EFFECTS OF SELECTIVE VARIABLE AMPLITUDE LOADING ON FATIGUE CRACK GROWTH

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ABSTRACT

In variable amplitude loading, there are interaction effects between the loading history and the crack propagation rate. The most important of these effects is the retardation in the crack propagation that may raise considerably the life of the cracked structure. The main objetive of this research is to analyse and quantify the retardation of crack propagation in a thin plate of the high resistance aluminum alloy 2024-T3. The specimens were tested under high-low loading sequences, for diferent crack sizes and overload ratios (Rol = Kmax ol/Kmax ca). It was verified that the retardation is proportional to Rol and that the fatigue crack growth after a descendente sequence loading (through the plastic zone created by the overload) was a function of the stress intensity factor, K. A simplified method, that could precisely represent the crack behaviour during retardation for different overload ratios and crack sizes, was developed based on the model of Wheeler and using a proposed correction for the plastic zone size.

KEYWORDS

Fatigue, plastic zone, retardation

INTRODUCTION

The aim of all the numerous methods known from the literature [1-5], is to express the correlation between the crack propagation rate and the stress intensity factor under constant amplitude loading, as precisely as possible. The most important of the interaction effects between the loading history and the crack propagation rate is the retardation in the crack propagation that may raise considerably the life of the cracked structure. The following mechanisms are thought to cause the retardation of crack growth: residual compressive stresses in the overload plastic zone, crack closure, crack tip straining, crack tip blunting and crack tip branching [6,7,8]. For variable amplitude loading several semi-empirical models, based on the concept of an effective crack-tip stress intensity factor, have volved in an attempt to predict fatigue crack growth retardation [9-12]. The aim of this investigation was to analyse and quantify the retardation of crack propagation in thin plates of the high resistance aluminum alloy 2024-T3. The specimens were tested under high-low loading sequences, for different crack sizes and overload ratios. The predominant state of stress at the crack tip during the overload cycle was often plane stress. For some conditions of the variables, a combination of stress states at the crack tip from plane strain and plane stress were produced, resulting in a proposed correction for the plastic zone size. Special block load sequences were selected for this investigation. They include overloads with different number of cycles in the high load, but all of them greater then the limiting saturation value. For the evaluation of the retardation effects, constant amplitude data were also required. Such tests were performed with different R - ratios.

EXPERIMENTAL DATA

The experimental program was performed on the high strength aluminum alloy Al 2024-T3. Mechanical properties of this material are: Yield stress , 417 MPa, Tensile strength, 516 MPa and Elongation 8,6%. All tests specimens used in this experimental program were single-edge-notched specimens. The thickness of the specimens was 1,27 mm, with 90 mm and length 466mm. The stress intensity expression for this sample geometry is given by:

$$K = \sigma\sqrt{a}\left[1,99 - 0,41(a/W) + 18,70(a/W)^2 - 38,48(a/W)^3 + 53,85(a/W)^4\right] \quad (1)$$

Pre cracking was performed under constant amplitude loading cycled at (5000 ± ± 2500)N. All tests were run at a cyclic rate of 10 Hz at room temperature. Cyclic crack growth measurements were obtained using visual optics. The experimental data used in the analysis of retardation in fatigue crack growth due to consecutive overloads, was obtained from the experimental program shown in figure 1.

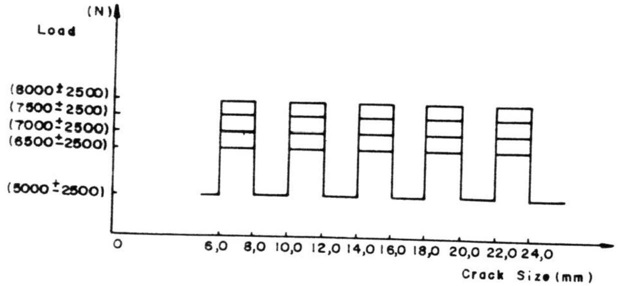

Figure 1. Experimental program.

A load (5000 ± 2500)N was used as a reference and the overloads were (6500 ± ± 2500)N, (7000 ± 2500)N, (7500 ± 2500)N and (8000 ± 2500)N. The ratios of overload maximum stress intensity, Kol, to the maximum stress intensity of subsequent constant amplitude loading, Kca, were 1,20, 1,27, 1,33 and 1,40, respectively. It was observed that Kol/Kca < 1,20 produces no retardation and Kol/Kca > 1,60 produces temporary arrest.

RESULTS AND DISCUSSIONS

The constant amplitude tests results can be represented quite well by the following equation:

$$\frac{da}{dN} = \frac{3,6 \times 10^{-8}\,(U.\Delta K)^{3,019}}{91,1 - K_{max}} \quad (2)$$

with da/dN in m/cycle, ΔK in $MPa.m^{1/2}$ and $U = 0,5 + 0,4.R$, where R is the ratio between the minimum and the maximum stress. The amount of crack retardation increases as the ratio of overload maximum stress intensity to the maximum stress intensity of subsequent constant amplitude loading increases . Tests with high-low load sequences showed a greater crack propagation life. There are different number of cycles in the high load for the several blocks applied to the specimen, but all of them greater then the limiting saturation value.

The objective of this study is to develop a simple fatigue crack growth retardation model that partially accounts of the mechanisms of residual stress. To this end, the model of wheeler [10] is employed.

$$a_r = a_o + \sum_{i=1}^{r} C_{pi}\, f(\Delta Ki) \quad (3)$$

where a_o is the initial crack length and C_{pi} is the retardation parameter taken in the following from:

$$C_p = \left(\frac{R_y}{ap-a}\right)^m, \text{ when } a + R_y < ap \quad \text{or} \quad (4)$$

$$C_p = 1, \text{ when } a + R_y \geq a_p \quad (5)$$

where: R_y - extent of current yield zone; ap-a - distance from crack tip to elastic-plastic interface and m - shaping exponent, must be stablished experimentally.

The proposed crack growth prediction model employ the plastic zone size created by the overload, given on the basis of the following equation:

$$r_p = \alpha\left(\frac{K_{max}}{\sigma_e}\right)^2 \text{ where } \alpha = \frac{1}{3\pi} \text{ for } t \geq 2,5\left(\frac{K_{max}}{\sigma_e}\right)^2 \quad (6)$$

$$\alpha = \begin{cases} \dfrac{1}{3\pi} & \text{for } t \geq 2,5\left(\dfrac{K_{max}}{\sigma_e}\right)^2 \\[2ex] \dfrac{1}{\pi} & \text{for } t \leq \dfrac{1}{\pi}\left(\dfrac{K_{max}}{\sigma_e}\right)^2 \\[2ex] \dfrac{1}{3\pi} + \dfrac{2}{3\pi}\left[\dfrac{2,5 - t\left(\dfrac{K_{max}}{\sigma_e}\right)^{-2}}{2,5 - \dfrac{1}{\pi}}\right] & \text{for } \dfrac{1}{\pi}\left(\dfrac{K_{max}}{\sigma_e}\right)^2 < t < 2,5\left(\dfrac{K_{max}}{\sigma_e}\right)^2 \end{cases}$$

The experimental data show that the retardation effects are proportional to Kol/Kca and the number of delay cycles is a function of the stress intensity factor, K. The retardation model developed in this work differs from the Wheeler model in that it considers $m = f(U.\Delta K)$. For 2024-T3 aluminum alloy:

$$m = 5,602 \,.\, \ell n\,(U.\Delta K) - 6,735 \quad (7)$$

with ΔK in $MPa.m^{1/2}$.

The number of delay cycles, experimental, predicted by Wheeler's model with the exponent m taken as 5,0 and using the proposed method, are represented in table 1. From table 1 it can be seen that Wheeler's model with m = 5,0 , which is an exponent value appropriate for 2024-T3 aluminum alloy, is non conservative when the base mean stress intensity is low, shorter cracks. When the base mean stress intensity reaches a critical level, longer cracks, the equation can represent the number of delay cycles and with even higher base mean stress intensities, longest cracks, the predictions deviate from test results. So, exponent m = 5,0 in Wheeler's model is an appropriate value for 2024-T3 aluminum alloy for a particular condition of the stress intensity factor. The proposed method can correctly represent the number of delay cycles for all the values of Kol/Kca. For the condition Kol/Kca igual 1,40 and crack size 20,00 mm, however, the proposed model is conservative. This experimental behaviour can be explained considering that when the base mean stress intensity reaches a critical level, tensile overloads became high enough to cause coarse intermetallic particles ahead of the crack to separate from the matrix. These incipient cracks reduce the stress intensity at the main crack tip and this increase the magnitude of retardation.

Table 1. Number of Delay Cycles

Kol/Kca \ Crack size (mm)	8,00			12,00			16,00			20,00			24,00		
	EXP.	m = 5,0	m = f(UΔK)	EXP.	m = 5,0	m = f(UΔK)	EXP.	m = 5,0	m = f(UΔK)	EXP.	m = 5,0	m = f(UΔK)	EXP.	m = 5,0	m = f(UΔK)
1,20	5000	16079	5062	4000	6591	4533	3800	4089	4198	4000	2737	3788	3000	1637	2802
1,27	11000	42617	9277	10800	15114	9136	8700	8865	9209	7000	5397	8353	6500	3263	6859
1,33	18000	101868	15708	18800	32032	17103	20000	17886	18812	17500	10058	17411	14900	6101	15761
1,40	25000	∞	25176	25000	64017	30386	35000	34847	37189	63700	17988	34775	26250	10913	34540

CONCLUSIONS

1. The amount of crack retardation increases as the ratio of overload maximum stress intensity, Kol, to the maximum stress intensity of subsequent constant amplitude loading, Kca, increases.
2. The experimental results indicate that the crack propagation following a high-low load sequence can be associated with three different behaviours related to the stress intensity factor.

3. The exponent m = 5,0 in Wheeler's model is an appropriate value for 2024-T3 aluminum alloy when the base mean stress intensity reaches a critical level. When the base mean stress intensity is low, some overstimation in the number of delay cycles occur and for even higher base mean stress intensities (longest cracks), the predictions are lower than the experimental results.
4. The retardation model developed in this research differs from the Wheeler model in that it considers $m = f(U.\Delta K)$. For 2024-T3 aluminum alloy:

$$m = 5,602 \ . \ \ell n(U.\Delta K) - 6,735$$

with K in MPa. $m^{\frac{1}{2}}$.
5. The proposed method can correctly represent the number of delay cycles for all the values of Kol/Kca.
6. For the condition Kol/Kca igual 1,40 and crack size 20,00 mm, however, the proposed model is conservative. This experimental behaviour can be explained by the fact that incipient cracks can reduce the stress intensity at the main crack tip, increasing the magnitude of retardation.

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