CUMULATIVE DAMAGE EFFECTS IN FATIGUE CRACK GROWTH PROPAGATION UNDER VARIABLE AMPLITUDE LOADING

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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 objective of this research is to analyse the applicability of Miner's theory, $\sum_{q=1}^{h} \frac{ni}{Ni} = K$, as a damage parameter in variable amplitude loading. Thin plates of the high resistance aluminum alloy 2024-T3 were tested under high-low loading sequences, for different crack sizes and overload ratios.

INTRODUCTION

The aim of all the numerous methods known from the literature (Paris and Erdogan |1|, Forman et al |2|, Elber |3|, Nelson and Fuchs |4| , Miller and Gallagher |5|), is to express the correlation between the crack propagation rate and the stress intensity factor under constant amplitude loading, as precisely as possible. Predicting the rate at which fatigue cracks will grow under variable amplitude loading is a major problem in the design and reliability assurance of a variety of structures if there are interaction effects between the loading history and the crack propagation rate. The application of high-to-low load sequences could cause the phenomenon termed crack retardation (Zhang et al |6|), that could cause a greater crack propagation life than would have been predicted on the basis of the summation of crack growth for each cycle using constant-amplitude growth rate data. The aim of the present study is to analyse and quantify the influence of the interaction effects on the applicability of Miner's theory in variable amplitude loading. Special block load sequences were selected for this investigation. They include overloads with different numbers of high-load cycles, all of which are greater than the limiting saturation value. For the evaluation of the retardation effects, constant amplitude data were also required. Such tests were performed for different R-ratios.

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MATERIAL AND METHODS

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 test specimens used in this experimental program were single-edge notch specimens. The thickness of the specimens was 1,27 mm and width 90 mm. Precracking 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 to analyse the applicability of Miner's theory in variable amplitude loading , was obtained from the experimental program shown in figure 1. 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. It was observed that Kol/Kca < 1,20 produces no retardation and Kol/Kca > 1,60 produces temporary arrest.

RESULTS AND DISCUSSION

Figures 2 and 3 show the effect of the load sequences on crack growth, for ratios of overload maximum stress intensity to the maximum stress intensity of the subsequent constant amplitude loading of 1,20 and 1,40, respectively. In table 1 the values of Σni/Ni are indicated for the ratio Kmax ol/Kmax ca equal 1,20 and 1,40 in the case of one block of overloads.

TABLE 1. Σni/Ni

CRACK SIZE (mm)		Σni/Ni	
Ascendent	Descendent	(5000 ± 2500)N → (6500 ± 2500)N	(5000 ± 2500)N → (8000 ± 2500)N
10,00	12,00	1,057	1,443
10,00	16,00	1,065	1,790
10,00	20,00	1,055	1,604
10,00	24,00	1,031	1,306
14,00	16,00	1,073	1,780
14,00	20,00	1,063	1,594
14,00	24,00	1,039	1,295
10,00	20,00	1,055	1,604
	24,00	1,031	1,306
14,00	20,00	1,063	1,594
	24,00	1,039	1,295
18,00	20,00	1,055	1,599
	24,00	1,030	1,301

From table 1, it is possible to observe the influence of the crack size in which the high-low sequence loading occurs on Σni/Ni. Higher values for Σni/Ni are observed for intermediate cracks (when the base mean stress intensity reaches a critical level), followed by short and long cracks. The retardation effects due to the overloads can be associated with Kol/Kca. The crack size in which the low-high sequence loading occurs, has little or no influence on the Σni/Ni value. The results for three overload blocks are indicated in table 2.

TABLE 2. Σni/Ni

BLOCKS				LOAD	
1º	2º	3º		(5000 ± 2500)N → (6500 ± 2500)N	(5000 ± 2500)N → (8000 ± 2500)N
10,00	14,00	18,00	asc.	1,185	2,822
12,00	16,00	20,00	desc.		
10,00	14,00	18,00	asc.	1,161	2,524
12,00	16,00	24,00	desc.		
10,00	14,00	22,00	asc.	1,168	2,541
12,00	16,00	24,00	desc.		
10,00	14,00	22,00	asc.	1,158	2,356
12,00	20,00	24,00	desc.		
10,00	18,00	22,00	asc.	1,149	2,361
12,00	20,00	24,00	desc.		
10,00	18,00	22,00	asc.	1,158	2,708
16,00	20,00	24,00	desc.		
14,00	18,00	22,00	asc.	1,166	2,698
16,00	20,00	24,00	desc.		

From table 2 it can be seen that in block loading if the crack size in which the low-high sequence is applied remains constant, a higher value of ni/Ni occurs in internediate cracks, for the ratio Kmax ol/Kmax ca equal 1,20 and 1,40. When four blocks are applied at crack sizes of 10,00 mm, 12,00 mm, 14,00 mm, 16,00 mm, 18,00 mm, 20,00 mm, 22,00 mm, 24,00 mm, Σni/Ni for Kmax ol/Kmax ca equal 1,20 and 1,40 are 1,223 and 3,141, respectively. The following expression represents the number of delay cycles as a function of Kmax ol/ Kmax ca:

$$ND = 553{,}8 \left(\frac{\text{Kmax ol}}{\text{Kmax ca}}\right)^{11{,}9} \tag{1}$$

So, in variable amplitude loading in which blocks are applied($ni < Ni$) during the crack propagation the total damage can be obtained on the basis of the proposed equation:

$$DT = \sum_{i=1}^{n} \frac{ni}{Ni} = 1 + D_D \tag{2}$$

Where D_D is the damage caused by the number of cycles of retardation, resulting from a descendent sequence loading. Table 3 shows the total damage experimental values and the results given by the proposed equation, for one, two, three and four blocks loading.

TABLE 3. Total Damage

BLOCKS				TOTAL DAMAGE	
				(5000 ± 2500)N → (6500 ± 2500)N	
				Experimental	Model
	10,00		asc.	1,057	1,050
	12,00		desc.		
10,00			14,00 asc.	1,129	1,101
12,00			16,00 desc.		
10,00	14,00		18,00 asc.	1,185	1,151
12,00	16,00		20,00 desc.		
10,00	14,00	18,00	22,00 asc.	1,223	1,202
12,00	16,00	20,00	24,00 desc.		

BLOCKS				TOTAL DAMAGE	
				(5000 ± 2500)N → (8000 ± 2500)N	
				Experimental	Model
	10,00		asc.	1,443	1,316
	12,00		desc.		
10,00			14,00 asc.	2,223	1,632
12,00			16,00 desc.		
10,00	14,00		18,00 asc.	2,822	1,949
12,00	16,00		20,00 desc.		
10,00	14,00	18,00	22,00 asc.	3,141	2,265
12,00	16,00	20,00	24,00 desc.		

CONCLUSIONS

1. In variable amplitude loading, interaction effects are responsible for differences in the fatigue crack growth, compared with constant amplitude loading.
2. 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.
3. Higher values of ni/Ni are obtained for intermediate cracks, when the low-high sequence remains constant.
4. It is possible to determine better values for the total damage , when the damage related to the number of retardation cycles is obtained.

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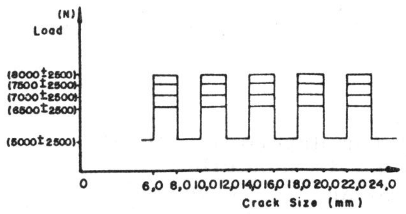

Figure I. Experimental program

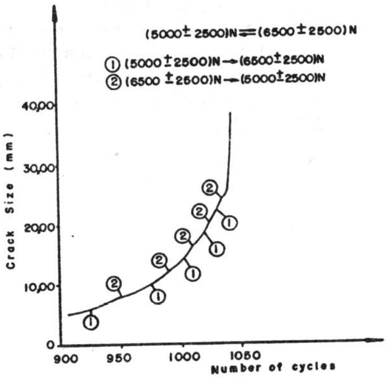

Figure 2. High-low sequence loading

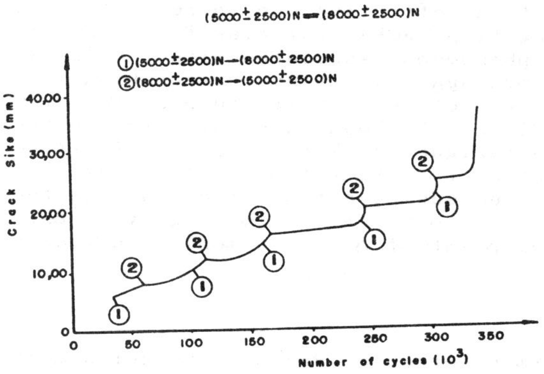

Figure 3. High-low sequence loading