), $K_{max\ OL}/K_{max\ RL}$ were used: 1.42 and 1.77.

Maximum and minimum stresses for reference loading are: σ_{max} = 40.2 MPa and σ_{min} = 20.1 MPa (R = 0.5). For overloads , σ_{max} = 57.0 MPa and σ_{min} = 36.9 MPa ; $K_{max\ OL}/K_{max\ RL}$ = 0.42 and σ_{max} = 71.4 MPa and σ_{min} = 51.3 MPa; $K_{max\ OL}/K_{max\ RL}$ = 1.77.

RESULTS AND DISCUSSIONS

Typical crack propagation curves under constant amplitude loading are shown in Figures 1 and 2.

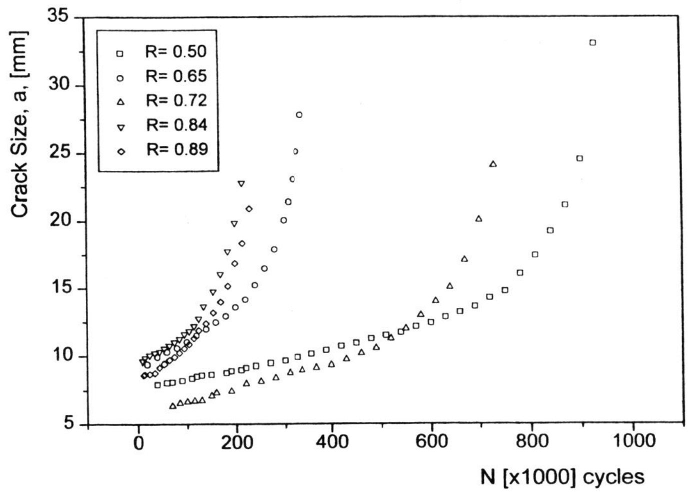

Figure 1. Fatigue crack propagation behavior under constant amplitude loading.

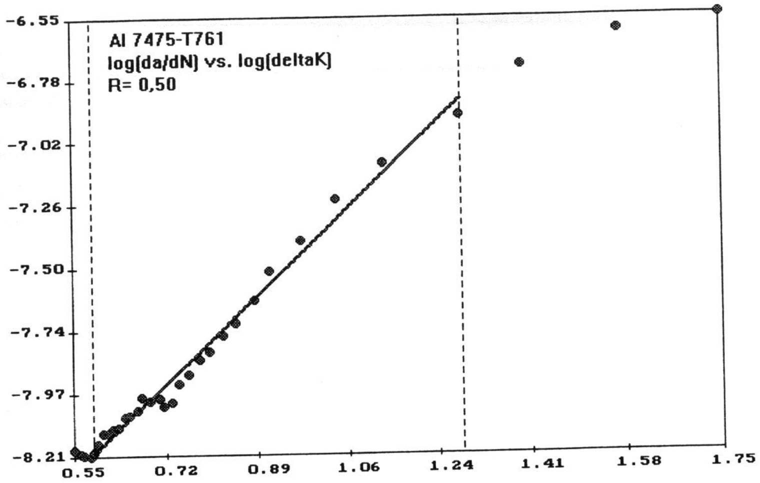

Figure 2. Fatigue crack propagation rate da/dN versus ΔK.

To predict the macro-crack propagation stage, the empirically based Paris' equation,

$$\frac{da}{dN} = C(\Delta K)^n \tag{1}$$

was used, where a is the crack length, C and n are geometry and material dependent parameters respectively, and ΔK is the range of the stress intensity factor.

The obtained experimental data were analysed using specialized software developed by Pastukhov. The values of crack length (a) and number of cycles (N) are represented as da/dN versus ΔK; C and n are calculated and fatigue life is predicted through cycle-by-cycle calculations of Paris equation (individual theoretical curve) and through a generalyzed equation (generalyzed curve) that analyses the stress ratio effect (R) considering the parameter n as invariant. The results are indicated in table 1, where C_{gen}, n_{ind} and C_{ind} are based on the generalysed and individual analysis, respectively. The new concept was proposed in order to reduce a number of parameters necessary for characterization of material performance in wide range of loading conditions. The crack growth rate is analyzed in terms of both independent parameters of cyclic load and constant of kinetic equation are real invariants in the considered range.

TABLE 1. Values of parameters C and n

TEST	Q max	Q min	R	C gen (n gen = 1.91)	Deviation (%)	n ind	C ind	Deviation (%)
1	12.60	6.30	0.50	4.92 E - 10	-0.67	1.94	4.58 E - 10	-0.67
2	17.85	11.55	0.65	9.56 E - 10	3.11	1.61	1.75 E - 09	-0.46
3	22.35	16.05	0.72	8.72 E - 10	-0.04	2.60	2.95 E - 10	-0.25
4	39.05	32.75	0.84	1.61 E - 09	1.43	2.29	8.22 E - 09	-0.14
5	59.85	53.55	0.89	1,96 E - 09	-1.30	1.71	2.68 E - 09	-0.88

It is possible to observe higher values for C with an increase in the stress ratio (R), which shows that an increase in R result in an acceleration of fatigue crack propagation. Very low values for the deviation indicate reasonable representativity between experimental data and theoretical curves.

The influence of number of overload cycles and the ratio $K_{max\ OL}/K_{max\ RL}$ are indicated in figures 3, 4, 5 and 6 for crack lengths igual to 10mm, 15mm and 20mm.

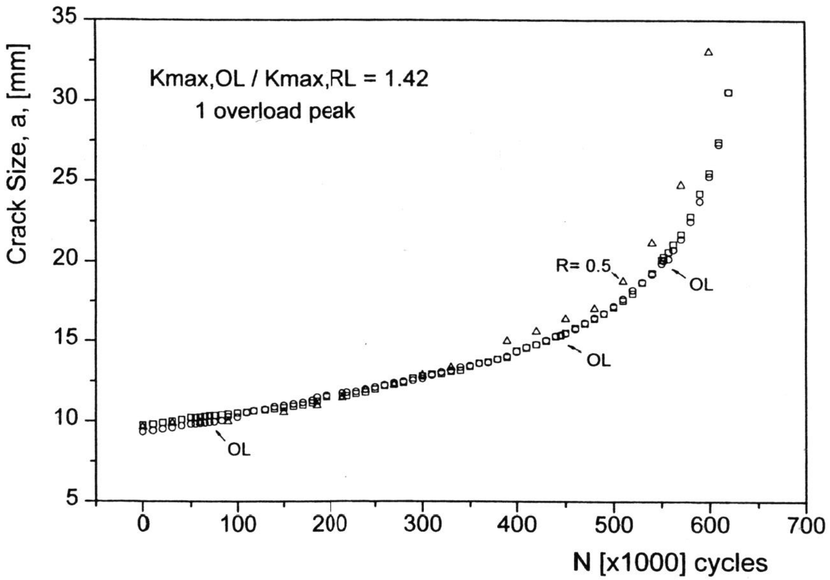

Figure 3. Crack length versus number of cycles. (1 cycle) $K_{max\ OL}/K_{max\ RL}$ = 1.42. Base line R ratio egual to 0.5.

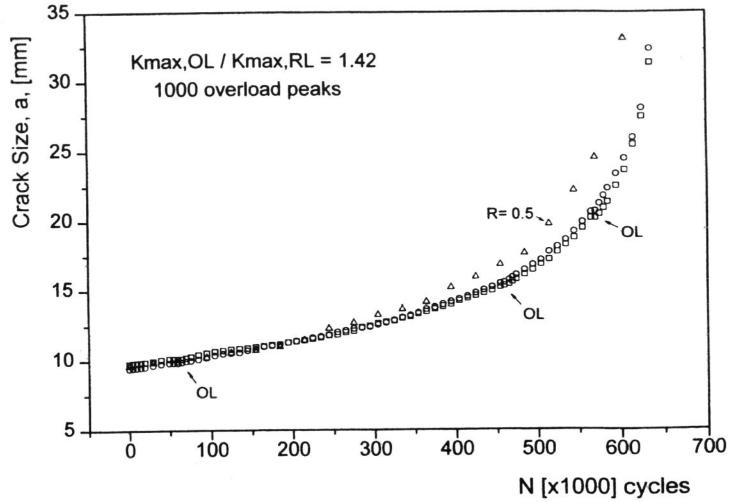

Figure 4. Crack length versus number of cycles (1000 cycles). $K_{max\ OL}/K_{max\ RL}$ = 1.42. Base line R ratio egual to 0.5.

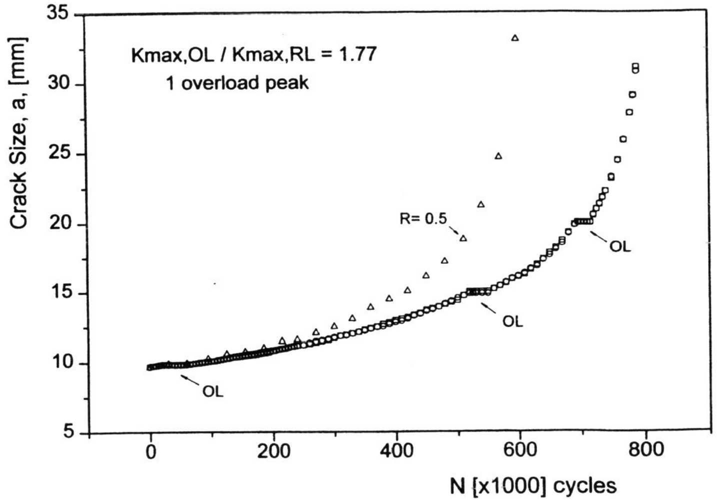

Figure 5. Crack length versus number of cycles (1 cycle). $K_{max\ OL}/K_{max\ RL}$ = 1.77 Base line R ratio egual to 0.5.

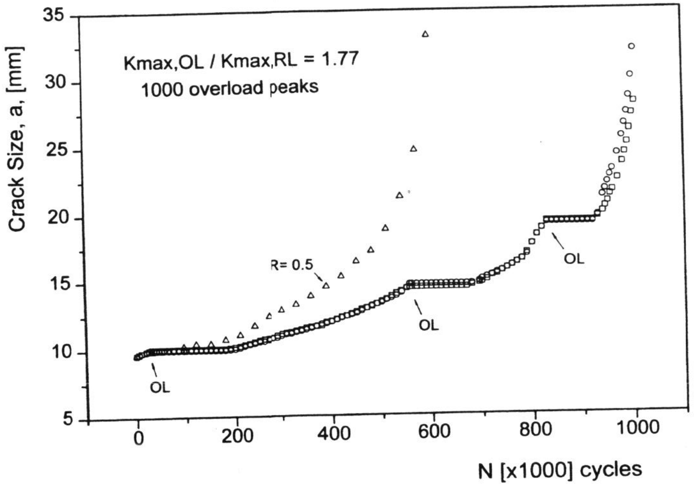

Figure 6. Crack length versus number of cycles (1000 cycles). $K_{max\ OL}/K_{max\ RL} = 1.77$. Base line R ratio egual to 0.5.

For both ratios, 1.42 and 1.77, the number of retardation cycles increases with the increase in the number of overload cycles and in the ratio $K_{max\ OL}/K_{max\ RL}$. It is also possible to conclude, from experimental data, that for large crack lengths, a decrease in the number of retardation cycles occur, when compared with small and intermediate crack lengths. The trend may be explained by the fact that the crack advances appreciably during the tensile overloads. As the stress levels ahead of the crack tip are high the retardation does not have a well defined behaviour once the main crack can interact with the subcritical cracks induced in front of it. Experimental tests with $K_{max\ OL}/K_{max\ RL}$ egual to 1.25 showed very little retardation effects, indicating that the ratio 1.25 is very close to a limit value below which no interaction effects result from variable amplitude loading.

A significant influence of number of overload peaks (N_{OL}) in the range from 1 to 1000 was observed, with difference in retardation amplitude (measured in number of cycles) of ≅ 5 times. For overloads applied during the initial phase of crack propagation process, the number of cycles of retardation strongly increases between $N_{OL} = 1$ and $N_{OL} = 100$, following by stabilization and small decrease for $N_{OL} = 1000$. For overloads applied at a more advanced phase of crack propagation this saturation in effect of N_{OL} was not observed.

According to the number of overload cycles studied (1, 10, 100 and 1000) it was possible to identify an increase in the number of retardation cycles for crack length egual to 10mm and 15mm. For crack length egual to 10mm, a saturation occured for number of overload cycles egual to 100, with a decrease in retardation effects for 1000 cycles. For crack length egual to 15mm, the number of retardation cycles increases with the increase in overload cycles form 100 up to 1000. An analitical model was successfully tested for all ratios $K_{max\ OL}/K_{max\ RL}$ studied. The procedure consisted, for each experimental point after the overloads, to calculate the difference related to the constant amplitude test in number of cycles necessary to reach the same crack size, searching for the stabilization that caracterize the magnitude of retardation.

The influence of underload cycles applied before and after overloads was also studied. The maximum and minimum stresses for the two underload used were: $\sigma_{max} = 33.9$ MPa and $\sigma_{min} = 13.7$ MPa; $\sigma_{max} = 37.1$ MPa and $\sigma_{min} = 16.9$ MPa. In figure 7, experimental number of retardation cycles are indicated as a function of loading program and for crack lengths of 10mm, 15mm and 20mm.

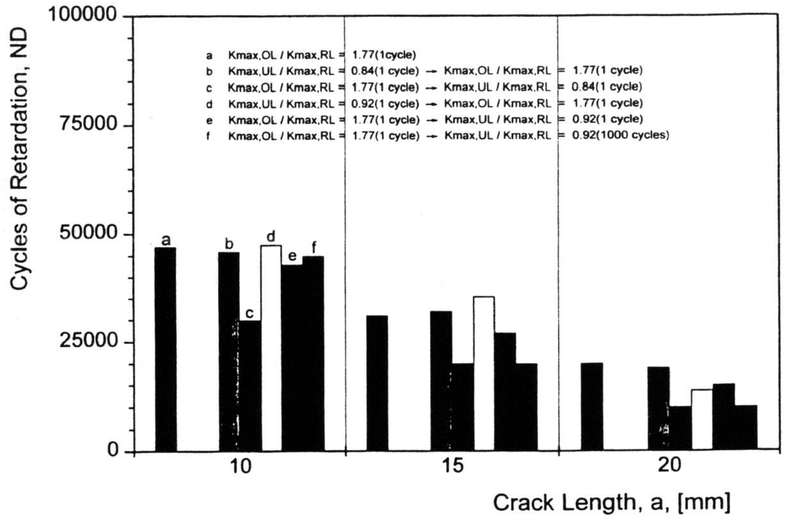

Figure 7. Number of retardation cycles versus crack length.

TABLE 2. Number of cycles of retardation

a [mm]	10	15	20
$K_{maxOL}/K_{maxRL} = 1.77$	47000	31000	20000
$K_{maxUL}/K_{maxRL} = 0.84$ (1 cycle) → $K_{maxOL}/K_{maxRL} = 1.77$ (1 cycle)			
	46000	32000	19000
$K_{maxOL}/K_{maxRL} = 1.77$ (1 cycle) → $K_{maxUL}/K_{maxRL} = 0.84$ (1 cycle)			
	30000	20000	10000
$K_{maxUL}/K_{maxRL} = 0.92$ (1 cycle) → $K_{maxOL}/K_{maxRL} = 1.77$ (1 cycle)			
	47500	35500	13800
$K_{maxOL}/K_{maxRL} = 1.77$ (1 cycle) → $K_{maxUL}/K_{maxRL} = 0.92$ (1 cycle)			
	43000	27000	15000
$K_{maxOL}/K_{maxRL} = 1.77$ (1 cycle) → $K_{maxUL}/K_{maxRL} = 0.92$ (1000 cycles)			
	45000	20000	10000

Under these circumstances, if the underload cycle is applied before the overload, very little effect can be observed, on the other hand a tendency to reduce the retardation cycles is associated with an underload just after the overload. The number of retardation cycles after underloads applied following descendent sequence loading is dependent on the underload level and number of underload cycles. These conclusions are indicated in Table 2.

CONCLUSION

1. Experimental data obtained in constant amplitude loading tests indicate that fatigue crack growth rate (da/dN) increases with stress ratio (R). It is possible to obtain a good correlation through Paris equation, resulting in small deviations between experimental and theoretical values. Analysis of C_{gen} and C_{ind}, n_{ind} indicate maximum deviation egual to 3.11% and 0.88%, respectively. Higher values of R result in an increase in C value (C_{ind} and C_{gen}).

2. In variable amplitude loading retardation in fatigue crack propagation was observed after descendent sequence loading. Higher number of cycles of retardation are obtained as a consequence of higher number of overload cycles. The tendency is the same for different crack lengths in which overload occur. It was also observed that for large crack lengths, smaller number of retardation cycles were obtained.

3. When underloads are applied before overloads, very little effect of variable amplitude loading on crack growth is observed. A tendency to reduce the retardation cycles is associated with underload cycles just after the overload. In this case, the number of retardation cycles is dependent on the underload level and number of underload cycles.

REFERENCES

Elber W. Fatigue crack closure under cyclic tension (1970). Engng Fracture Mech. 2, 37-45.

Chubb, J.P., T.A. Morad, B.S. Hockenhull and J.W. Bristow (1995). The effect of exfoliation corrosion on the fracture and fatigue behaviour of 7178 T6 aluminium. Int.J.Fatigue, vol. 17, nº 1, 49-54.

Mayer, H.R., S.E. Stanzl, E.K. Tschegg and J.Schijve (1992). Fatigue crack growth of A*l* 2024 T3 under low amplitude two-step loading. Fatigue Fract. Engng Mater.Struct., vol. 15, nº 3, 265-275.

Pantelakis, Sp.G., Kermanidis, Th.B. and Pavlou, D.G. (1995). Fatigue crack growth retardation assessment of 2024- T3 and 6061 T6 aluminium specimens. Theor. and Appl. Fract. Mech., 22, 35-42.

Sanctis, M. de and L. Lazzeri (1992). An evaluation of fatigue and fracture mechanics properties of ultra-high strength 7xxx series Al alloys. Fatigue Fract. Engng Mater. Struct., vol. 15, nº 3, 249-263.

Tokaji K. and T. Ogawa (1990). The effects of stress ratio on the growth behaviour of small fatigue cracks in an aluminium alloy 7075- T6 (with special interest in stage I crack growth). Fatigue Fract. Engng Mater. Struct., vol. 13, nº 4, 411-421.