FATIGUE CRACK GROWTH PREDICTION IN 7475-T7351 ALUMINIUM ALLOY UNDER RANDOM LOADING USING MODIFIED ROOT MEAN SQUARE MODEL

D.R. Tadjiev and S.T. Kim
Department of Mechanical Engineering, Yeungnam University, 712-749 South Korea

ABSTRACT

This paper presents fatigue crack growth prediction under random loading in specimens of 7475-T7351 high strength aluminium alloy. The modified root-mean-square (RMS) model was used to make predictions. To predict fatigue crack growth under random loading the loading history for each specimen was analyzed to determine the RMS maximum and minimum stresses, and then predictions were made by assuming the tests had been conducted under constant amplitude loading at the RMS maximum and minimum stress levels. The modified RMS model proposed incorporates Paris equation with the RMS stress ratio introduced to account for the effect of mean load on fatigue crack propagation in order to obtain more accurate prediction ratios. The ratio of the predicted life to the test life for specimens tested ranged from 1.56 to 0.54. These ratios are very good considering that the normal scatter in fatigue crack growth rates may range from a factor of 2 to 4.

1 INTRODUCTION

Most crucial structures subjected to fatigue experience random amplitude service loading while in operation. It is of great importance for engineers to estimate the time a fatigue crack will take to grow from initial size to the critical value in designing such structures (e.g. bridges, airplanes etc.) and determining inspection intervals. Estimating the time a fatigue crack will take to grow from initial size to the critical value is called fatigue crack growth prediction. Fatigue crack growth prediction requires thorough understanding of the failure mechanisms associated with random loading fatigue [1, 2]. Usually the fatigue strength of an alloy is measured using constant amplitude tests to determine the strain-life or stress-life curve for the material. However, it has been well documented [2-6, 8] that the experimental fatigue lives for the specimens and components subjected to the random amplitude loading can be well below the fatigue lives predicted using constant amplitude test results. Moreover, it is not possible to predict fatigue crack growth accurately without a thorough knowledge of the load-time history experienced by structure while in operation [2, 4]. Fatigue analyses under random loading are necessary for application of damage tolerance principles to the design of engineering structures and, for the application of damage tolerance concepts it is necessary to make a reliable estimate of the number of load cycles required to propagate the crack from the minimum detectable size to the critical size. In this paper the fatigue crack growth in 7475-7351 aluminium alloy was studied experimentally. The fatigue life predictions were made using the modified RMS model.

2 EXPERIMENTAL PROCEDURE

2.1 Material and specimen's configuration

The material used for this research was 7475-T7351 aluminium alloy which is a controlled toughness alloy developed for applications that require a combination of high strength, superior fracture toughness and resistance to fatigue crack propagation both in air and aggressive environment. The 7475 aluminium alloy is basically a modified version of 7075 alloy. When compared to other structural aluminium alloys, 7475 (under T7351 temper condition) exhibits superior fatigue life [9]. Chemical composition and mechanical properties for 7475-T7351 aluminium alloy are available in the literature [7].

All test specimens used in the experimental study were standard surface crack specimens fabricated from 25.4 mm thick 7475-T7351 aluminium plates in longitudinal transverse (L-T) direction. Figure 1 illustrates the configuration of the specimens. The center notch in the specimens was fabricated using the electrical discharge machining (EDM) process, with the maximum width of the notch less than 0.245 mm.

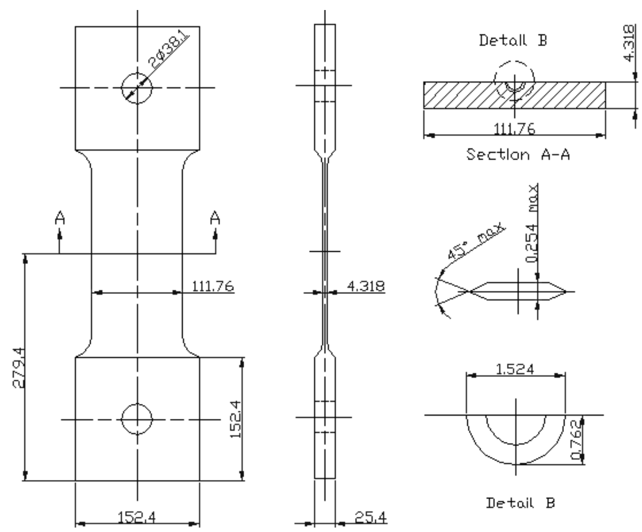

Figure 1: Part-through crack specimen configuration.

The EDM slot in each specimen was precracked to produce a crack approximately 2.54 mm in length including the EDM slot. Precracking was performed under constant amplitude loading cycled at 56 MPa maximum stress, with stress ratio R=0.1. All tests were run at a cyclic rate of 5Hz in ambient laboratory air at room temperature (20-22^{0}C, relative humidity 40-60%). Cyclic crack growth measurements were obtained using traveling microscope and CCD camera.

2.2 Random Fatigue testing

Random fatigue tests were performed using a 100kN Servo-Hydraulic Instron-1332 testing machine in agreement with the ASTM E647 standard. All test specimens were subjected to random loading spectrum presented in Figure 2.

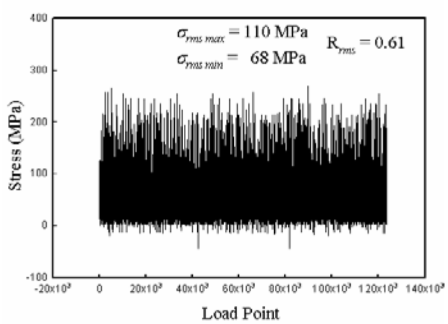

Figure 2: Random loading spectrum.

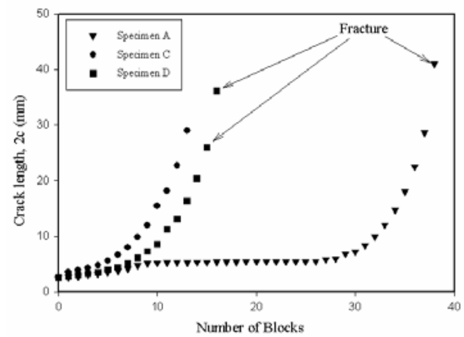

Figure 3: Crack growth – comparison.

3 RESULTS AND DISCUSSION

3.1 Fatigue crack growth under random block loading

In Figure 3 the fatigue crack growth in specimens of 7475-T7351 aluminium alloy under random loading is summarized. Actual (test) lives of specimens A, D and C were 38.02, 16.08 and 13.99 blocks respectively. One block was composed of 123586 load points.

3.2 Prediction procedure

The following relationships were used to calculate the RMS stresses:

$$\sigma_{\max\ rms} = \left[\frac{1}{M} \sum_{i=1}^{m} (\sigma_{\max})^2 \right]^{1/2} \text{ and } \sigma_{\min\ rms} = \left[\frac{1}{M} \sum_{i=1}^{m} (\sigma_{\min})^2 \right]^{1/2} \quad (1)$$

where σ_{max} and σ_{min} are the maximum and minimum stresses derived from data obtained during random fatigue tests respectively, and M is the total number of σ_{max} or σ_{min} values. The RMS stress ratio, R_{rms}, was calculated as:

$$R_{rms} = \frac{\sigma_{\min rms}}{\sigma_{\max rms}} \quad (2)$$

For surface crack specimens we used Newman's stress intensity solution to calculate the RMS stress intensity range:

$$\Delta K_{rms} = (\sigma_{\max rms} - \sigma_{\min rms}) \cdot \sqrt{\frac{\pi a}{Q}} M_e \tag{3}$$

where: a - is initial depth of crack; Q – is elastic shape factor for an elliptical crack:

$$Q = 1 + 1.47\left(\frac{a}{c}\right)^{1.64} \qquad \text{for } a/c \le 1.0 \tag{4}$$

M_e – is elastic magnification factor given by:

$$M_e = \left[M_1 + \left(\sqrt{\frac{Q \cdot c}{a}} - M_1 \right) \left(\frac{a}{t} \right)^p \right] \cdot \left[\sec \frac{\pi \cdot c \cdot a}{Wt} \right]^{1/2} \tag{5}$$

The front-face correction for elastic magnification factor is given by:

$$M_1 = 1.13 - 0.1\left(\frac{a}{c}\right) \qquad \text{for } 0.02 \le a/c \le 1.0 \tag{6}$$

and p is the exponent for elastic magnification factor in eqn. (5) is given by:

$$p = 2 + 8\left(\frac{a}{c}\right)^3 \tag{7}$$

Since the same random fatigue spectrum was used for all three specimens, calculated values of $\sigma_{max\ rms}$, $\sigma_{min\ rms}$ and R_{rms} were the same for all the specimens tested. These values along with the results of calculations are presented in Table 1.

Table 1: The *RMS* stresses and stress ratios for the specimens of 7475-T7351 aluminium alloy analyzed and magnification factors calculated to determine fatigue life

Specimen	$\sigma_{max\ rms}$ MPa	$\sigma_{min\ rms}$ MPa	R_{rms}	a mm	c_i mm	c_f mm	Q	M_1	p	M_e
A	110	68	0.61	0.762	1.275	20.485	1.636	1.07	3.728	1.07
D	110	68	0.61	0.762	1.285	18.065	1.622	1.07	3.659	1.07
C	110	68	0.61	0.762	1.280	14.490	1.625	1.07	3.676	1.07

After all parameters were defined, the fatigue lives of the specimens were predicted by numerically integrating the Paris equation in the modified RMS model from the initial crack length (c_i) to the final crack length (c_f). Taking into account the stress intensity solution used for surface cracks, the Paris equation in the new model has the form:

$$\frac{dc}{dN} = \frac{C}{1-R_{rms}}(\Delta K_{\mathrm{rms}})^m = \frac{C}{1-R_{rms}}((\sigma_{rms\max} - \sigma_{rms\min}) \cdot \sqrt{\frac{\pi a}{Q}} M_e)^m \tag{8}$$

This equation is numerically integrated for N using the following input data:
a) C and m – are the coefficient and exponent, respectively for the Paris equation. From baseline fatigue crack growth rate data for 7475-T7351 aluminium alloy [7] values of $C=8.07\cdot 10^{-8}$ and $m=3.765$ have been chosen.
b) ΔK_{rms} and R_{rms} – the RMS stress intensity range and stress ratio which are calculated by using eqns. (2) and (3) stated above.

The results of the fatigue crack growth prediction analysis using the modified RMS model are presented in Table 2 (N_p - predicted life, N_t – test life).

Table2: Results of the fatigue crack growth prediction analysis

Specimen	N_p	N_t	N_p/N_t	Error bound, %
	cycles			
A	$2.532\cdot 10^6$	$4.699\cdot 10^6$	0.54	46
D	$2.503\cdot 10^6$	$1.980\cdot 10^6$	1.26	26
C	$2.509\cdot 10^6$	$1.600\cdot 10^6$	1.56	56
Average (N_p/N_t) ratio				1.12
Standard deviation				0.42
Coefficient of variance				0.37

3.3 Discussion

The experiments on the 7475-T7351 aluminium alloy were conducted on the specimens with notches, so that the fatigue lives of the specimens were mainly determined by crack propagation rather than by crack initiation process. Fatigue crack growth predictions were made for three specimens subjected to random loading. Predictions obtained by applying the modified RMS model showed quite good agreement with the experimental results. Predicted fatigue lives and the ratios of the predicted lives to the test lives (N_p/N_t) for all of the specimens are presented in Table 2. It may be observed from the calculation results that the predicted fatigue lives in all specimens analyzed was almost the same ($\sim 2.5\cdot 10^6$ cycles). This tendency may be explained by the fact that all specimens had the same configuration and similar a/c ratio (a/c ratio is the main factor which affect stress intensity range in specimens with elliptical and semi-elliptical cracks), and therefore the results obtained are reasonable in the given fatigue life predictions.

4 CONCLUSIONS

The validity of the modified RMS model was confirmed experimentally on the specimens of 7475-T7351 aluminium alloy. Prediction ratios ranged from 1.56 to 0.54. It was determined during the research that the modified RMS model may be successfully used to predict fatigue crack growth in high strength aluminium alloys under random loading. The analysis procedure utilized in this paper is relatively simple and easy to use. As a first step, the loading history for each specimen is analyzed to determine the RMS maximum and minimum stresses. Then the predictions are made by assuming that the tests had been performed under constant amplitude loading at the RMS maximum and minimum stress levels. Finally, Paris equation, where the RMS stress ratio is introduced to account for the effect of mean load on fatigue crack propagation, is used to predict fatigue life of the specimen under random loading.

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