On the Study of The Stress Ratio Effects on Fatigue Crack Propagation Threshold in The Time Domain

J Z ZHANG[+]

[+] School of Mechanical Engineering, Harbin University of Science and Technology, Harbin, China, 150080.

email: jzzhang8888@yahoo.co.uk

Abstract

In-situ SEM observations have revealed that fatigue crack propagation is caused by the shear band decohesion around the crack tip and the formation and cracking of the shear band is mainly caused by the plasticity generated in the loading part of a load cycle. This shear band decohesion process has been observed to occur in a continuous way over the time period during the load cycle. Based on this observation a theoretical analysis has been performed and a model has been set up to consider the effect of the applied stress ratio on fatigue crack propagation threshold. The obtained results have been compared with published test data and good agreement has been achieved. This method is very easy to use and no fatigue crack closure measurement is needed, therefore this model is significant in engineering application.

INTRODUCTION

It is well known that fatigue crack propagation rate and threshold value vary with the applied load ratio or R ratio (= minimum applied load/maximum applied load). In the past, several concepts have been developed to explain the R ratio effects, including fatigue crack closure [1], residual compressive stress [2]. More recently the two parameter ΔK and K_{max} model [3], and the partial fatigue crack closure model [4] have been proposed to explain the effects of R ratio.

Recently in-situ SEM observations have revealed that fatigue crack propagation is caused by the shear band decohesion around the crack tip and the formation and cracking of the shear band is mainly caused by the plasticity generated in the loading part of a load cycle and occur in a continuous way over the time period during the load cycle [5-7]. Based on this observation a framework has been set up in order to analyse fatigue crack propagation [8].

In this study the prediction of fatigue crack propagation threshold based on the above framework and its comparison with experimental obtained data from the literature will be present.

BRIEF SUMMARY OF THE FRAMEWORK

The fundamental aspect of the new methodology is to analyse the fatigue crack propagation process using a new parameter, da/dt [8]. The da/dt defines the fatigue crack propagation rate per moment in the time domain, while the conventional used parameter da/dN defines the fatigue crack propagation rate per stress cycle in the load history. The basic relationship between da/dt and da/dN can be described as:

$$\mathrm{d}a/\mathrm{d}N = \int_{ti}^{tf} (\mathrm{d}a/\mathrm{d}t)\mathrm{d}t = \int_{ti}^{tf} f(t)\mathrm{d}t = F(t_\mathrm{f}) - F(t_\mathrm{i}) \tag{1}$$

where

$$\mathrm{d}a/\mathrm{d}t = f(t) \tag{2}$$

$$F(t) = \int (da/dt)dt \qquad (3)$$

ti denotes the beginning time of the stress cycle and tf denotes the finishing time of the stress cycle. The above equations are valid for an arbitrary fatigue loading spectrum. However, in order to simplify the analysis process, a constant amplitude loading spectrum is assumed in the following analysis. Under constant amplitude loading the equation (1) can be expressed as:

$$da/dN = \int_{ti}^{tf} (da/dt)dt = \int_{t1}^{t2} f(t)dt + \int_{t2}^{t3} f(t)dt \qquad (4)$$

here t1 denotes the beginning time of the stress cycle (minimum applied stress) and t2 denotes the half time of the stress cycle (maximum applied stress) and t3 denotes the finishing time of the stress cycle (minimum applied stress) as shown in figure 1.

For most metallic materials when tested in air condition, the amount of fatigue crack rewelding is small during the unloading part of the fatigue stress cycle, and the fatigue crack propagation mainly occurs during the loading part of the stress cycle [5]. Therefore for simplifying the analysis process, the following relationship is assumed:

$$\int_{t2}^{t3} f(t)dt = 0 \qquad (5)$$

then from equation (4), the following equation is obtained:

$$da/dN = \int_{ti}^{tf} (da/dt)dt = \int_{t1}^{t2} f(t)dt = F(t2) - F(t1) \qquad (6)$$

As seen from figure 1 for every t1<t<t2, there is a unique value of the applied stress S corresponding to it, therefore equation (6) can be written as:

$$da/dN = \int_{ti}^{tf} (da/dt)dt = \int_{t1}^{t2} f(t)dt = F(t2) - F(t1) = G(S_{max}) - G(S_{min}) \qquad (7)$$

here S_{max} is the maximum applied stress value of the stress cycle and S_{min} is the minimum applied stress value of the stress cycle.

A typical function of G=G(S) is shown in figure 2.

Under small scale yielding condition, the stress strain fields around the fatigue crack tip can be uniquely defined by the stress intensity factor, K. This indicates that at any moment of the fatigue crack propagation history the fatigue crack propagation rate per moment, da/dt, can be uniquely decided by the stress intensity factor, K.

However, in order to obtain the fatigue crack propagation rate per stress cycle, da/dN, the initial and final values of the stress intensities are required. Therefore, the equation (7) could be written as:

$$da/dN = \int_{ti}^{tf} (da/dt)dt = \int_{t1}^{t2} f(t)dt = F(t2) - F(t1) = G(S_{max}) - G(S_{min})$$

$$= H(K_{max}) - H(K_{min}) \qquad (8)$$

where K_{max} is the maximum applied stress intensity factor of the stress cycle and K_{min} is the minimum applied stress intensity factor of the stress cycle.

THE BASIC EQUATIONS GOVERNING THE STRESS RATIO EFFECTS

Based on the above frame work, the equations governing the stress ration effect will be set up. Now let us to consider two constant stress spectrums. The first stress spectrum has a maximum applied stress, S_{1max}, and a minimum applied stress, $S_{1min}=0$; the second stress spectrum has a maximum applied stress, S_{2max}, and a minimum applied stress, $S_{2min.}$ The following relationship is assumed:

$$S_{2max} > S_{1max}, S_{2min} > S_{1min}=0 \qquad (9)$$

as shown in figure 3. Assuming the materials's fatigue crack propagation rates under small scale yielding follows the Paris law;

$$da/dN=C(\Delta K)^{m} \qquad (10)$$

here C and m are material constant, then from figure 2 it can be found that for the two stress spectrums in order to reach the same fatigue crack propagation rate, the following relationship should exist:

$$\Delta S_{2}=\Delta S_{1} \times \{(1-R)/[(1-R)^{m}]^{1/m}\} \qquad (11)$$

here $\Delta S_2 = S_{2max} - S_{2min}, \Delta S_1 = S_{1max} - S_{1min}$ \qquad (12)

For most alloys, the value of m falls between 2 and 4.

COMPARISON WITH EXPERIMENTAL RESULTS

Figure 4 shows the comparison between predicted results used equation (11) and the experimental obtained results from [9]. It can be seen that the experimental obtained results falls between the predicted results using m=2 and m=4, and good agreements are obtained.

CONCLUSIONS

An equation has been developed in describing the stress ratio effects on fatigue crack propagation threshold. Good agreement has been obtained between experimental obtained results and the predicted results. Therefore it is verified that the effectiveness of this equation which is based on the new frame work in describing fatigue crack propagation in the time domain.

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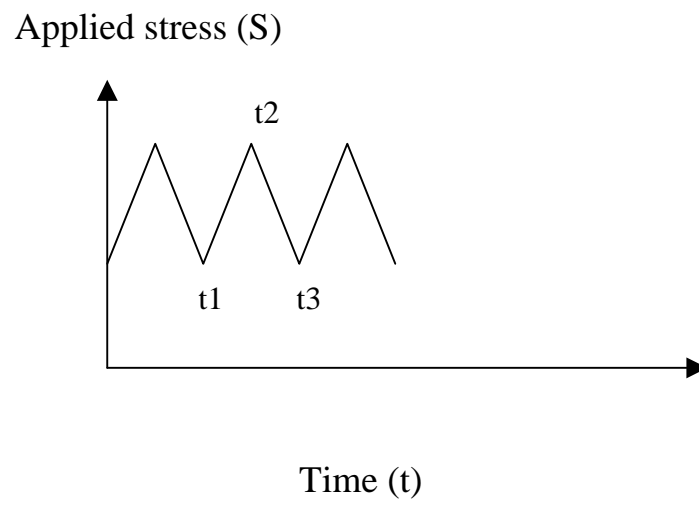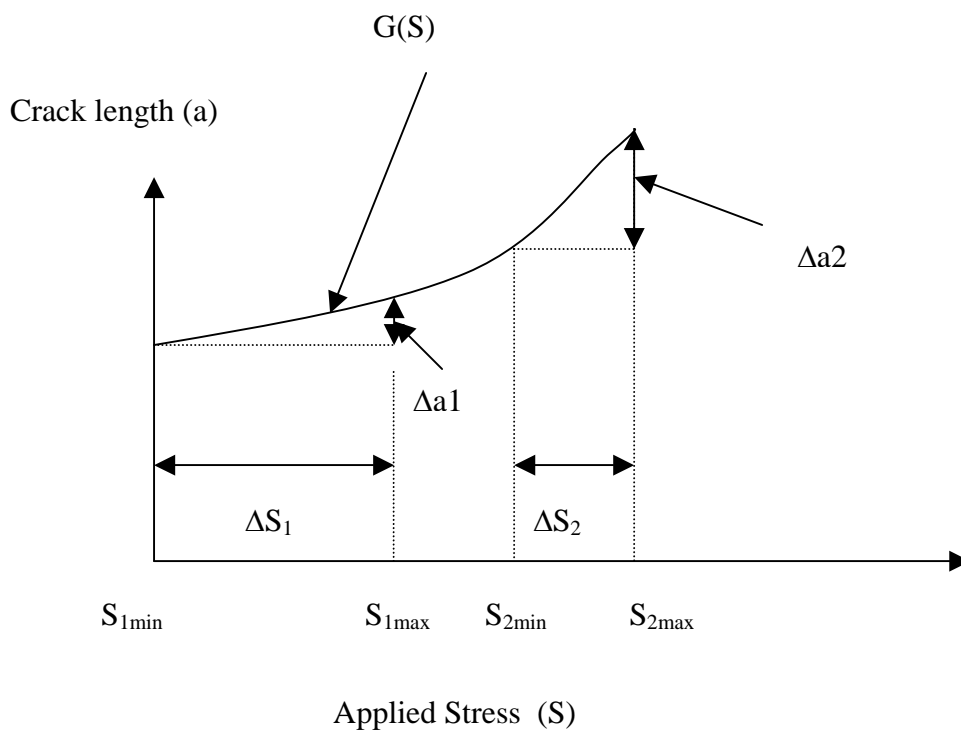9. Paris, P.C, Tada, H., Donald JK, *International Journal of fatigue,* vol. **21***,* S35-46, 1999.

Applied stress (S)

Figure 1 The applied stress in the time domain.

G(S)

Crack length (a)

Δa2

Δa1

ΔS$_1$

ΔS$_2$

S$_{1min}$ S$_{1max}$ S$_{2min}$ S$_{2max}$

Applied Stress (S)

Fig. 2   The Function G=G(S)

Applied stress (S)

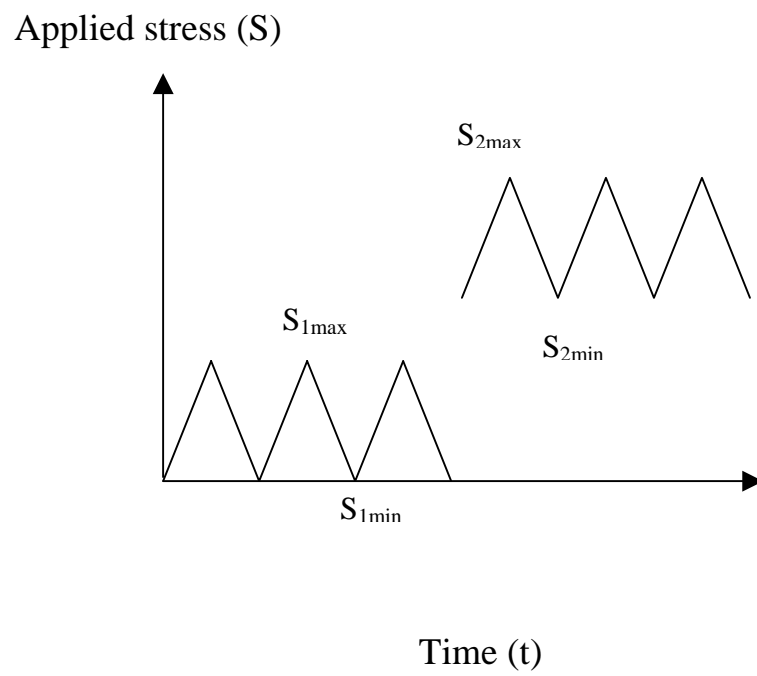S_{2max}

S_{1max}

S_{2min}
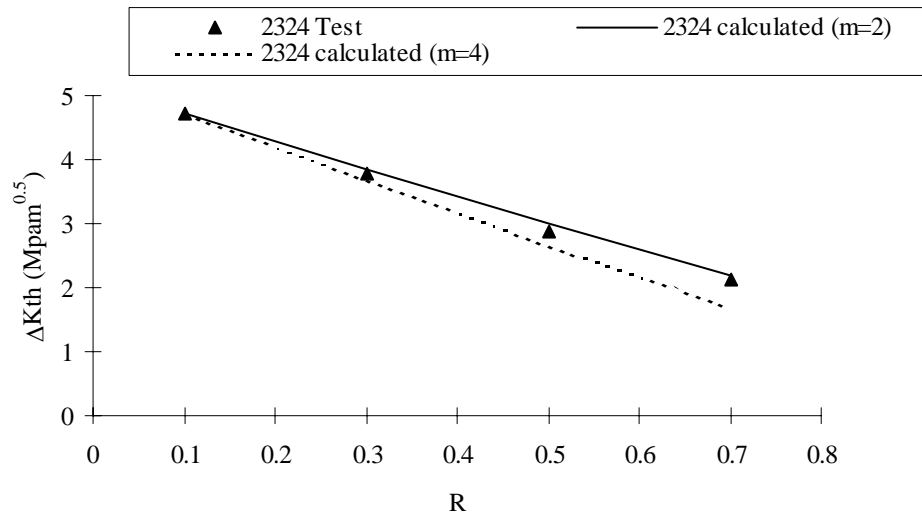
S_{1min}

Time (t)

Figure 3 Stress cycles.

Figure 4 Comparison between predicted threshold values from equation (11) and

the experimental obtained data for 2324 aluminium alloy [9].