FATIGUE LIFING METHODOLOGY TO ENHANCE THE STRUCTURAL INTEGRITY OF CRITICAL COMPONENTS IN GAS TURBINE ENGINES.

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In previous papers, techniques similar to Damage Tolerant Design and Data Base Lifing methods were used to predict crack shapes and cyclic lives for a notch specimen. Accurate predictions were obtained provided marked microstructural interactions did not occur and stress levels were such that notch root plasticity was not significant. At higher stresses, inaccuracies were attributed to plasticity induced closure at the notch root, but, measurements to support this supposition were not available. In this work crack closure levels have been evaluated for uniform stress fields and at notches. The results are used to modify the previously developed life prediction model which took no account of crack closure. The modification has significantly improved the prediction of both crack shape and cyclic lives in the notch specimen.

INTRODUCTION

Component lifing techniques are constantly being developed, assessed and improved in order to optimise the often conflicting requirements of safety, reliability and efficiency. Traditionally, initiation or 'life to first crack' failure criteria have been used to establish safe service fatigue lives in gas turbine engines. These approaches have provided a good safety record but their limitations in terms of engine performance are well known: the large safety factors lead to over design which can result in heavier, less efficient engines; predicted lives that are potentially unsafe if defects arise in the components; inefficiency in terms of removal from service of relatively undamaged components which still have a significant residual service life. Recently crack propagation based criteria have been introduced in order to address some of the limitations. Such techniques include, Damage Tolerant design and Data Base lifing methods. Whilst the merits of these fracture mechanics approaches have been demonstrated, the boundaries of their performance envelope have not been clearly defined. The principal objective of this research programme was to explore these boundaries and to provide engineers with a comprehensive design database for an important engineering alloy.

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EXPERIMENTAL PROGRAMME

The near alpha titanium alloy, IMI 829*, was chosen for the study since not only is it an important alloy in engineering terms but it also has a relatively coarse grain size thereby facilitating small crack growth studies and promoting interactions between the crack front and the microstructure. The batch evaluated had a prior beta grain size of 0.5 mm and an alpha colony size of 0.2 mm.

Long crack growth behaviour was studied on 12.5 mm thick Compact Tension specimens (CT). Base line data for small cracks growing in simple stress fields were obtained on plain Corner Crack specimens (CC). The cracks developed from a 0.25 mm deep by 0.1 mm thick slit at one corner of the 10 mm square section.

A specifically designed double edged notch, DEN, specimen, was used as a vehicle for the study of growth behaviour in more complex stress fields and as a pseudo component for life prediction calculations. The test piece has a cross sectional area at the notch root equal in size to the CC specimen. The notch radius, of 3 mm, gave an elastic stress concentration factor, k_t, of 1.9 with respect to the net section. Part through cracks were grown from a slit, similar to the CC specimens and, positioned at one corner of the notch root.

Constant load amplitude tests were carried out at ambient temperature with load ratios, R, between 0.1 and 0.6. A range of stresses was applied using a frequency of 1Hz. Crack growth was monitored by computer controlled optical and potential difference techniques. The potential difference (PD) system used a 30 Amp pulsed DC supply which permitted resolution of crack length to better than 0.01 mm.

Basic fatigue crack growth rates were evaluated from the CT and CC tests using published solutions for stress intensity factors (1). The notch specimen was analysed in detail by means of an in-house developed 3D, elasto-plastic, finite element code. Both uncracked and cracked situations were considered. In the former case, stress and strain distributions along and away from the notch root were obtained. For the latter, J-integral values, and hence stress intensity factors, K, were determined around the crack front (2). Crack growth rates were calculated by means of a three point secant technique and expressed in terms of ΔK to allow direct comparison between the different sets of test data.

During selected tests a single triangular wave of 100 seconds duration was applied at intervals throughout the propagation life. This allowed the PD system to monitor crack closure by recording the voltage across the crack as the load varied. For a small number of tests, acetate sheets were used to replicate the crack at several load levels throughout a loading half-cycle. These were examined by an optical microscope to provide an alternative means of quantifying crack closure loads. Crack shapes were also recorded at the end of the test using a heat tinting technique to mark the fatigue fracture surface. Full experimental details on the closure measurement are documented elsewhere (3).

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* Trade Name: IMI Limited

RESULTS

Characterisation of Behaviour

Long and small crack growth rate data, obtained from CT and CC specimens, are shown in figure 1. There are two clear regimes of behaviour both described by an equation of the form:

$$\frac{da}{dN} = C\Delta K^m \tag{1}$$

Regression analysis (solid lines in figure 1) gave $m = 3.6$ and $C = 1.4 \times 10^{-12}$ (MPa; m units) for small cracks and $m = 6.1$ and $C = 6.6 \times 10^{-16}$ (MPa; m units) for long cracks. The transition occurs at $\Delta K = 23\ \mathrm{MPa}\sqrt{\mathrm{m}}$. Within the general trend for small cracks, local accelerations and decelerations in growth rate were apparent which have been related to microstructural features such as alpha colony and prior beta grain boundaries (4).

The notch specimens were tested at several applied stress ranges. However, for the present publication, the discussion focuses on 350 MPa and 550 MPa. The former is borderline with respect to the development of plasticity, but at 550 MPa the cyclic yield stress is exceeded at the notch root and a plastic enclave develops. The fatigue lives at 350 and 550 MPa are $>10^6$ and 2×10^4 cycles respectively (5).

Notch Prediction

The numerical programme used small and long crack data from the CC and CT specimens to predict not only the cyclic lives of the notched test pieces but also the shape of the cracks that develop. The analysis is based on the work of Pickard (6). It uses numerical integration to relate propagation cycles (ΔN) to increments of crack growth (Δa).

It has been shown previously (5) that there is good correlation between predicted and measured shapes of part through cracks for a stress of 350 MPa, figure 2. The rate of crack growth at the notch root is far higher, as anticipated, giving rise to an essentially elliptical crack shape. In some cases, however, discrepancies were observed. These were due to local arrests of the crack at alpha colony or prior beta grain boundaries. The accuracy of the prediction for 350 MPa is reinforced in figure 3 where measured and calculated crack lengths ‘a’ and ‘b’ are plotted against cycles.

At 550 MPa, plasticity has a significant effect on the prediction. The crack shape comparison is given in figure 4 with the measured data on the right hand side. It is evident that the prediction gives a more elliptical shape than is observed. The predicted lives to a 2.5 mm crack length are also in error being smaller by over a factor of two, figure 5. An obvious observation is that the stress polynomial is based on elastic conditions and is, therefore inappropriate. However, the finite element analysis suggested that modification to the stress function to allow for plasticity is small. Furthermore, a test at 550 MPa but with R=0.6 provided measured crack shapes that were consistent with the predicted ellipses. On this basis, it was concluded that the calculation procedure was inaccurate because of notch root closure.

Crack Closure

Much work using the PD and replica techniques has been carried out to characterise crack closure in the DEN and CC specimens (3). When growth rates are related to an effective stress intensity parameter, $\Delta K_{eff} = (K_{max} - K_{op})$, anomalies between a range of R values, long and small crack growth data and geometry differences are reduced or eliminated. The replica technique provided visual confirmation of the validity of the PD measurements.

For the essentially quarter circular cracks in the CC geometry the PD system was sensitive to closure for a large range of crack lengths. Figure 6, illustrates the typical variation per cycle between crack voltage and applied load in the presence of crack closure. The linear fit to the early part of the curve illustrates the technique for evaluating the opening load. Crack opening loads were normalised with respect to the peak load to give P_{op}/P_{max}. In the case of the CC specimen, this ratio was approximately 0.22 for the range of crack lengths studied.

In the case of the DEN, a P_{op}/P_{max} value of about 0.4 was observed at 550 MPa. This remained constant for the range of crack lengths studied. However, work on a 2mm thick version of the DEN with a through thickness crack uncovered some additional characteristics (3). The P_{op}/P_{max} ratio was found to be about 0.4, at small crack lengths up to approximately 0.75mm but then to fall to a new constant value of 0.22 at lengths in excess of 2 mm. This reduction in closure level was attributed to the diminishing influence of the notch and the associated plasticity induced closure.

The PD system responds to crack closure at any position along the crack front. It does not discriminate between the outside surface and interior, or between the notch root and the side face in the thick DEN. It was assumed that the P_{op}/P_{max} of 0.4 in the DEN related to the position of maximum closure at the notch root. It was further assumed that closure down the side face away from the notch root decayed in a similar way to the thin DEN. On this basis, P_{op}/P_{max} was taken to be 0.4 for all crack lengths along the notch root and for side face cracks up to 0.75 mm. At this point, the side face crack has grown out of the influence of the notch root plastic zone. Beyond a length of 2 mm, side face P_{op}/P_{max} can be assumed to be 0.22. In between, the thin DEN measurements suggest a linear fall off. The numerical package was modified to account for these closure loads. The crack growth behaviour of CC and CT specimens was re-expressed in terms of ΔK_{eff} to be consistent with the modified closure analysis of the DEN.

The results of the closure corrected calculation of crack growth in the DEN at 550 MPa are presented in figures 7 and 8. Predicted and measured crack shapes are compared in figure 7. By comparing this with figure 4, it can be seen that the degree of agreement between predicted and measured shapes has been much improved. Similarly, there is a much closer correlation between predicted and measured propagation lives when closure is taken into consideration, figures 5 and 8.

DISCUSSION

The research programme has focused on fracture mechanics techniques used in component life prediction schemes such as Damage Tolerance and Data Base Lifing. In particular it has highlighted the impact of plasticity on the accuracy of the calculation method, through an evaluation of notch effects over a range of stress conditions.

It has been demonstrated, that the prediction of crack shape and of life to a specific crack size is excellent for low levels of stress (350 MPa) where notch root plasticity is limited and closure is dominated by crack tip effects. It is sufficient under these conditions to use uncorrected growth rate data from simple laboratory specimens and a stress analysis based solely on the full applied load range.

At higher stress levels (550 MPa) notch root plasticity gives rise to markedly different crack closure behaviour. There is now a significant difference between the simple and complex stress fields. These differences are such that crack closure must be taken into consideration in the numerical model. This has been achieved through the application of experimentally measured closure values from part through cracks in thick DEN specimens and from through cracks in thin DEN specimens. The resultant model, although at an early stage, has reduced the differences between predicted and measured crack shapes and improved predicted lives to given crack lengths.

It must be recognised, however that crack closure is a 3D problem and that the PD system gives a global view of the phenomenon. The replica technique is more limited from an experimental point of view but does provide valuable information on surface effects and as such has helped to interpret the PD measurements. Through this interpretation, it has been possible to derive a viable picture of closure for the plain side surface and notch root of the DEN specimen. However, it has not been possible to quantify closure effects in the interior of the specimen. The present analysis, therefore, is surface dominated and the small inaccuracies that are still apparent may be due to this lack of understanding. Clearly an appreciation of full 3D closure is essential for the further development of component lifing. This is currently being addressed through an amalgamation of more detailed experimental measurements and 3D finite element modelling.

CONCLUSIONS

Fracture mechanics based lifing techniques have been evaluated using small and long fatigue crack data from CC and CT specimens to predict crack development in a DEN testpiece. The following conclusions can be drawn:

i) At a stress level where significant notch root plasticity does not occur (fatigue lives of ~ 10^6 cycles), both the shape of the crack front, and the number of cycles to specific crack lengths along the notch root and down the sideface can be predicted from the basic growth rates without any consideration of closure effects.

ii) At a stress level where there is general yield within the notch root (fatigue lives of 2 x 10^4 cycles), the simple analysis breaks down. An approach which allows for plasticity induced closure at the notch root greatly enhances the prediction of crack shape and of the number of cycles to specific crack lengths.

iii) Closure characterisation of the part through cracks using a PD monitoring system, suggests $P_{op}/P_{max} \cong 0.22$ for uniformly stressed CC specimens. In the DEN specimen it is found that at 550 MPa ($N_f = 2 \times 10^4$ cycles), $P_{op}/P_{max} \cong 0.4$ in the notch root but progressively decreasing along the side face to the CC value at a crack length of 2 mm.

SYMBOLS USED

a = crack length along the notch root (mm)

b = crack length away from the notch (mm)

P_{op}/P_{max} = crack opening load/maximum load

REFERENCES

(1) Mom, A.J.A., "Revised Working Document for the AGARD Cooperative Test Programme on Titanium Alloy Engine Disc Material", (Report NLR TR 86019 L, 1986).

(2) Spence, S.H., Evans, W.J. and Nicholas P.J., "The Growth of Microstructurally Small Cracks in a Near Alpha Titanium Alloy", Joint FEFG/ICF International Conference on Fatigue of Engineering Materials and Structures, Singapore, 1991, pp 673-669.

(3) Evans, W.J. and Goulding, A. "Closure Measurements of Part Through Cracks", to be published.

(4) Evans, W.J. and Spence, S.H., "Modelling Fatigue Crack Growth at Notches", Conference on "Processing, Properties and Applications of Metallic and Ceramic Materials" edited by H.M. Loretto and C.J. Beevers, 935-944, 1992.

(5) Evans, W.J. and Spence, S.H., "Life Prediction Modelling For Titanium Alloys", Conference on "Theoretical Concepts and Numerical Analysis of Fatigue" edited by A.F. Blom and C.J. Beavers, pp 377-400, 1992.

(6) Pickard, A.C., "The Application of 3-Dimensional Finite Element Methods to Fracture Mechanics and Fatigue life Prediction", Ch. 4, EMAS, Cradley Heath, Warley, West Mids, U.K., 1986.

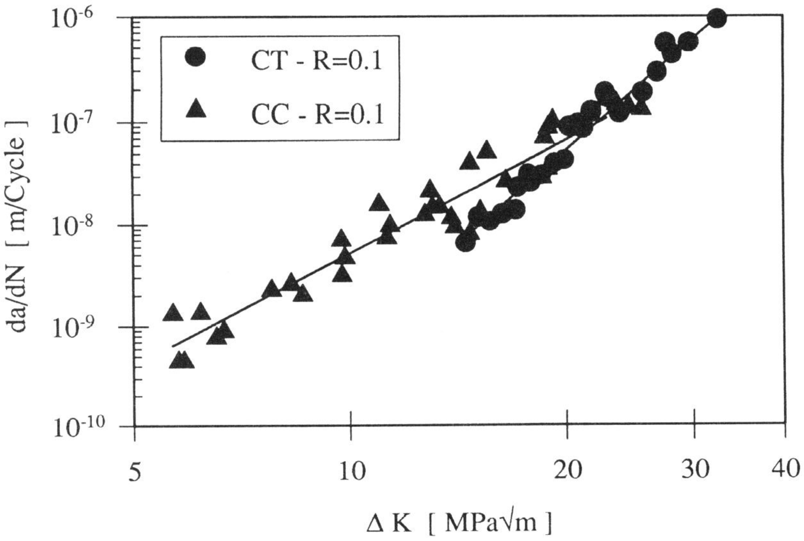

Fig. 1. Small and Long Crack Growth Behaviour

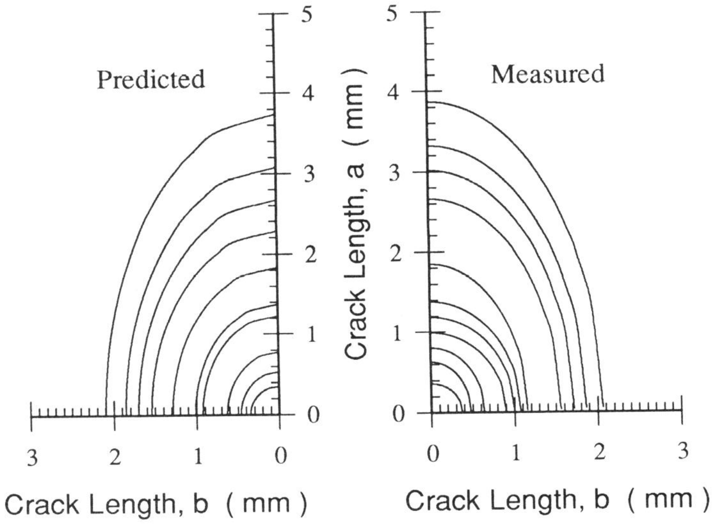

Fig. 2. Predicted and Measured Crack Shapes at 350 MPa
(no closure correction)

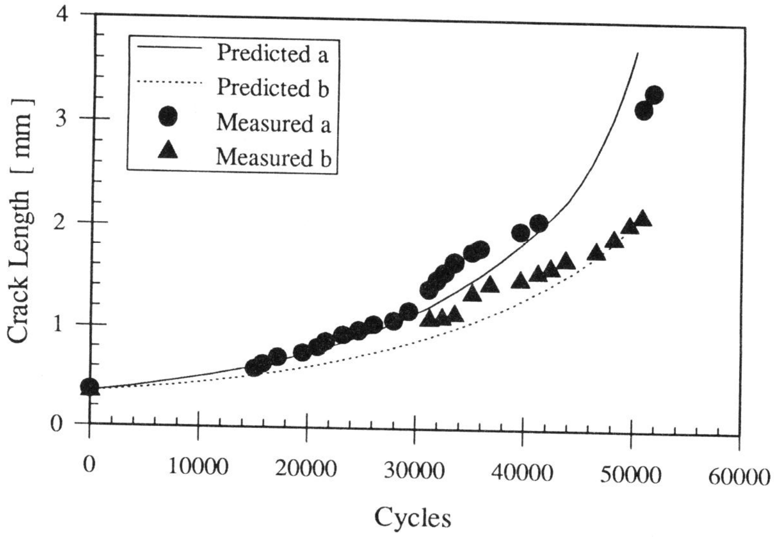

Fig. 3. Predicted and Measured Crack Growth Curves at 350 MPa (no closure correction)

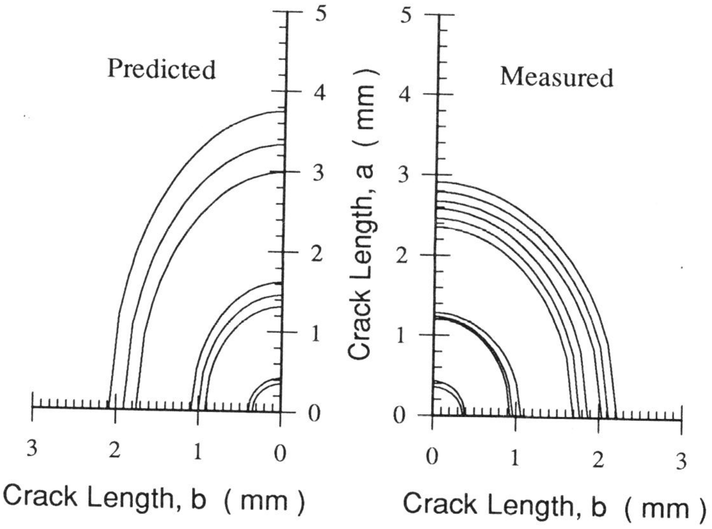

Fig. 4. Predicted and Measured Crack Shapes at 550 MPa (no closure correction)

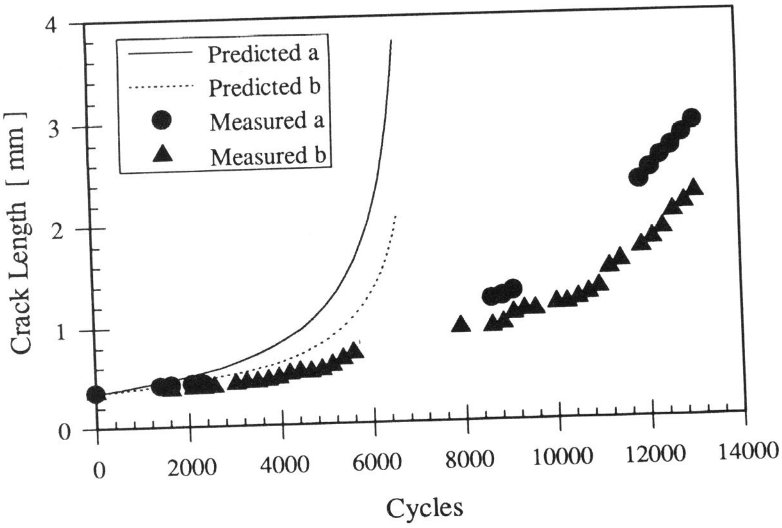

Fig. 5. Predicted and Measured Crack Growth Curves at 550 MPa
(no closure correction)

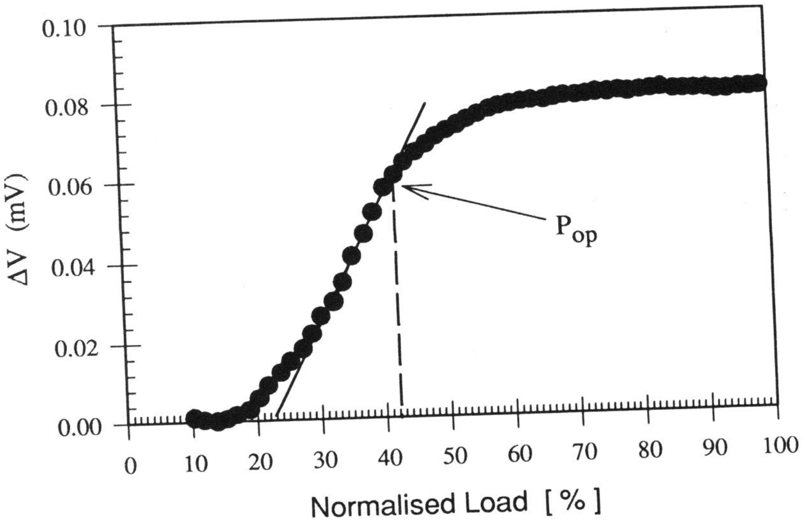

Fig. 6. Variation of PD Signal Throughout a Cycle
Illustrating Crack Opening Load

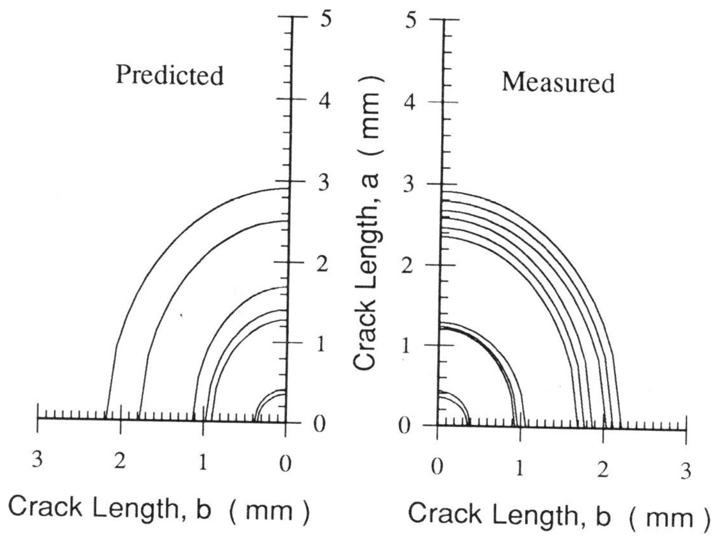

Fig. 7. Predicted and Measured Crack Shapes at 550 MPa
(closure corrected)

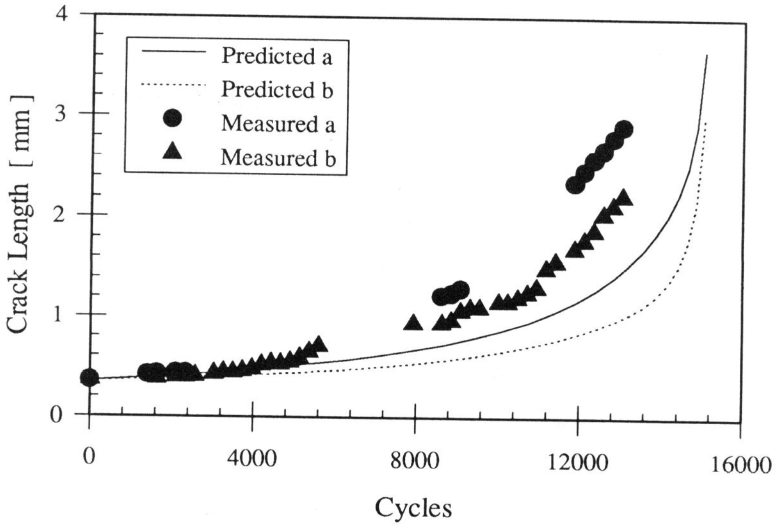

Fig. 8. Predicted and Measured Crack Growth Curves at 550 MPa
(closure corrected)