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Evaluation of creep-fatigue crack growth in type 316L (N) steel

Smith D.J.(1), **Curbishley I.**(2), **Huthmann H.**(3)
(1) University of Bristol, United Kingdom
(2) AEA Technology, United Kingdom
(3) Siemens AG, Germany

ABSTRACT

Results from a collaborative study to examine creep, fatigue and creep and fatigue crack growth in 316L(N) steel are examined. It is demonstrated that during the dwell for creep-fatigue conditions the increment of crack growth is lower than predicted from pure creep tests. A model is used to predict growth rates for combined conditions. Conservative predictions of growth rates would be made using a simple addition of pure creep and fatigue crack propagation rates.

INTRODUCTION

In modern plant operating at elevated temperatures, components can be working under conditions when creep and fatigue processes are present. In addition to being able to predict the time required to initiate a crack it is also essential that predictions of subsequent crack be available. Type 316L(N) steel is used in high temperature power plant components and is subjected to complex loading histories. There have been a number of wide ranging studies to explore the how cracks propagate in this material for both creep [1, 2] and fatigue conditions [3]. However, there has been no systematic collection and evaluation of crack growth behaviour under creep-fatigue conditions. This paper is based on work carried out under the auspices of CEC DG IX Working Group on Codes and Standards, where a collaborative study was carried out to examine combined creep fatigue crack growth in Type 316L(N) steel. Some of the work has been reported earlier, [4] and full details can be found in reference [5].

EXPERIMENTS AND RESULTS

The work reported here is based on experimental studies carried out at 4 laboratories, AEA-Risely, UK, Siemens AG (KWU)-Bergisch Gladbach, Germany , Ecole de Mines-Paris, France and University of Bristol, UK. Tests, at temperatures between 550 and 700°C were carried out to examine creep crack growth, fatigue crack growth and combined fatigue and creep crack growth; the work reported here is for 600°C. The test methods and results are summarised in [5]. Crack growth rates are summarised in Figures 1 and 2. Figure 1 shows creep crack growth rates da/dt, as a function of the measured fracture mechanics parameter C*, where

$$C^* = \frac{P\dot{\Delta}_c}{BW}F \qquad (1)$$

where P is the load, $\dot{\Delta}_c$ is the load point creep displacement rate, B and W specimen thickness and width respectively and F a function which depends on the geometry and creep properties of the material. It is noticeable that the results in Figure 1 exhibit significant "tails", a feature of creep crack propagation that Webster and Ainsworth [6] suggest arises from initial slow damage accumulation.

Figure 2 illustrates fatigue crack growth rates, da/dN, as a function of the total applied stress intensity factor, ΔK. Crack growth rates are shown for high frequency tests, and also growth rates for fatigue tests with 1 and 10 hour dwells (t_h) at maximum load. The results have been collated from all 4 laboratories. It is evident that the introduction of a dwell leads to higher crack growth rates compared to pure fatigue tests. However, in some instances the crack growth rate is high followed by decreasing rates before accelerating again.

For the fatigue tests with dwells it was often not possible to discriminate between the creep crack growth and fatigue crack growth components of the overall creep-fatigue crack growth. The results do, however, provide a pointer that, for this material at least, the most practical way of describing crack growth is likely to be in terms of the overall creep-fatigue behaviour, whether it be as a fatigue enhanced creep crack growth type relation, or a description of creep enhanced fatigue crack growth, rather than attempting to make separate direct measurements of crack propagation rates during the creep and fatigue components of the loading cycles.

ANALYSIS

Estimates of crack growth during dwells

A number of analyses were carried out to examine the crack growth results for tests with dwells. Aspects related to crack initiation under creep-fatigue conditions have been explored earlier [4]. For comparison of the creep crack growth rates during the hold periods with the growth rates from pure creep tests, the hold period growth rates were determined from

$$da/dN_{creep} = da/dN_{total} - da/dN_{fatigue} \qquad (2)$$

The fatigue crack growth rate was given by a Paris equation as shown in Figure 2, and the notional creep crack growth component determined from Equation 2. The term notional is used to describe creep crack propagation because it is difficult to separate experimentally the creep and fatigue contributions.

To estimate C* during the hold period t_h, equation 1 was modified so that the creep displacement rate was given as

$$\dot{\Delta} \approx \delta\Delta_c / t_h \qquad (3)$$

where $\delta\Delta_c$ is the increment of creep displacement during a hold period.

The resulting creep crack growth rates from tests with 1h and 10h dwells are shown in Figure 3, and compared with results from a pure creep crack growth test. With the exception of one test, the results show that the creep crack growth rates for the dwell periods tests lie below the growth rates for the creep crack growth tests. From this it is evident that the total crack growth rates for creep fatigue loading can be calculated conservatively by the simple addition

$$da/dN_{total} = da/dN_{fatigue} + da/dN_{creep} \qquad (4)$$

Although the creep-fatigue crack growth behaviour is conservatively predicted by Equation 4, the mechanism of the creep-fatigue crack growth behaviour is not fully described by such a simplified approach.

Crack Growth Model

Earlier work [4, 7] has suggested that a fit to experimental results of the type shown in Figure 2 can provide estimates for the additional damage accumulated to give the evaluate da/dN_{creep}. Rather than using an empirical fit as proposed by Skelton [7] evaluation of the crack growth rates has shown that direct estimation of the total crack growth rate will be overestimated using Equation 6. This aspect is explored further in the following, where we use the parameter C* to provide an estimate of the creep part of the growth rate. Numerical estimates of C* [8] are determined. Since the numerical estimate takes account of initial stress redistribution and primary creep C* is now denoted as C[t] and the estimates can be made for plane stress and plane strain conditions. To take account of the "tails" in the creep crack growth results shown in Figure 1, it has been shown [5] that an approximate correlation between the experimental creep crack increment and C[t] (for plane strain), from several creep crack growth tests at different loads, is

$$\Delta a = 3\{1 - \exp(-2x10^{-5} C[t].t)\} \qquad (5)$$

where t is the elapsed time in the test. This increment represents the crack growth increment per cycle da/dN_{creep} if t is replaced by t_h.

Predictions are shown in Figure 2. The model surprisingly predicts initial crack growth rates which are very similar to the experiments. However, Figure 2 shows that as the crack grows, (to higher ΔK) the model significantly overestimates the growth rate.

CONCLUDING REMARKS

From the few tests where it is possible to apportion crack growth in creep-fatigue tests, it can be concluded that the crack growth in the dwell periods is less than predicted from the pure creep crack growth correlation. From that it is indicated that the predominant mechanism of creep-fatigue crack growth may either be one of enhanced fatigue crack growth, or one of attenuated creep crack growth. Mechanistically, the former alternative seems the more likely.

The recommendation made, on the basis of the present development of understanding of creep-fatigue crack growth processes, and the data available in this study, is that for Type

316L steel at 600°C, conservative predictions of creep fatigue crack propagation rates can be made by the simple addition of pure creep and pure fatigue crack propagation rates predicted from appropriately partitioned equivalent loading conditions. The fatigue crack growth component may be characterised in terms of ΔK, whilst the creep crack growth component may be characterised in terms of the C* parameter. Caution should however be exercised in extrapolating this recommendation to other temperatures, or significantly different stresses.

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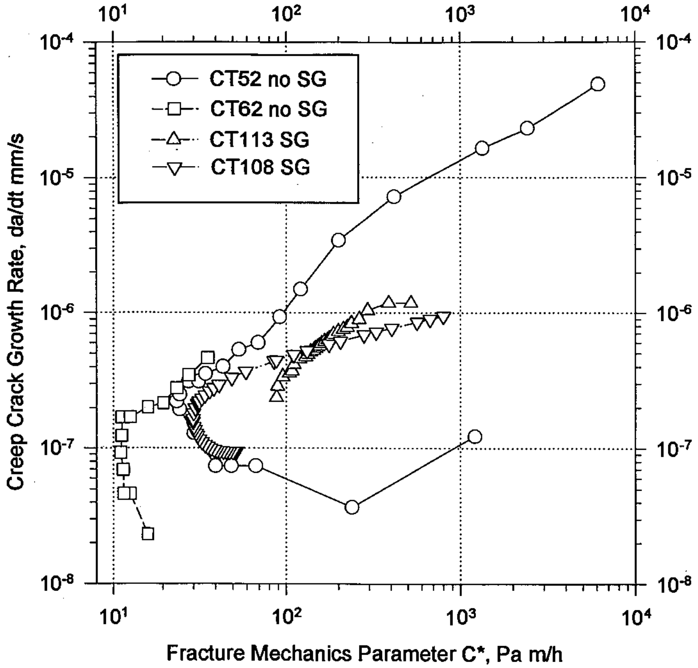

Figure 1 Creep Crack Growth Rates for Type 316l(N) Steel at 600°C

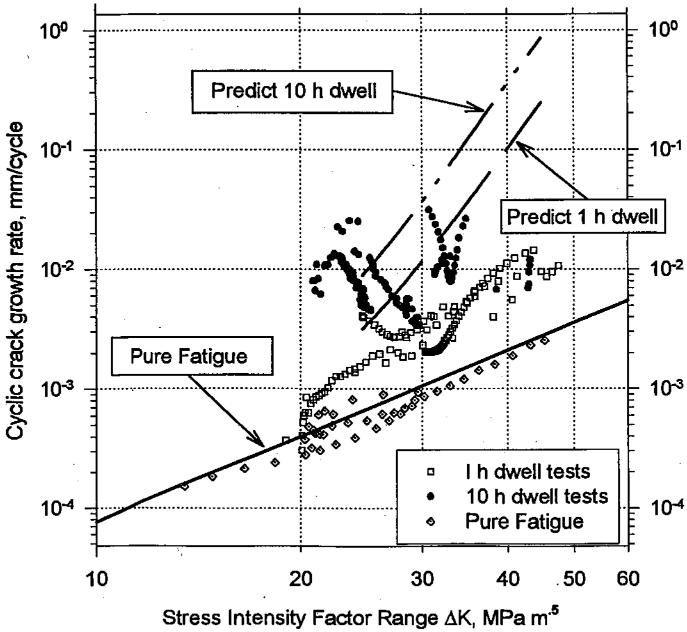

Figure 2 Cyclic Crack Growth Rates for Pure Fatigue
and Fatigue Tests with Dwells for Type 316L(N) Steel at 600°C

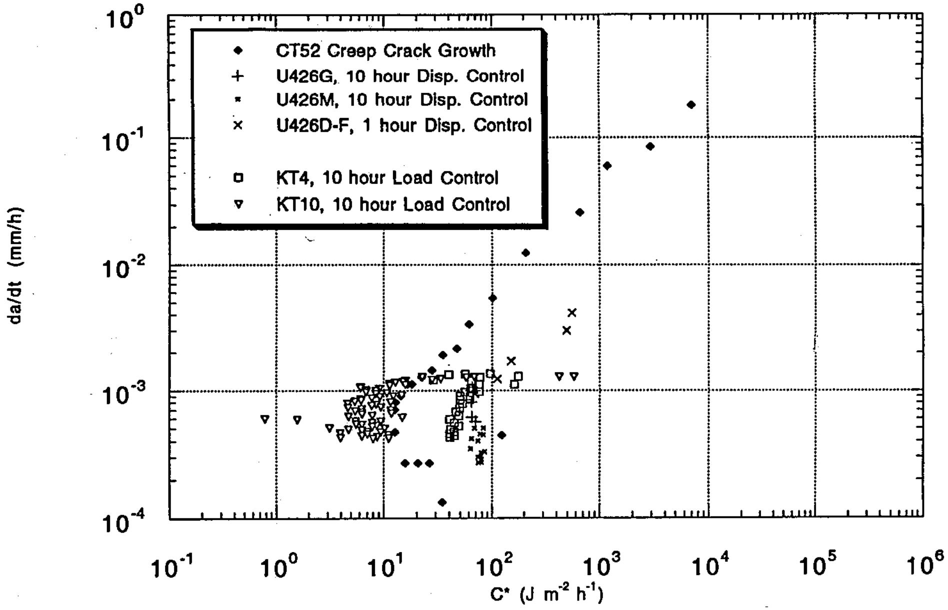

Figure 3 Creep Crack Growth Rates from Pure Creep and Fatigue Tests with Dwells for Type 316L(N) Steel at 600°C