Superposition Models for the Growth of Fatigue Cracks at Elevated Temperature

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ABSTRACT

Five mathematical models of fatigue at elevated temperatures are examined and compared. Each model is based on the assumption that the net rate of crack growth is the sum of a fatigue component, which is not affected by temperature, and a time-dependent process that becomes increasingly important at elevated temperature. The time-dependent processes investigated are oxidation, creep, fatigue-assisted creep, and fatigue-assisted oxidation in the alloys Fe-1%Cr-0.5%Mo and Fe-0.5%Cr-0.5%Mo-0.25%V. Each of the models was tested against the results by interpolation as well as extrapolation. It is found that, the most accurate predictions are obtained with the model based on the linear superposition of fatigue and fatigue-assisted oxidation.

KEYWORDS

1%Cr-0.5%Mo, 0.5%Cr-0.5%Mo-0.25%V, elevated-temperature fatigue, creep-fatigue, oxidation-assisted fatigue.

LIST OF SYMBOLS

a	length of fatigue crack
$\frac{da}{dN}$	rate of crack growth per cycle
ΔK	alternating stress intensity
K_{max}	maximum stress intensity in cycle
K_{open}	crack opening stress intensity
ΔK_{eff}	effective stress intensity (K_{max} - K_{open})
K_{1c}	critical stress intensity for unstable crack growth
ΔK_{th}	threshold alternating stress intensity
R	ratio of minimum to maximum load in fatigue cycle
t	time
T	absolute temperature
Z_{ox}	oxidation rate
Q_1	thermal activation energy for fatigue
Q_2	thermal activation energy for creep
R	universal gas constant
A,B,C,D,E,m	empirical coefficients

INTRODUCTION

The fatigue of metals at elevated temperatures is a problem of considerable practical importance, since it affects engineering components as disparate as aircraft jet engines and electrical power-generating equipment. However, there has long been a measure of disagreement regarding the importance and role of oxidation during crack propagation (Ericsson, 1979).

Many workers, for example Yamaguchi and Nishijima(1986), Brinkman(1985), Fine and Weertman(1985) and Armstrong and Neate(1985), believe that the effect of oxidation is negligible, and that the rate of fatigue-crack growth is higher at elevated temperature than at room temperature because of the larger role played by creep deformation. Other workers such as Ericsson(1979), James(1976), Haigh *et al.*(1976) and Taplin *et al.*(1984) however, have demonstrated that the effects of environmental factors can be very significant in high-temperature fatigue.

This paper examines and compares models in which the net rate of crack growth is regarded as the result of the linear superposition of a fatigue process and a time-dependent process. These models are simple in formulation, relatively easy to apply, and can be used for the prediction of the growth rates of cracks.

EXPERIMENTAL TECHNIQUES

Fatigue cracks were grown in samples of two alloys, namely Fe-1%Cr-0.5%Mo and Fe-0.5%Cr-0.5%Mo-0.25%V, at a frequency of 1 Hz and at temperatures ranging from 425 to 600°C. The frequency chosen was low enough to permit time-dependent processes to influence the rate of crack growth, but not low enough to cause the individual fatigue tests to be unnecessarily protracted. The Fe-1%Cr-0.5%Mo alloy had been in service as part of a power generation steam pipe for 125 000 hours at a nominal temperature of 520°C, and the Fe-0.5%Cr-0.5%Mo-0.25%V alloy had been in service for 100 000 hours at a temperature of 540°C.

Fatigue tests were conducted in a computer- controlled servohydraulic testing machine. In some early tests, crack length was measured by the d.c. potential-drop method, but all subsequent tests employed an automatic 'beachmarking' technique. This method is unambiguous and very accurate, and permits the optional construction of 95 per cent confidence intervals for each of the data points.

The Fe-1%Cr-0.5%Mo alloy was tested at 425, 450, 475, 525, and 550°C. Tests on the Fe-0.5%Cr-0.5%Mo-0.25%V alloy were conducted at 20 and 550°C so that the models could be fitted to the experimentally derived data, and at 500 and 600°C <u>after</u> the models had been fitted so that the accuracy of the interpolation or extrapolation of the data by each model could be determined.

The rate of oxidation of Fe-0.5%Cr-0.5%Mo-0.25%V was determined for six temperatures ranging from 400 to 700°C. For each temperature, two or three specimens, which had been ground to a 120-grit finish and weighed to the nearest 0.1 mg, were allowed

to oxidize in a furnace for 24 hours. It is recognized that the oxidation rate varies with time but, since the tests were all the same duration, it was considered that they would provide some indication of the variation in the rate of oxidation with temperature. An empirical expression was fitted to the data (Figure 1) in order that the rate of oxidation could be described as a function of temperature for later use in the models.

FATIGUE AND OXIDATION

In a model in which the rate of crack propagation depends on two independent processes, namely a fatigue process and a purely time-dependent process, the net rate of propagation would be the sum of the fatigue component and the time-dependent component, which could be oxidation, (Haigh *et al.*, 1976) or creep (Saxena,1981). Hence:

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_{fatigue} + \left(\frac{da}{dN}\right)_{time} \qquad \text{.......................(1)}$$

The pure fatigue component can be modelled by any suitable expression. In the present investigation, the 'effective *K*' expression of Elber (1971), which is based on the Paris Law, was used.

$$\left(\frac{da}{dN}\right)_{fatigue} = A.(\Delta K_{eff})^m \qquad \text{..........................(2)}$$

since

$$K_{max} = \frac{\Delta K}{(1-R)}, \quad \text{and } \Delta K_{eff} = K_{max} - K_{open},$$

$$\left(\frac{da}{dN}\right)_{fatigue} = A.(\Delta K/(1-R) - K_{open})^m \text{...............(3)}$$

If da/dt depends solely on the oxidative attack of the metal surface, it might in the first instance be expected that, for a particular frequency,

$$\left(\frac{da}{dN}\right)_{time} = C.(Z_{ox})^D \text{..........................(4)}$$

Equations (1), (3) and (4) can be combined to yield the following expression:

$$\frac{da}{dN} = A.(\Delta K/(1-R) - K_{open})^m + C.(Z_{ox})^D \text{...............(5)}$$

which was fitted to the data for the Fe-0.5%Cr-0.5%Mo-0.25%V alloy at 20 and 550°C by a non-linear regression program. However the fit was totally unsuitable, since very low values were assigned to the coefficient C. It was considered that the application of a more general form of this model to the results of the tests on Fe-1%Cr-0.5%Mo would be more successful, particularly, since data for this alloy were available for a wide range of temperatures.

According to some workers (McGowan and Liu,1983; Krausz and Krausz,1984), the rate of the time-dependent process is likely to be controlled by activation energy.
Accordingly:

$$\left(\frac{da}{dN}\right)_{time} = B.e^{(-Q1/RT)} \quad \text{..........................(6)}$$

The combination of equations (1), (2), and (6) yields the following expression for, the total rate of crack growth:

$$\frac{da}{dN} = A.(\Delta K_{eff})^{m} + B.e^{(-Q1/RT)} \quad \text{.....................(7)}$$

This expression was fitted to the results of the tests on Fe-1%Cr-0.5%Mo for temperatures between 425 and 550°C. The resulting curves are shown in Figure 2, and the coefficients calculated are listed in Table 1.

It can be seen that the model is unable to account for the trends in the data. This is because the predicted rate of the time-dependent process is independent of the alternating stress intensity, ΔK. At low values of ΔK, the simple additive model predicts a certain minimum rate of crack extension, corresponding essentially to growth by the time-dependent mechanism alone, and the predicted rates of extension are therefore greater than the actual values.

A possible further objection to a model of this type is that the time-dependent process, although not cycle-dependent, might have a stress-dependent component. This would be the case for a process involving creep or creep cavitation.

CRACK GROWTH BY CREEP AND FATIGUE

In the case where the net rate of crack growth at elevated temperatures is the sum of a pure fatigue component and a time-dependent creep component then:

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_{fatigue} + \left(\frac{da}{dN}\right)_{creep} \quad \text{.....................(8)}$$

It has been noted by Henshall and Gee(1986) that the rate of crack growth by creep in Fe-1%Cr-0.5%MO at 565°C, at least under conditions that are close to linear elastic, can be described by an expression of the type:

$$\frac{da}{dt} = B.(K_{max})^{c} \quad \text{......................(9)}$$

The net rate of crack growth per cycle is

$$\left(\frac{da}{dN}\right)_{creep} = \int_{t_0}^{t_1} B.(K_{max})^{c}.dt \quad \text{......................(10)}$$

The integration of this expression for the particular instance of the symmetrical 1 Hz triangular waveform (assuming that the total crack growth during the unloading portion of the waveform is the same as that during the loading portion), yields the following expression:

$$\left(\frac{da}{dN}\right)_{creep} = 2.B.(2 \times 10^{6}.K_{max})^{c}.\left\{\frac{0.5^{c+1}}{C+1}\right\}, \quad \text{..........(11)}$$

where B and C have the values reported by Henshaw and Gee, and K_{max} is expressed in MPa$\sqrt{m}$.

The rates of growth predicted by this expression are nearly two orders of magnitude lower than those observed in the fatigue of Fe-1%Cr-0.5%Mo at 550°C. For example, at a K_{max} value of 30 MPa$\sqrt{m}$, the calculated value of $(da/dN)_{creep}$ is only 1.8×10^{-9} m/per cycle. Riedel and Wagner (1984) obtained similar results for the same alloy at 535°C. Clearly, the increased rates of crack propagation in these low-alloy steels during fatigue at 550°C are not due to the linear superposition of the effects of creep and fatigue.

FATIGUE AND CREEP-FATIGUE

The rate of crack propagation induced by creep is possibly increased by the alternating stress intensity at the crack tip. According to this hypothesis, the rate of creep-induced crack growth could be given by the expression:

$$\left(\frac{da}{dN}\right)_{creep} = E.(K_{max})^{D}, \quad \text{..............................(12)}$$

where the coefficients E and D are assumed to take into account the fatigue-induced acceleration of the crack growth rate due to creep. The variation in the rate of creep in a metal with temperature reveals that the process is controlled by a definite activation energy. Accordingly the coefficient E in equation (12) can be equated to

$$E = B.e^{(-Q2/RT)} \quad \text{..................................(13)}$$

Equation (8) now becomes

$$\frac{da}{dN} = A.(\Delta K/(1-R) - K_{open})^m + B.(K_{max})^D.e^{(-Q2/RT)} \quad ....(14)$$

The activation energy for creep in iron is about -281 kJ/mol (Reed-Hill,1973). This value was substituted, into equation (14), and the remaining coefficients (Table 1) were determined by non-linear optimization of the data for the alloy Fe-0.5%Cr-0.5%Mo-0.25%V at 20 and 550°C. The resulting fit of the model to the data was good (Figure 3).

The usefulness of this creep-based model was tested as follows:

The growth rates of cracks at different temperatures were interpolated or extrapolated, and the predicted values were then compared with independently derived experimental results. Figure 4 shows that, under the conditions of the tests, the variation in the growth rate of fatigue cracks with temperature is not consistent with the creep-assisted mechanism postulated in equation (12).

FATIGUE AND STRESS-ASSISTED OXIDATION

It has been shown that the linear superposition of normal oxidation and fatigue cannot adequately account for the observed rates of crack growth in the materials tested. However, the kinetics of oxidation at the tip of a growing fatigue crack might depend on the magnitude of the alternating stress intensity as described by Skelton and Bucklow (1978). The integrity of the oxide film at the crack tip is expected to depend on ΔK since, as K rises, the film will crack and possibly spall. In addition, gas-stabilized cavitation (if it occurs) will be influenced by the magnitude of K_{max} as well, since cavitation is sensitive to stress. Internal-oxidation voiding or vacancy-injection voiding also depend on both K_{max} and ΔK since in both cases the integrity of the oxide layer at the crack tip would control the diffusion of oxygen.

A linear superposition model for stress-assisted oxidation can be derived in a fashion similar to that used for the derivation of the model for creep. Equation (12) can be rewritten as

$$\left(\frac{da}{dN}\right)_{time} = f(\Delta K_{eff}, Z_{ox}) \quad ....(15)$$

ΔK_{eff} is used rather than K_{max} because the spalling and destruction of the oxide film at the crack tip is likely to depend on the fluctuation in the stress intensity rather than on the maximum stress intensity.

The rate of crack extension due to oxidation in stressed material is likely to be in unstressed material related to the rates of oxidation. Since some of the difference is caused by the action of the alternating stress intensity in breaking up the protective oxide film at the crack tip, the effective rate

of crack extension due to oxidation can be set to:

$$\left(\frac{da}{dN}\right)_{time} = B. \ (\Delta K_{eff})^D.Z_{ox}, \quad ....(16)$$

where B and D account for the dependence of the rate of oxidation on ΔK.

The total rate of crack growth is given by

$$\frac{da}{dN} = A.(\Delta K_{eff})^m \ + \ B.(\Delta K_{eff})^D.Z_{ox} \quad ....(17)$$

This expression was fitted to the 20 and 550°C data for the alloy Fe-0.5%Cr-0.5%Mo-0.25%V. The resulting variation in the crack growth rate with temperature is shown in Figure 5. The predictions of this model for crack growth rates at 500 and 600°C, are plotted in Figure 6, which shows that the correspondence between the measured and the predicted growth rates at 500 and 600°C is good. This implies that the thermal activation energy for the propagation of fatigue cracks in this instance is similar to that measured for oxidation, and is probably related to it. A model that takes account of this fact can be used to predict the growth rates of cracks by interpolation or extrapolation of existing experimental data.

CONCLUSIONS

The crack growth in alloy steels at temperatures between 450 and 550°C and at loading frequencies of 1 Hz is not the sum of independent fatigue and oxidation processes, nor is it well described by the linear superposition of growth rates of fatigue cracks and creep cracks. However, a model that describes the rate of crack growth as the sum of a pure fatigue component and a stress-dependent oxidation component accounts for the trends in crack growth under the conditions of the tests.

ACKNOWLEDGEMENTS

This paper is published by permission of the Council for Mineral Technology (Mintek). The test materials were supplied by ESKOM. Some of the work described was carried out while the author was at the University of the Witwatersrand, and thanks are due to Professor G.G. Garrett for his support during that period.

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TABLE 1

COEFFICIENTS FOR THREE MODELS OF FATIGUE-CRACK GROWTH

Equation no.	Coefficient						
	A	B	D	m	Q_1 kJ/mol	Q_2 kJ/mol	K_{open}
(9)	1.73×10^{-11}	1.24×10^{-2}	-	3.01	-78.3	-	-
(16)	5.491×10^{-10}	6.84×10^{5}	3.75	1.94	-	-281	12.61
(19)	8.074×10^{-11}	9.25×10^{-11}	2.03	2.40	-	-	9.45

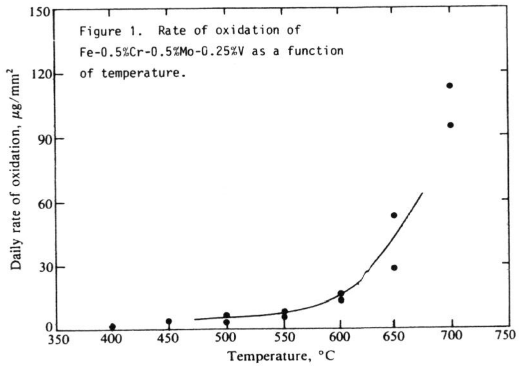

Figure 1. Rate of oxidation of Fe-0.5%Cr-0.5%Mo-0.25%V as a function of temperature.

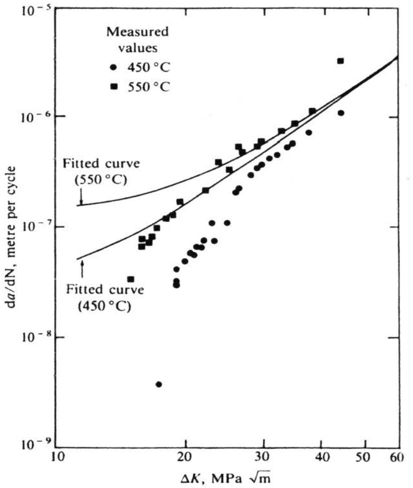

Figure 2. Linear superposition of fatigue and a time-dependent process for Fe-1%Cr-0.5%Mo.

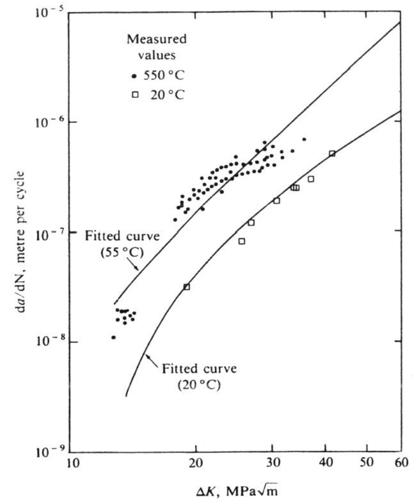

FIGURE 3. Linear superposition of fatigue and creep fatigue for Fe-0.5% Cr-0.5% Mo-0.25% V

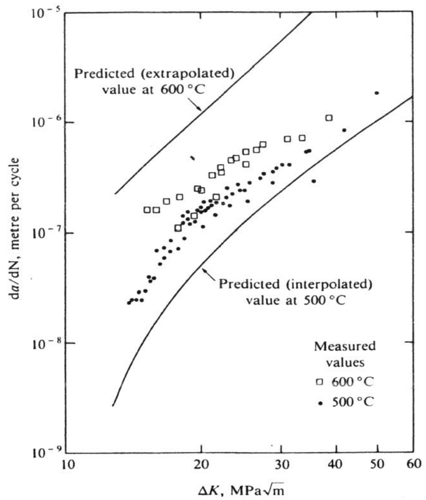

FIGURE 4. Predicted values of da/dN by the fatigue plus creep-fatigue model

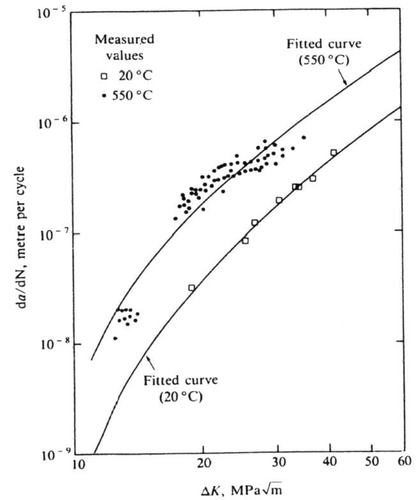

FIGURE 5. Linear superposition of fatigue and stress-assisted oxidation for Fe-0.5% Cr-0.5% Mo-0.25% V

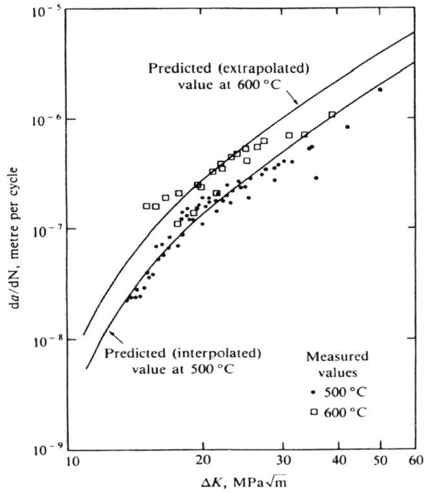

FIGURE 6. Predicted values of da/dN by the fatigue plus stress-assisted oxidation model