A STUDY OF FATIGUE CRACK UNDER BLOCK LOADING SPECTRUM

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The objective of this research is to analyse and predict the fatigue life of fatigue crack subjected to fully reversed loading blocks of the same pattern. On the basis of the constant amplitude crack propagation description, the prediction analysis is proposed in terms of crack tip deformation parameters to calculate the fatigue life during block loading spectrum in conjunction with the experimental results. The behaviour of a fatigue crack initiated at an average depth of 100 μm and 6300 μm electro-discharge machined edge notched in a 0.45% carbon steel specimens is optically studied. The fatigue cracks were measured with a magnification of 1000. The specimens were tested at different block maximum stress levels. The resulting correlation between experimental and calculated fatigue lives are discussed.

INTRODUCTION

Prediction of lifetime of engineering structures subjected to fatigue spectrum loading is an important problem in design against service loading. Simulation methods are widely used for prediction under such loading. Recently, Zapatero et al (1) used a linear elastic fracture mechanics, LEFM, strip-yield model to study the effect of the finite length loading sequences and the effect of overloads into an irregular loading history. Although their predictions were good, they found that the results of each particular simulation may be over or under conservative depending on the maximum peak in the loading history. Marquis (2) used the stress intensity factor range based on LEFM concept to analyse the propagation of short cracks under spectrum loading, where a<1 mm. He concluded that LEFM assumptions would not be valid until a crack depth of nearly 4 mm is obtained.

A linear damage rule would predict no fatigue effect from small cycles as part of a load spectrum. However, Dahle et al (3) concluded that these cycles can produce a significant portion of the fatigue damage when they are part of a spectrum containing large cycles. The linear damage rule is extended to include load sequence effects through a state variable which is interpreted as the crack opening stress. However, opening stresses for

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short fatigue cracks have experimental difficulties to be determined. Holm et al (4) discussed the difference between the cycle counting approach and the level crossing approach from the general fatigue life estimation assumptions. The cycle counting approach assumes that the total damage is independent of the order in which the stress cycles appear. The level crossing approach, however, assumes that the damage is independent of the order in which the stress intervals of arbitrary length appear.

Since crack tip deformation, CTD, is the deriving force for fatigue cracks and the elastic plastic deformation contain all the material memory, a model based on that deformation is aimed. Hammouda et al (5) has developed a model for fatigue cracks based on CTD under constant amplitude loading, CAL, using the finite element analysis. The proposal is to apply such model to block load sequences.

EXPERIMENTAL DETAILS

The 0.45% carbon steel, with the chemical composition (wt%) of 0.45 C, 0.26 Si, 0.43 Mn, 0.025 P, 0.002 S and balance Fe was used. The microstructure of the material was ferrite-pearlite with a ferrite grain size of 36 μm. The material's mechanical properties were obtained from monotonic tensile and ascending stepped cyclic tests, i.e. yield stress 395 MPa, ultimate tensile stress 783 MPa and cyclic yield stress, σ_{yc}, 230 MPa. Flat edge cracked mechanically polished specimens were prepared with the gauge section of 14 mm x 12.7 mm x 2.5 mm. The short and long crack specimens have spark eroded notches with an average depths of 100 μm and 6300 μm, respectively.

The axial fatigue tests were performed using fully reversed loading blocks of the same pattern on a computerized servo-hydraulic closed-loop MTS fatigue machine. Uni-axial fatigue crack growth, FCG, tests with a sinusoidal wave form were carried out up to fracture at a frequency of 8 Hz. Crack extension could be determined with the aid of optical microscope technique consisting of a travelling microscope and a video camera connected to a video monitor with a resulting magnification of 1000. The displays images were used to measure crack length along the width direction of the specimen surface.

Specimens undergo with loading cycles with different amplitude within a loading block having 31 cycles as schematised in figure 1. The varying parameter was the maximum stress of the block and the values of the other amplitude cycles vary in relation to the maximum stress. Three tests were performed under CAL with the amplitudes of 46, 198 and 276 MPa. Specimens were tested under loading blocks with peak stresses ranging from 0.2 to 1.2 of σ_{yc}. The stresses such as 46 and 80.5 MPa were applied on the long crack specimens, and the others were carried out on the short crack specimens.

MODELLING CRACK GROWTH UNDER LOADING SPECTRUM

The model developed by Hammouda et al (5) for mode I FCG under CAL is used to predict the FCG during loading spectrum. The factors controlling CTD were numerically investigated using an elastic-plastic two-dimensional finite element analysis. The model correlates crack tip opening displacements, CTOD, in terms of the extent of the crack tip plastic deformation zone, CTPDZ, the strain field generated within that zone, the specimen width, w, and the crack length, a. The CTOD is the displacement ahead of the crack tip. For a stationary crack the CTOD at maximum load, δ_s/a, could be given as

$$\delta_s/a = 0.0244\,\gamma_s^{0.1177}\,(1 + 2.6(a/\Delta_m)^{0.662}\ (a/w)^{0.073})^{-1.3} \tag{1}$$

where γ_s is the average shear strain within the monotonic CTPDZ, Δ_m. Similarly, the value of cyclic CTOD, $\Delta\delta/a$, for a growing crack was given by

$$\Delta\delta/a = 5.88\,\Delta\gamma_s\,(1 + 2.8(a/\Delta_c)^{0.537}\ (a/w)^{0.12})^{-1.69} \tag{2}$$

where $\Delta\gamma$ is the average shear strain range within the cyclic CTPDZ Δ_c. γ_s, Δ_m, $\Delta\gamma$ and Δ_c are given in reference (5) as a function of stress and stress range, where model was described in details. On the other side, FCG rate was expressed in terms of a CTD parameter, $(\Delta\delta/Y^2)\ (\delta_s/\delta_r)^{0.54}$, as given by Hammouda and Sallam (6). Y is the geometry factor and δ_r is the maximum value of cyclic CTOD which equals to $\Delta\delta$ as cracks considered in the present work had their tips closed at the minimum load.

The crack growth increment per each cycle da in loading spectrum is predicted from an initial crack length by using a crack growth equation $da = A\,((\Delta\delta/Y^2)\ (\delta_s/\delta_r)^{0.54})^B$ and summing the fatigue damage from each equivalent cycle. A and B are material constants and determined via regression analysis of the CAL test results in figure 2 which includes data for short and long cracks. All cycles in the spectrum were included in a computation of da except the cycles which have $(\Delta\delta/Y^2)\ (\delta_s/\delta_r)^{0.54}$ less than the threshold value. The fatigue life is predicted when the calculated crack reaches the specimen's width.

RESULTS AND DISCUSSIONS

Correlation of experimental FCG rates with CTD parameter during CAL is presented in figure 2. The FCG data was processed by an incremental second order polynomial curve fitting technique to fit overlapped sets of five successive data points. Predictions of crack growth curves during loading spectrum are presented in figure 3 and 4 for short and long crack specimens, respectively. The predicted curve fall slightly below the experimental data for 80.5 and 207 MPa tests through 10 to 100 thousands of cycles. However, the predicted lines and experimental symbols are approximately overlapped for more than three decades of number of cycles for most of the tests.

Figure 5 shows a comparison of the predicted lifetime with those experimentally obtained from the same loading histories. The tests with stresses above general yielding have a shorter lifetime than those with stresses below the cyclic yield stress. On the other words, damage accumulates more rapidly the higher the level of loading spectrum. Some results exhibited a high scatter, it may be related to test conditions and material.

The applied model takes into account the effects of the parameters which characterise the CTPDZ, the strain field generated within that zone, the opening and closure of the crack tip and fatigue cracks whatever its length. Moreover, damage accumulation under loading spectrum depends on the order in which the stress cycles appear, since, the crack growth increment per each cycle da in block was determined according to the initial crack length for the first cycle in the spectrum, the summation of da and the cyclic stress through each cycle. Although no microstructure effect is considered here, it becomes less significant as using low cycle fatigue tests. Schijve (7) discussed the problem of multiple-site damage in aircraft structures and drawn an attention that extensive elastic-plastic FE calculation is required. He concluded that failure criterion should preferably be based on local CTD characteristics.

CONCLUSIONS

A CTD model of FCG during CAL was employed to predict crack growth during loading spectrum. Damage accumulation during block loading spectrum depends on the stress level and crack length, where it accumulates more rapidly the higher the level of stress. The results presented here are promising in this regard, since most of the model predictions are close to the experimental results.

SYMBOLS USED

a = crack length (μm or mm)

w = specimen width (mm)

γ = average shear strain

δ = crack tip opening displacement (μm)

Δ = extent of crack tip plastic deformation zone (μm)

σ = stress (MPa)

REFERENCES

(1) Zapatero, J., Moreno, B. and Dominguez, J., Fatigue Fract. Engng. Mater. Struct., Vol. 20., 1997, pp. 759-770.

(2) Marquis, G., Fatigue Fract. Engng. Mater. Struct., Vol. 19., 1996, pp. 739-753.

(3) Dahle, T. and Larsson, B., “Fatigue Design”, Edited by J. Solin et al, ESIS Puplication 16., ESIS and MEP Ltd., London, 1993.

(4) Holm S., Josefson, B., De Mare, J. and Svensson, T., Fatigue Fract. Engng. Mater. Struct., Vol.18., 1995, pp. 1089-1100.

(5) Hammouda, M., El-Sehily, B. and De Los Rios, E., Fatigue Fract. Engng. Mater. Struct., Vol. 19.,1996, pp. 475-484.

(6) Hammouda, M. and Sallam, H., ICF8, Vol. 2., 1993, pp. 3-11.

(7) **Schijve, J., Fatigue Fract. Engng. Mater. Struct. Vol. 18., 1995, pp. 329-344.**

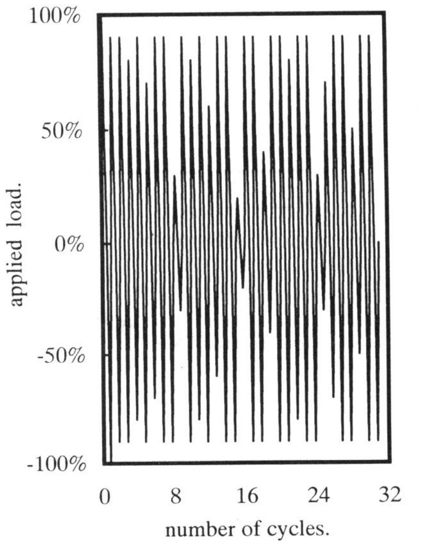

Figure 1 Schematic diagram for loading spectrum

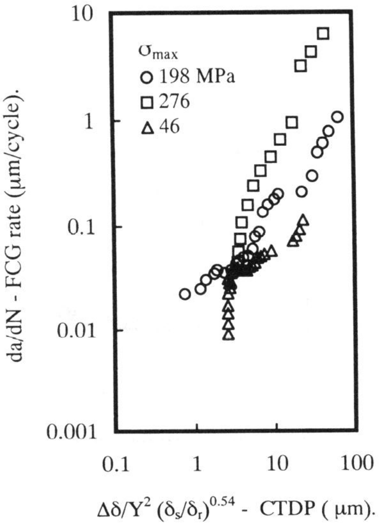

Figure 2 Correlation of experimental FCG rates with CTDP under CAL

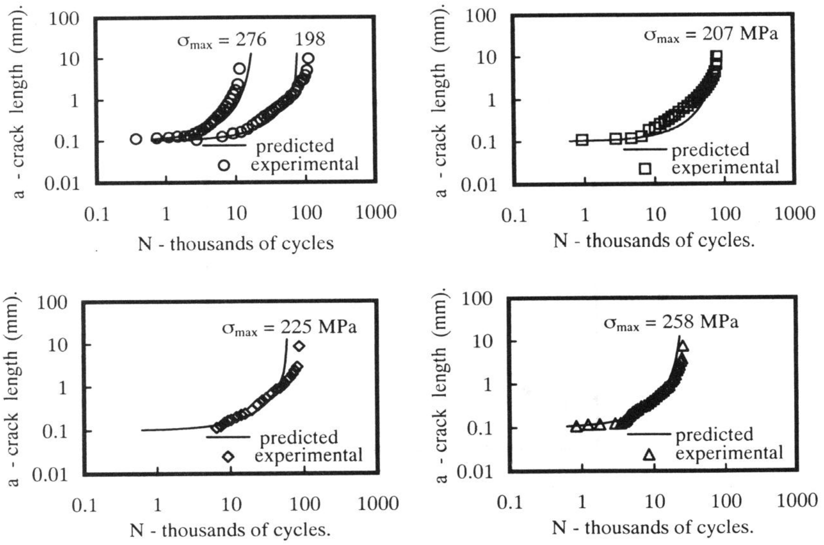

Figure 3 Predictions of short crack growth curves during loading spectrum

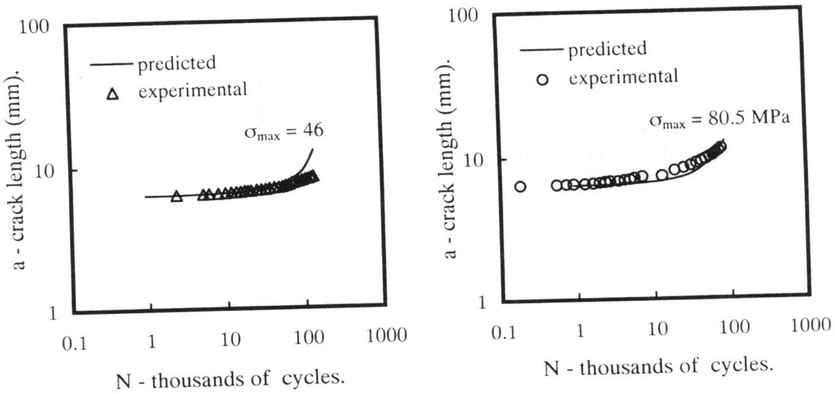

Figure 4 Predictions of long crack growth curves during loading spectrum

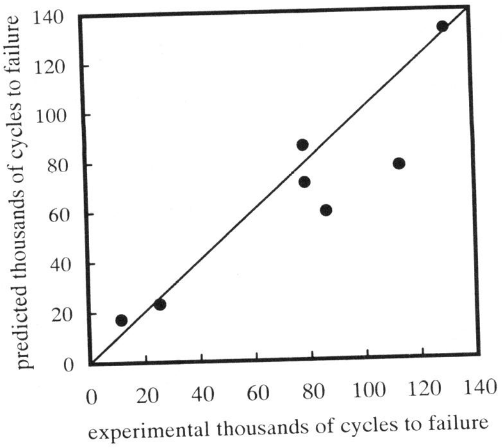

Figure 5 Comparison of experimental and predicted number of cycles to failure under loading spectrum