**PREDICTION OF FATIGUE INTERACTION FROM STATIC CREEP AND HIGH FREQUENCY FATIGUE CRACK GROWTH DATA**

K. NIKBIN, J. RADON
Department of Mechanical Engineering, Imperial College, London, SW7 2BX.

## ABSTRACT

Many engineering components operating at elevated temperatures are subjected to combined steady and cyclic loading which can give rise to creep, fatigue and combined creep/fatigue failure. In many cases only static creep and high frequency data is available. In this paper the relationship between crack growth rates under static load and cracking rate under slow cyclic rates ( <0.1Hz) has been examined. Crack growth behaviour at elevated temperatures under combinations of creep, creep fatigue and fatigue are investigated for an aluminium alloy RR58 tested at 150 °C and an 11Cr Martensitic steel FV448 tested at 550 °C. Attention is focused on the intermediate (steady state ) region of cracking. It is shown that for static and low frequency tests (<0.1Hz) good correlation are obtained in general for crack growth rate versus the C* line integral. At high frequencies where transgranular fatigue processes control, it is demonstrated that the crack growth per cycle can be described by the Paris Law. At intermediate frequencies correlation can be obtained using static creep and pure fatigue data if a linear cumulative damage law is assumed.

## KEYWORDS

Creep, fatigue, crack growth, steel, aluminium

## INTRODUCTION

Considerable economic savings are possible if the useful lives of engineering components can be prolonged and the period between maintenance inspection extended. The need for determining tolerable defect sizes is becoming more important as the sensitivity of non-destructive evaluation equipment improves. Smaller and smaller cracks are being detected and the question of whether a cracked component can be returned to service, or must be replaced, is being encountered more frequently in, for example, the electric power generation, chemical process, and aircraft industries. Most components in these industries which operate at high temperatures are subjected to non-steady loading during service. Creep, fatigue, thermal fatigue and environmental processes may contribute to the failure of such a component (SOLOMON, H. D. and COFFIN, L. F. Jr. [1973], SAXENA, A. and BASSANI, J. L. [1984] ). The dominant mode of failure in a particular case will depend upon such factors as material composition, heat treatment, cyclic to mean load ratio, frequency, temperature and operating environment.

Design against service failure and residual life assessments of engineering components operating at elevated temperatures requires a knowledge of crack propagation rates under creep, fatigue and combined creep/fatigue loading. Crack propagation behaviour at elevated temperatures under these combinations of loading are investigated. The main concern of this paper is with the behaviour of components which may contain cracks. Attention is focused on the steady state region of cracking. The processes which contribute to a crack-tip controlled failure depend on two different modes of failure. Where creep dominates time-dependent intergranular failure occurs and where fatigue dominates crack growth is linked a transgranular time independent mode of failure. Laboratory tests can be performed over a wide range of frequencies in order to predict the creep/fatigue frequency interaction range. However historical crack growth tests do not invariably have data under a full range of frequencies and generally tend to have high frequency fatigue data and static creep data. A simple method is shown in order to make use of such data to predict creep fatigue interaction.

## FATIGUE AND CREEP CRACK GROWTH MODELS

Typically at room temperature a cracked test-piece under cyclic loading conditions and in the absence of any environmental complications, crack growth is governed by fatigue processes. The mode of fracture is normally transgranular and crack growth per cycle (da/dN), where a and N are crack length and number of cycles respectively, can be obtained in terms of stress intensity factor range ($\Delta K$) by the Paris Law ( PARIS, P. C. and ERDOCAN, F. [1963])

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

where m and C are material constants with $2 < m < 5$ for most engineering materials. The factor C is sensitive to the minimum to maximum load ratio R (SCHIJVE, J. [1979]). At elevated temperatures, with cyclic loading, both time dependent and cyclic dependent crack growth can be observed. The time dependent cracking can be governed by environmental or creep processes. Generally, when time dependent mechanisms control, fractures are intergranular and when cycle dependent fatigue processes dominate they are transgranular. When fatigue mechanisms control, as at room temperature, cracking rate can usually be described in terms of the Paris Law but when creep mechanisms dominate, it is more appropriate to use non-linear fracture mechanics concepts and express cracking rate $\mathring{a}$ as a function of the creep fracture mechanics parameter $C^*$ as:

$$\mathring{a} = D\,C^{*\phi} \tag{2}$$

where D and $\phi$ are material constants which can be measured experimentally or determined from models of the cracking mechanism. However, $\phi$ is a number slightly less than unity and D is determined chiefly by the material creep ductility and the constraint local to the crack tip (NIKBIN, K.M., et. al [1983]). An increase in crack growth rate is obtained with an increase in the degree of constraint and with a decrease in ductility. In the models of Nikbin, Smith and Webster (NSW), (NIKBIN, K.M, et. al. [1986]) a process zone is postulated at the crack tip. It is supposed that the zone encompasses the region over which creep damage accumulates locally at the crack tip and that crack advance takes place when the creep ductility $\varepsilon^*_f$ appropriate to the state of stress at the crack tip is exhausted there. Equation (2) can therefore be simplified to

$$\mathring{a} = (300/\,\varepsilon^*_f\,)\,C^{*0.85} \tag{3}$$

where $\mathring{a}$ is in mm/hr, $C^*$ in MJ/m$^2$hr. From previous work carried out (DJAVANROODI, F., et.al. [1994]) it has been shown that the creep and fatigue components of crack growth can be added cumulatively. Equations (1) and (3) can then be utilised to calculate the fatigue and creep components of the high temperature cyclic tests.



## MATERIALS AND EXPERIMENTAL PROCEDURE

Details of the experimental procedure have been presented previously (WEBSTER, G. A. [1982], NIKBIN, K.M., [1976]). Table one gives the material information for the martensitic steel and the RR58. Only an outline of the test techniques will be included here. For FV448 material test were conducted at temperature of 550 °C on CT specimen with B = 25 mm and W = 50 mm. All CT specimens were provided with 10% deep side grooves on each side after fatigue pre-cracking. Crack growth experiments have been conducted over a range of frequencies between $10^{-3}$ and 10 Hz. During each test displacement was measured continuously with electrical transducers and crack extension by a combination of optical and electrical potential difference methods to an estimated accuracy of + 0.1 mm. The wave shape employed was sinusoidal for frequencies of 0.1 Hz and greater, and square-wave for frequencies lower than this.

For the RR58 aluminium alloy tests were previously carried at 150 °C ( NIKBIN, K.M., [1976]. ) using contoured double cantilever beam (DCB) specimens. As these tests were performed at a time where creep/fatigue interaction was not investigated only static data and room temperature high frequency data is available. Use is made of the cumulative damage summation to predict a creep/fatigue interaction curve from the available data.

**Table 1:** Compositions and heat treatments
Chemical composition (wt% unless otherwise stated)

**a) 11-12% Cr martensitic steel, designated FV448.**

| C | Si | Mn | Cr | Mo | Ni | V | Nb |
|---|---|---|---|---|---|---|---|
| 0.12 | 0.3 | 0.75 | 10.5 | 0.65 | 0.8 | 0.25 | 0.3 |

Heat Treatment: 1\2 hour at 1150°C - Oil quenched at room temperature - Tempered, 2 hours at 680°C - Air cooled

**b) Aluminium alloy RR58**

| CU | Mg | Mn | Si | Fe | Ti | Zn | Ni |
|---|---|---|---|---|---|---|---|
| 2.64 | 1.65 | 0.03 | 0.23 | 1.15 | 0.06 | 0.06 | 1.15 |

aged 30 h at 190 °C

## RESULTS AND DISCUSSION

The effects of frequency on crack growth were examined. Attention was confined to intermediate crack propagation rates and near threshold behaviour was not considered. Cyclic crack growth data obtained over a range of frequencies at a constant value of R=0.1 for FV448 are shown in Figures (1). A trend of increase in da/dN with a decrease in frequency f at a given value of $\Delta K$ is evident. In general it has been found at a given value of R and at high frequencies that da/dN is approximately insensitive to frequencies, whereas below this frequency range da/dN increases with a decrease in frequency indicating time dependent effects at the low frequencies. Previously (WEBSTER, G. A. [1982], DJAVANROODI, F., et.al. [1994]), the frequency insensitive region has been associated with transgranular fractures and the time dependent region with intergranular failures.

Examination of data indicates that crack growth rate (da/dN) can be correlated in terms of the stress intensity factor range $\Delta K$. The slopes in the steady state region are approximately equal over the frequency range and appear to be within the range normally observed for room temperature fatigue cracking.

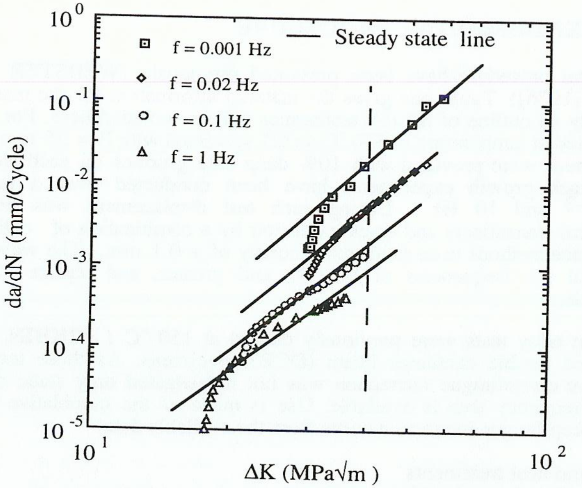


Fig: 1 Effect of frequency on creep/fatigue crack growth of FV448 tested at 550 °C

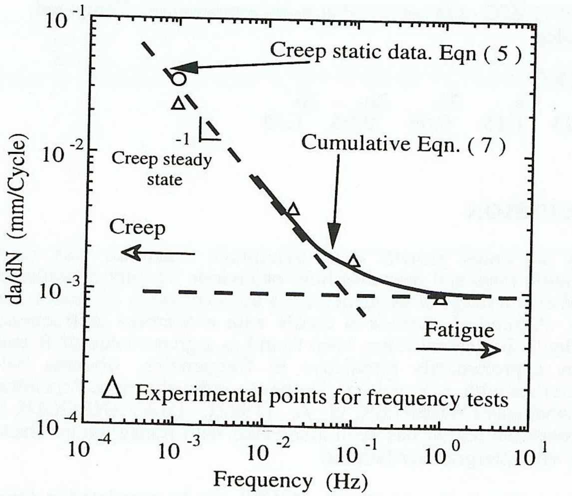


Fig: 2 Creep/fatigue over a range of frequencies at constant ΔK=40 MPa√m for FV448 steel at 550 °C



The sensitivity of da/dN to frequency at constant ΔK stress intensity factor is shown in figure (2). The influence of frequency on crack growth can be explained in terms of the relationship between da/dN and crack propagation rate å from

$$da/dN = å / (3600.f) \tag{4}$$

Typically the range of frequencies that the components could see in its lifetime could range between $10^{-4}$ to 100 Hz. From previous experience(WEBSTER,G.,A.,[1982], DJAVANROODI, F., et.al. [1994]), it has been found that a simple cumulative crack growth model adequately describes these two failure modes. When both time dependent and fatigue processes act together it can be argued that the combined crack growth/cycle is given by:

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_t + \left(\frac{da}{dN}\right)_f \tag{5}$$

where the subscripts t and f refer to the time dependent and fatigue components respectively. The form of equation (5) suggests little interaction so that either one mechanism or the other will be expected to control failure except over a narrow frequency range. The cumulative rates can then be derived from

$$da/dN = D\, C^{*\phi}/(3600\ .f) + C\Delta K^m \tag{6}$$

By using crack growth data produced under cyclic loading ranging in the dwell periods of frequencies of 0.1 Hz and less the creep/fatigue interaction can be analysed in the steady state crack growth range. The dominant mode of crack growth failure is determined by frequency and it has been found that at slow frequencies of less than .001 Hz creep crack failure mode correspond to the static creep crack growth tests. The slope of -1 in figure (2) shows the time dependent nature of cracking in the low frequency range. Furthermore from fracture surface observations it has been found that a change from frequency insensitive behaviour to frequency sensitive crack growth is associated with a change from a transgranular to an intergranular mode of fracture suggesting that the frequency independent region is controlled by fatigue processes and the frequency dependent region by creep mechanisms.

Historically crack growth data of engineering materials have been produced under either static loading at high temperatures or high frequency, greater than 1 Hz, fatigue loading at room temperature. Equation (4) can be extended so that available static and high frequency data can be made use of in order to predict a creep/fatigue interaction frequency range for the steady state crack growth rate region. Close agreement with the cyclic experimental results has demonstrated the applicability of equations (4-6) and the validity of using a linear cumulative damage approach. Hence for a cyclic load test with equal hold periods at the maximum and minimum loads and assuming negligible crack growth at the minimum load, the crack growth/cycle can be given by

$$da/dN = å / (7200.f) \tag{7}$$

where å is the static crack growth rate and f is the frequency. This equation can be substituted in equation (5) to analyse static data within the cumulative damage law. The assumption is made that cracking occurs during 50% of the cycle time at maximum load. It is clear that the factor of 2 in equation (7) compared to equation (4) can vary depending on the wave shape and the extent of creep relaxation that may occur during the unloading period. Also using the high frequency data at room temperature it is assumed that da/dN will correspond to high frequency data at 150 °C as fatigue crack growth is assumed to be time independent.

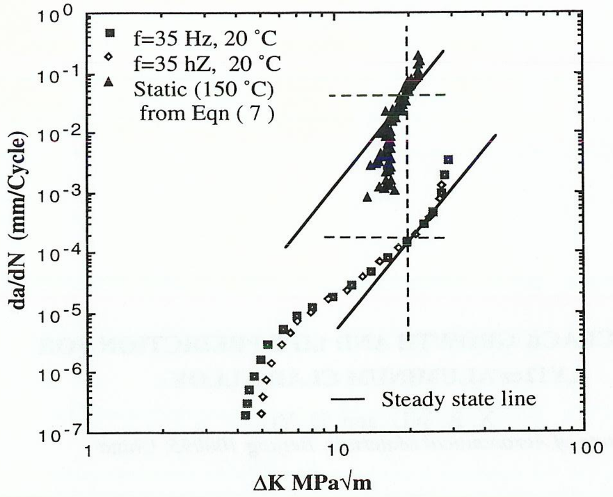


Figure: 3 Correlations of creep and fatigue crack growth tests versus ΔK for static and cyclic loading

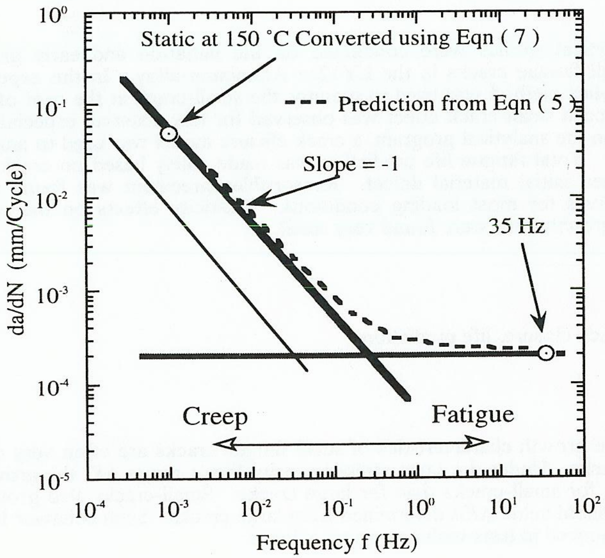


Fig: 4 Effect of frequency on crack growth per cycle for RR58 under static and cyclic loading at a ΔK=20 MPa √m



By predicting a creep/fatigue interaction frequency range, in the steady state crack growth regime it is then possible to predict the failure parameters that would occur in components which undergo cyclic tests. Figure (3) shows crack growth data from static and high frequency fatigue of an aluminium alloy RR58, used in the Concorde wings. The da/dN for the static crack growth is then derived from equation (5) assuming a cyclic frequency of 0.001 and R=0.1. Figure (4) shows the corresponding da/dN versus frequency at a constant ΔK=20 Mpa√m for the static and high frequency fatigue data. The slope of -1 showing the time independent creep cracking behaviour is drawn through the static data point converted by equation (7). The fatigue component is drawn through the 35 Hz test point.

## CONCLUSION

A martensitic steel FV448 and an aluminium alloy RR58 which exhibit creep brittle cracking behaviour were investigated in the creep/fatigue range using the stress internsity factor K and the creep correlating parameter C*. The relationship between crack growth rate under static load and cracking rate under slow cyclic rates ( <0.1Hz) has been examined. Linear elastic fracture mechanics concepts and the Paris law can be used to estimate crack extension and maximum tolerable defect sizes where fatigue processes dominate. When creep processes govern the creep fracture mechanics parameter C* is more relevant for determining cyclic crack propagation rates.Since most of the damage takes place at maximum load, the creep fracture parameter C* was calculated at the maximum load of the cycle. A linear cummulative damage law was used to evalauate the creep/fatigue interaction for the Aluminium alloy using only static creep and pure fatigue data. From the prediction line using equation (5) it has been shown the interaction region for the RR58 to be mainly in the 1-0.1 Hz region (figure 4). In comparison the FV448 data in figure (2) shows an interaction region of 1- 0.01 Hz. The form of equation (5) suggests little interaction so that either one mechanism or the other will be expected to control except over a narrow frequency range in the creep/fatigue transition region. The results of this investigation can be used to provide a basis for predicting creep/fatigue crack growth interaction in engineering components subjected to either static or high frequency cyclic loading at elevated temperatures.

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