MICRO-FRACTURE MECHANICS BASED MODELLING OF FATIGUE CRACK GROWTH IN ALUMINIUM ALLOY AL7010-T7451 UNDER RANDOM LOADING

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Fatigue studies have been carried out on an aluminium 7010-T7451 alloy, under constant-amplitude and random loading conditions, using cylindrical plain hour-glass specimens. A modified Navarro-de los Rios crack growth model, which is capable of incorporating the mean stress effects on crack growth, was used to predict crack growth rates and fatigue life under random loading incorporating the root mean square (RMS) concept. This relatively simple approach predicted crack growth rates and lifetimes comparable to experimental results and implies that fatigue life under random loading can be predicted from constant amplitude experimental data, simply with the use of the RMS concept together with a pertinent crack growth law.

INTRODUCTION

Service loads on most fatigue-critical structures are usually of a random nature. Thus it is of great importance to understand the failure mechanism of random loading fatigue and to have a method for estimating crack growth and fatigue lifetime under random loading. An added complexity in random loading fatigue is that experimental data produced from constant-amplitude tests cannot be directly used for cases under random loading because of load interaction effects. Indeed it is a challenge for both engineers and scientists to extrapolate the scientific principles developed for constant-amplitude fatigue to variable amplitude cases.

A vital issue in random loading fatigue is to understand and quantify the effects of load interaction on crack initiation and growth. Methods such as the Palmgren-Miner (**1-2**) which neglect load interactions have been widely criticized and deemed unrealistic Hashin and Laird (**3**). To overcome this limitation, three models have been proposed: the crack closure model by Elber (**4**), the plastic zone model by Willenborg (**5**) and the crack tip residual stress model by Wheeler (**6**), and they have been widely used in practice.

The majority of the studies on random loading fatigue concentrated primarily on long crack propagation, neglecting the stage of crack initiation and subsequent short crack growth. However, it is well known that the earlier stage of crack initiation and propagation may constitute a large proportion of fatigue life depending on the stress level used. Furthermore the load interactions in the short crack region may differ substantially from

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those displayed by long cracks Jono and Sugeta (7). It is the objective of this research to examine fatigue damage under random loading in both short and long fatigue crack propagation regimes, and to develop a method of predicting lifetime based on constant-amplitude data.

EXPERIMENTAL PROCEDURE

The material tested was Al7010-T7451. Its nominal chemical composition, by % wt, was: Zn 5.93, Mg 2.17, Cu 1.62, Fe 0.045, Si 0.048, Cr 0.000, Zr 0.11, Ti 0.037, Mn 0.003, Ni 0.000, remainder Al. The mechanical properties of this material were as follows: 2% proof stress 423 MPa, tensile strength 493 MPa, elongation 8.8%, and Young's modulus 71.5 GPa.

Fatigue tests were carried out at room temperature in laboratory air. The uniaxial tests were performed using hourglass shaped specimens. All the specimens were mechanically polished to a 1μm finish. Acetate replicas of the surface were taken frequently for every specimen in all the experiments. Total surface crack lengths were measured from the replicas using an image analysis system.

Two types of experiments were performed:

1) Constant-amplitude testing: constant amplitude tests at R of 0.1 to obtain the material parameters required for modelling.

2) Random testing: four types of different load spectra were used for testing (**Fig.1**). Type A is a home designed spectrum, type B and C originated from ASTM round-robin tests Chang (**8**), representing respectively Air-to-Air mission and Air-to-Ground mission, and type D was extracted from data supplied by British Aerospace. Two different stress levels in type A, four in type B, three in type C and two in type D were used in the tests. These blocks of random spectra were repeated until failure.

EXPERIMENTAL RESULTS

The experimental results of fatigue life for each test are shown in **Table 1**. Typical crack growth data under random loading are presented in **Fig. 2**, displaying the relationship between crack length and number of cycles. The plots of crack growth rate versus half crack length for major cracks in the FL1 group of tests are shown in **Fig. 3** illustrating the typical crack growth behaviour observed associated with short and long crack.

No obvious retardations or accelerations of crack growth rate were observed (see **Fig. 2**), which is possibly due to (i) the limited resolution of the optical technique used for short crack length measurement, and (ii) to the nature of random loading, which in fact balance the effects of accelerations and retardations.

A point of interest is that the lifetime of group FL1 tests bear not direct relationship to the stress level, for example, the lifetime of test FL1-2 was lower than those of FL1-1 and FL1-4, although the latter were subjected to higher nominal stresses (see **Table 1** and **Fig.1 (b)**). This implies that the effective driving force for crack growth is affected by the applied load, load interaction effects and the effect of microstructure; none of them individually can account for the complicated crack growth mechanism observed.

TABLE 1 - Experimental results and model predictions of fatigue life for random loading conditions

Specimen No.	Experiments	Predictions	
	$N_{f,T}$	$N_{f,P2}$	$N_{f,P2}/N_{f,T}$
CA1 (135MPa)*	10000000	10000000	
CA2 (144MPa)	683900	846978	1.24
CA3 (335MPa)	21086	23683	1.12
CA4 (224MPa)	95830	113822	1.18
CA5 (183MPa)	165320	164273	0.99
CA6 (158MPa)	303770	322208	1.06
CA7 (277MPa)	49896	42606	0.86
RANDOM1	89865	113784	1.27
RANDOM2	404252	292603	0.73
FL1-1	292370	280795	0.96
FL1-2	262434	375758	1.43
FL1-3	390462	536716	1.37
FL1-4	283649	195583	0.69
FL2-1	214144	185471	0.87
FL2-2	417290	256332	0.61
FL2-3	579250	510669	0.88
AERO1	595438	518244	0.87
AERO2	989828	>10000000	

* the number in brackets is stress range at constant amplitude tests at a load ratio of 0.1

MICRO-FRACTURE MECHANICS BASED FATIGUE CRACK GROWTH MODEL

Of several models developed for short crack growth, the N-R model Navarro and de los Rios(**9**), is used here for modelling random loading crack growth, particularly because this model describes both short and long crack growth, incorporating also the effect of microstructure.

Details of the development of the N-R model were given in (**9**). Crack growth rate is proportional to crack tip opening displacement through a Paris type relationship.

$$\frac{da}{dN} = \alpha \left\{ \frac{2(1-\upsilon)}{\pi G} \sigma_f c_i \left[n_i \ln\left(\frac{1}{n_i}\right) + \sqrt{1-n_i^2}\left(\frac{\pi}{2}\frac{\sigma}{\sigma_f} - \cos^{-1} n_i\right)\right]\right\}^b \tag{1}$$

where α is a coefficient which depends on the applied stress level and b is a constant. They are obtained by relating the experimental fatigue life under constant-amplitude loading to the calculated crack tip opening displacement (in this study, α=0.0073, b=1.25).

This crack growth model was extended by Wei & Rios (**10**) to incorporate the effects of mean stress through the load ratio term R. Thus giving:

$$\frac{da}{dN} = \alpha \left(\frac{1+R}{1-R}\right) \left\{ \frac{4(1-\upsilon)}{\pi G} \sigma_f c_i \left[n_i \ln\left(\frac{1}{n_i}\right) + \sqrt{1-n_i^2}\left(\frac{\pi}{2}\frac{\sigma}{\sigma_f} - \cos^{-1} n_i\right)\right]\right\}^b \tag{2}$$

THE RMS METHOD AND RANDOM LOADING FATIGUE

Barsom (**11**) and Husdon (**12**) demonstrated that fatigue-crack growth data from random loading tests can be correlated with data from constant-amplitude loading tests. The essence of this approach is to reconstruct an equivalent constant-amplitude load for the complex random load histories in terms of Equations 3-5. These are:

$$S_{max,rms} = \left[\frac{1}{M}\sum_{i=1}^{m}(S_{max})^2\right]^{1/2} \quad (3) \qquad S_{min,rms} = \left[\frac{1}{M}\sum_{i=1}^{m}(S_{min})^2\right]^{1/2} \quad (4) \qquad R_{rms} = \frac{S_{min,rms}}{S_{max,rms}} \quad (5)$$

An obvious advantage of this RMS method is its simplicity since it dispenses the use of highly complicated cycle counting techniques for obtaining equivalent load-time histories from random load spectra. It should be noted, however, that the cases investigated by Barsom and Hudson were only for long cracks, and to the authors' knowledge no attempts have been made to apply the concept to short cracks. The application of the RMS concept to short cracks requires a micro-mechanics model which is able to describe short crack growth behaviour under constant-amplitude loading with various mean stress levels. The modified N-R model (**10**), incorporating mean stress levels as described by Equation 2, provides a possibility for the extension of the RMS concept to short cracks.

For the calculation of the RMS, the maximum stress $S_{max,rms}$,, minimum stress $S_{min,rms}$, and load ratio R_{rms} for each random loading test are obtained using Equations 3 to 5, respectively, and are listed in **Table 2**. The N-R model incorporating load ratios (Equation 2), can now readily implement changing S_{max}, S_{min}, and R of constant-amplitude by, respectively, $S_{max,rms}$, $S_{min,rms}$, and R_{rms}.

TABLE 2 - Root-mean-square stresses, stress range and stress ratios for the random loading tests

Specimen No.	$\sigma_{max,\ rms}$	$\sigma_{min,\ rms}$	$\Delta\ \sigma_{rms}$	R
RANDOM1	263.35	98.98	164.37	0.38
RANDOM2	233.56	88.51	145.05	0.38
FL1-1	240.7	95.7	145	0.4
FL1-2	236.1	93.82	142.28	0.4
FL1-3	232.4	92.4	140	0.4
FL1-4	249	99	150	0.4
FL2-1	216.98	60.33	156.66	0.28
FL2-2	207.76	57.76	150	0.28
FL2-3	196.64	54.65	142	0.28
AERO1	238.19	98.19	140	0.41
AERO2	192.49	79.36	113.14	0.41

RESULTS AND DISCUSSION

The predicted fatigue life using the RMS method is presented in **Table 1**, together with experimental results. The calculated crack length increments for some tests are shown in **Fig. 2**. **Table 1** and **Fig. 2** show that random loading fatigue can successfully be simulated by the modified N-R model incorporating the RMS concept, and that conservative estimates of life time were obtained from some of the tests. The unconservative results reflect the limitation of this method to fully consider load interaction effects.

It should be noted (**Table 1**) that this approach cannot predict the lifetime of tests at stress levels below the fatigue limit of the material (135 MPa for Al7010-T7451), as for example in test AERO2. This is due to the limitation of the N-R model which was developed for constant-amplitude loading conditions.

The success in using the RMS concept for short cracks can be ascribed to the true randomness of the load spectra used and to the applicability of the modified N-R model to variable amplitude loading. For non-random loading sequences, where relatively few high-load cycles cause long delays in fatigue crack growth, the RMS approach will probably not be applicable.

CONCLUSIONS

The root-mean-square concept can be applied to random loading fatigue in the short crack region provided it is combined with the modified N-R model which incorporates the mean stress effects, the only exception being when the applied load is below the fatigue limit. Its success is mainly due to the true nature of pure random loads, plus the correct description of crack growth behaviour by the modified N-R model.

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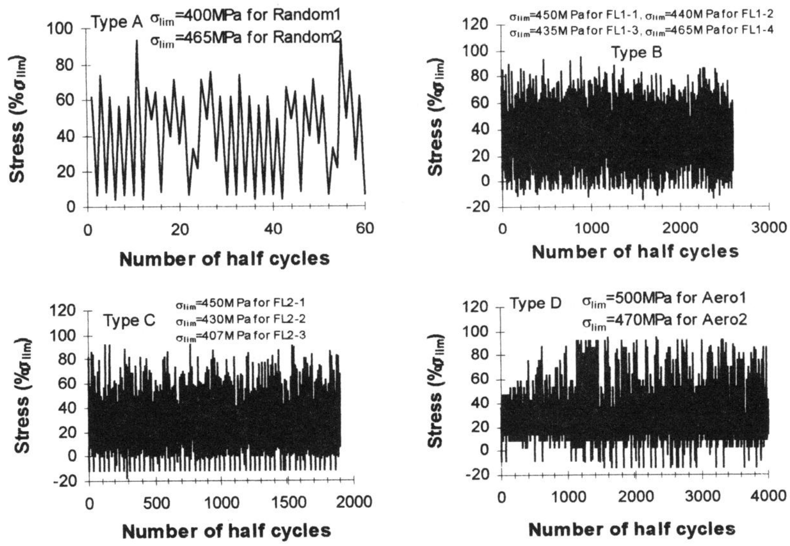

Figure 1 Sample load histories for each test

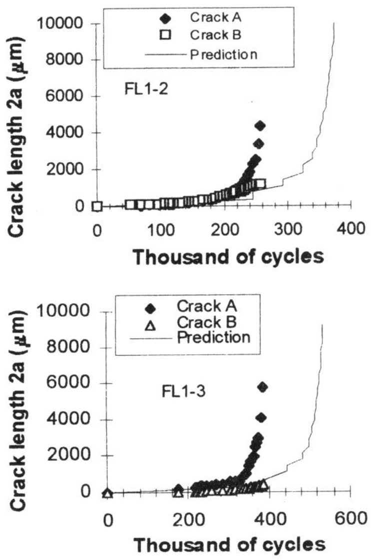

Fig. 2 Experimental and predicted crack growth behaviour

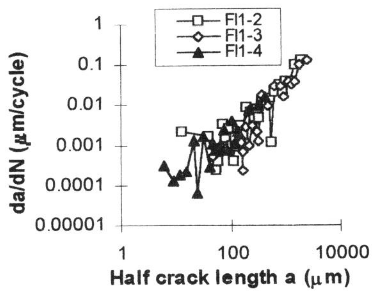

Fig. 3 Experimental crack growth rate for major cracks in tests FL1