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Crack Propagation of Aluminum Alloy 2024 T351 under Constant Amplitude Loading using Crack Closure Concept

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Abstract. The crack propagation behavior in a 2024 T351 Aluminum Alloy under constant amplitude loading has been studied. This study is analyzed in term of crack opening load measurements using a compliance technique. The results obtained under constant amplitude fatigue tests show that different crack propagation stages can be identified. Significant effects due to load ratio changes have been quantified.

Introduction

To characterize the behavior of a material, Paris law [1] is often used. This law relates the crack growth rate da/dN and the cyclic amplitude stress intensity factor ΔK. This relationship can show several stages separated by transitions (Fig.1) [2-4]. Predominant microstructural size, the ambient environment and the loading frequency can modify the behavior of the crack growth curves (da/dN vs ΔK) and the transitions [3].

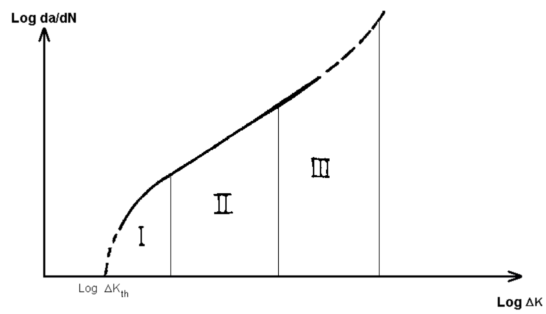

Fig. 1. Typical evolution of da/dN to respect ΔK

There exists a threshold of non propagation under which a preexistant long crack does not grow [5]. The value of ΔKth is a function of the load ratio R and the environment [3, 5]. For medium crack growth rates ((10-8 < da/dN < 10-5) m/cycle for aluminium alloys), the relationship between da/dN and ΔK is characterized by independent constant slope of the load ratio R.

This stage is also characterized by the existence of fatigue striations whose interval can be directly correlated with macroscopic crack growth rate [6-8]. In this stage, the crack growth behavior is characterized in considering the effect of crack closure effect [9]. The crack closure effect is taken account by the factor UE which represents the loading efficiency, thus:

$$U_E = \Delta K_{eff} / \Delta K \quad (1)$$

with $\Delta K_{eff} = K_{max} - K_{op}$ where K_{op} is opening stress intensity, and ΔK_{eff} effective stress intensity factor .The crack growth rate can be given by the following relationship:

$$\frac{da}{dN} = C'\left(\Delta K_{eff}\right)^{n'} \quad (2)$$

For crack rate growth rates greater than 10-6 m/cycle, we observe an increase in the crack growth as we approach the static rupture conditions [10]. Recently, an energetic approach [11, 12] based on the theoretical model of Weertman [12] permits a better comprehension of mechanisms of propagation with a possible correlation between macroscopic and microscopic mechanisms. This study permits us to determine the laws of the behavior which take into account different regimes of fracture separated by transitions.

Material and Experimental Procedures

The study was conduced on the high strength aluminium alloy 2024 T351 whose composition and nominal properties are given respectively in the tables 1 and 2.

Table 1. Nominal composition of the aluminum alloy 2024 T 351

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Mean%	0.1	0.22	4.45	0.66	1.5	0.01	0.04	0.02	Bal

Table 2. Mechanical Properties of the aluminum alloy 2024 T 351

Monotonic yield stress (MPa)	302
Elongation (%)	10.1
Strength coefficient, K, (MPa)	343
Hardening coefficient, n	0.06
Ultimate tensile strength (MPa)	474
Cyclic yield stress (MPa)	500
Cyclic strength coefficient, K', (MPa)	8811.4
Cyclic Hardening coefficient, n''	0.078

Constant amplitude fatigue crack growth tests were conducted using an Instron servo-hydraulic machine at five R ratios of 0.01, 0.1, 0.33, 0.54, and 0.70. The crack growth rate covered is the in the range 10-8 < da /dN < 10-4 m/cycle. The crack tests have been done on CT specimen with a 12 mm thickness. The stress intensity factor K is determined according to the ASTM recommendations [13].

Experimental Results

The crack curve showing da/dN in function of ΔK and Kmax is given in Figs.3a and 3b. The results are comparable to those obtained by Wanhill [3] for the material. The crack growth rates obtained at R = 0.01 and R = 0.1 are similar. We noted that on the figures 3a and 3b, the existence of transitions (T1, T2, T3) characterized by a change of on the curves when the relation da/dN vs ΔK is different. The different transitions observed are identified in table 3. The analysis of these results proves the existence of four domains of cracks [14].

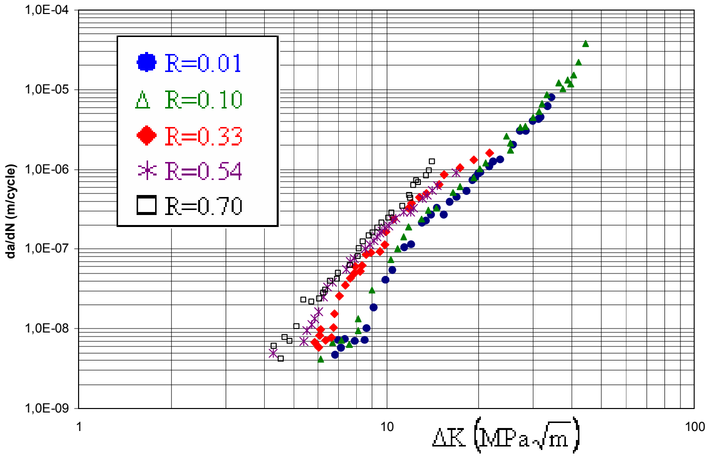

Fig. 3a. Evolution of the crack growth rate da/dN with respect to the factor ΔK

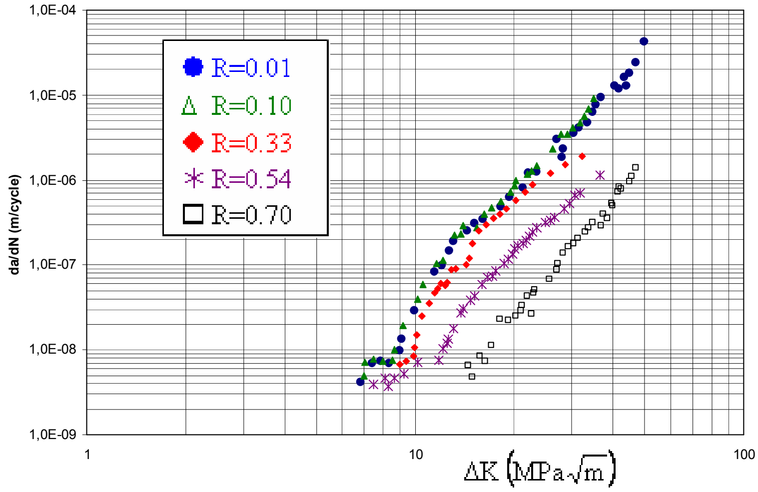

Fig. 3b. Evolution of the crack growth rate da/dN with respect to stress intensity factor Kmax

Table 3. Transitions in crack growth behavior (da/dN: m/cycle, ΔK and Kmax: MPa $\sqrt{m}$)

R		0.01	0.10	0.33	0.54	0.70
T_1	ΔK K_{max} da/dN	8.5 8 10^{-8}	7.5 8.5 10^{-8}	6 9 $8\ 10^{-9}$	6 12 $7.5\ 10^{-9}$	5 15 $8\ 10^{-9}$
T_2	ΔK K_{max} da/dN	12 12 $1.30\ 10^{-7}$	11 12 $1.30\ 10^{-7}$	9 12 $1.70\ 10^{-7}$	7 15 $7.2\ 10^{-8}$	- - -
T_3	ΔK K_{max} da/dN	30 30 $3\ 10^{-6}$	24 35 $3\ 10^{-6}$	21 31 $1.60\ 10^{-7}$	13 - $7\ 10^{-7}$	12 37 $4\ 10^{-7}$

All the tests were carried out under computer control at 20 Hz in ambient air and at selected crack length , the evolution of the crack mouth opening displacement δ (measured by a clip gage) and the differential displacement δ' with respect to the load P were recorded on a XY plotter at a frequency of 0,2 Hz. δ' is defined by : δ' = δ- αP, were α is the specimen compliance at a particular crack length The measurements were carried out during one cycle for constant amplitude tests. Typical δ vs. P and δ' vs. P diagrams for constant amplitude loading conditions are given in Fig. 4. Constant amplitude loading tests: the crack opening load P_{op} at the beginning of the horizontal portion of the δ' vs P diagrams [15].

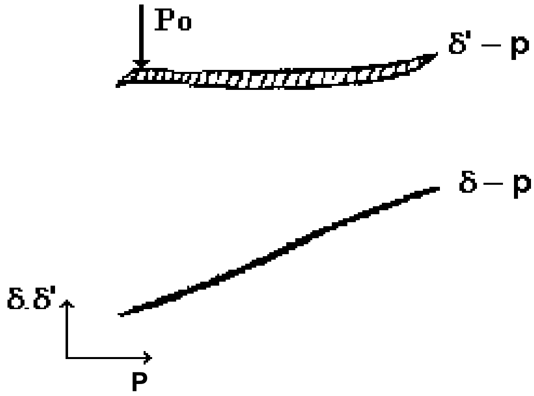

Fig. 4. Measurement of opening loading- δ vs P and δ' vs P diagrams

Analysis in Terms of Crack Closure

The relation between da/dN and measured ΔK_{eff} values is shown in Fig. 5.

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

K_{op} being associated to measured Pop level. In this figure, measurements of ΔK_{eff} near threshold crack growth behaviour for this material is added [16].

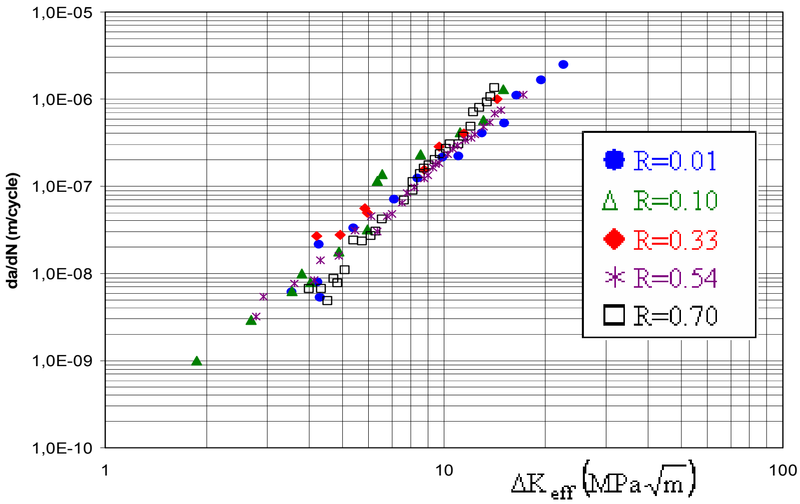

Fig. 5 Evolution of the crack growth rate da/dN with respect to the factor ΔK_{eff}

This diagram shows that the relationship between da/dN and ΔK_{eff} can be expressed in terms of the relation between da/dN and K_{max} (Fig. 4b) irrespective of the R value, but with the definition of two different slopes, with a transition about da/dN = 10-8 m/cycle. Thus the constants of Elber's relation (4) are different on either side of the transition. The relation can be expressed as follow:

$$da/dN = C'(U_E(K_{max} - K_{op}))n' \tag{4}$$

The values of the constants C' and n' are given in Table 4.

Table 4. Constants C' and n' of Elber's relation

Considered range	C'	n'
da/dN < 10^{-8} m/cycle	3.83 x 10^{-10}	2.50
da/dN > 10^{-8} m/cycle	1.51 x 10^{-10}	4.0

The evolution of the crack load was analyzed in terms of efficiency factor, U_E. The evolution U_E with respect to K_{max} is given in Fig. 6.

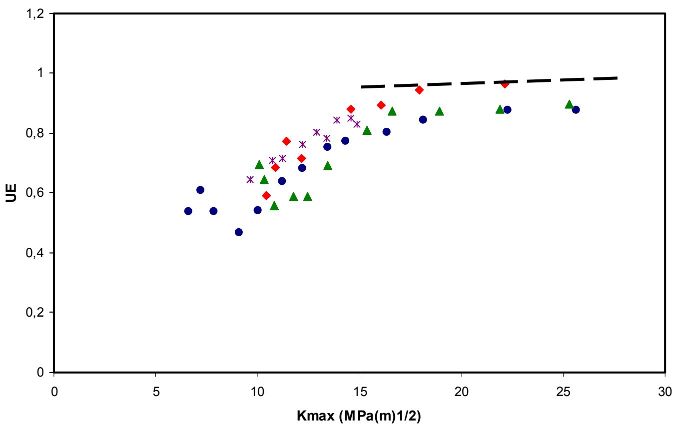

Fig. 6. Evolution of the efficiency factor U_E with Kmax

This figure shows that U_E depends on K_{max} and R and the following empirical relationship was determined:

$$U_E = A + B.K_{max} + C.R \quad (5)$$

The values of A, B and C is different K_{max} ranges determined by regression techniques are given in Table 5.

Table 4. Values of the constants of the relationship (5)

Range of K_{max} (MPa $\sqrt{m}$)	A	B	C
$6< K_{max} < 10$	0.03	0.047	0.36
$10< K_{max} < 17$	0.03	$0.047 \times K_{max}$	0.36
$K_{max} > 17$	0.03	0.80	0.36

The relations of the crack growth can be expressed for the different stages as:

- For $R \leq 0.54$:

Stage I

$$\frac{da}{dN} = 3.83 \times 10^{10} \{U_E \Delta K\}^{2.50} \quad (6)$$

with $U_E = 0.51$

Stages II and III

$$\frac{da}{dN} = 8.66 \times 10^{11} \{U_E \Delta K\}^{3.45} \quad (7)$$

with $U_E = A + B.K_{max} + C.R$

To take account of the particular behaviour observed at R=0.70, a unique relation of crack growth can be used and as following:

$$\frac{da}{dN} = 9.80 \times 10^{12} \{\Delta K\}^{4.4} \quad (8)$$

According this analysis, a comparison between the life estimations by different models and the measured life is given in table 5 for the constant amplitude loading:

Table 6. Comparison of measured and estimated lives (crack growth life from a=24mm to fracture) under constant amplitude loading conditions

R	Load P_{max}	N measured	N estimed Actual analysis	ER%
0.01	400	1148000	1000000	12.90
	600	123000	92000	25.20
0.10	400	111000	1080000	3.30
	500	314000	377000	20.00
0.33	480	795000	1088000	36.88
	540	478000	499000	4.00
0.54	600	813000	785000	3.44
0.70	833	941000	853000	9.55

The relative error in percentage is also calculated by:

$$Error\% = \left(\frac{EstimatedLife \quad MeasuredLife}{MeasuredLife} \right) \times 100 \qquad (9)$$

By examining table 6, the following observations can be made: The different models underestimate the life for all values ratios, but the actual method give an agreement result and the relative error is within 3.00 < RE < 36.88.

Summary

On the basis of reference tests at constant amplitude loading, crack closure measurements and analysis based on crack closure and microscopic analysis, the following conclusions can be drawn:

* The crack opening level for spectra is almost the same at low K_{max} values and depends upon the global R ratio.

* The different propagation regimes which are separated by characteristic transitions. Moreover, the influence of the load ratio R and the maximum stress intensity factor K_{max} is taken into account by the analysis method.

On the other hand, a phenomenal relationship between da/dN and ΔK can be given according to crack growth regimes. The relation take into account the difference in behavior of mechanism governed the cracking.

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