CRITICAL EXAMINATION OF PARAMETERS FOR PREDICTING CREEP CRACK GROWTH

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ABSTRACT

Creep crack growth data have been obtained on a ½CrMoV steel and a 1CrMoV steel at 565°C. The test pieces investigated have covered compact tension (CT), single edge notch bend (SENB) and double cantilever bend (DCB) geometries. The results have been examined in terms of stress intensity factor K; reference stress σ_{ref} and the creep parameter C*. It is shown that C* correlates the cracking data on the different geometries more satisfactorily than K or σ_{ref}. Extrapolations of the results for design predictions are likely to be more reliable using the C* characterisation than the other two.

KEYWORDS

Creep crack growth, fracture mechanics, reference stress, C* parameter.

INTRODUCTION

The necessity for accurate design codes for modern power plant has stimulated the discussion and disagreement about the need for and use of parameters to characterise crack growth under creep conditions. Much experimental work has been carried out in this field (for a review see Ellison and Harper 1978) and many different parameters have been used to characterise crack growth. The most used parameters are the stress intensity factor, K, the reference stress, σ_{ref}, and the time dependent equivalent of the J contour integral, C*. However, much of the experimental work describes the result of applying one parameter to a single material which has been tested in a limited number of specimen geometries. While this approach reflects the reality that few laboratories have the resources or expertise to test reliably a range of specimen geometries and materials, it does not produce results which can easily be compared and analysed to determine the 'best' parameter to use to characterise creep crack growth.

In an attempt to overcome this specialisation, a collaborative project was set up by workers from two laboratories, Imperial College, London, and Bristol University. Both had extensive experience in testing one material in two different geometries. (Harper and Ellison 1977; Nikbin et al, 1977). Blocks of material were exchanged and then tested in the manner normal to each laboratory. The data were then analysed in each laboratory and results of characterising creep crack growth by K,

σ_{ref} and C* were compared.

The results of this work have an immediate practical interest as the materials which were used in the experimental programme have similar time to rupture properties but very different creep ductility behaviour. Both are also used in power and chemical plant operating at high temperatures.

ANALYSIS

The test-pieces of interest in this investigation are the compact tension (CT), single edge notch bend (SENB) and double cantilever bend (DCB) geometries. Their dimensions are shown in Fig. 1. Values of K were obtained as a function of crack length a and load P for these specimens from the compliance function

$$K = P\left[\frac{E}{(1-\nu^2)\,2B_n}\,\frac{dc}{da}\right]^{\frac{1}{2}} \tag{1}$$

where E is Young's modulus, ν Poisson's ratio and c compliance. For the DCB test-pieces dc/da was obtained from the experimental data of Nikbin (1976); for CT geometry eqn.(1) was re-expressed as

$$K = \frac{P}{\sqrt{B_n BW}}\,Y \tag{2}$$

and for the SENB specimens as

$$K = \frac{6M}{\sqrt{B_n BW^3}}\,Y_o \tag{3}$$

where M is bending moment and Y and Y_o are functions of a/W which have been tabulated by Haigh and Richards (1974).

The reference stress was calculated from limit load analysis using

$$\sigma_{ref} = \frac{\sigma_Y P}{m P_L} \tag{4}$$

where σ_Y is yield stress, P_L the plastic collapse load of an un-notched specimen and m is the ratio of the collapse load of a cracked specimen to that of the same un-cracked specimen. Values of m have been determined by Haigh and Richards (1974) for CT and SENB test-pieces and by Smith and Webster (1980) for the DCB geometry. Since all the specimens contained side-grooves, it was assumed that plane strain conditions were approached.

The C* parameter was derived from the method described by Harper and Ellison (1977). This method uses limit load analysis to determine a potential function U* of a body under creep conditions which corresponds to the potential energy function, U, in elastic-plastic analysis. Differentiating the potential function U* with respect to the crack length gives the C* parameter. The final expression for C* is given by:

$$C^* = -\frac{n}{n+1}\,\frac{P\dot{\Delta}}{BW}\left[\frac{1}{m}\cdot\frac{dm}{d\frac{a}{W}}\right] \tag{5}$$

where $\dot{\Delta}$ is the displacement rate at the loading point and n is the stress index of creep. For n >> 1 this expression is only weakly dependent on stress index and $n/(n+1) \rightarrow 1$. Equation 5 was used to determine C* for the DCB and CT specimens.

For the SENB geometry, it is more convenient to express equation (5) as

$$C^* = -\frac{M\dot{\theta}}{B_n W}\cdot\left[\frac{1}{m}\cdot\frac{dm}{d\frac{a}{W}}\right] \tag{6}$$

where $\dot{\theta}$ is the rotation rate.

The terms in square brackets in equations (5) and (6) have been evaluated as a function of crack length for the CT and SENB specimens by Harper and Ellison (1977) and for the DCB geometry by Smith and Webster (1980).

EXPERIMENTAL TECHNIQUE

The materials which were tested were a ½% CrMoV steel and a 1% CrMoV steel. (Hereafter, these materials will be referred to as the ½ Cr and 1 Cr materials respectively.) The ½ Cr steel was tested in a quenched and tempered condition, whereas the 1 Cr steel was tested after a heat treatment which ensured that the material was in the fully bainitic state. The result of these heat treatments was that the ½ Cr steel simulated heat affected zone material while the 1 Cr steel was representative of the bulk material in power plant.

The uniaxial creep properties of both the materials are well known (Ellison and Paterson 1976; Nikbin, 1976) and are shown in Fig. 2. Although the rupture lives are similar, there was a marked difference in the ductilities of the materials. The ½ Cr steel was considerably more brittle, with a creep ductility in the range 0.3 to 4%, than the 1 Cr steel which had a ductility of 5 to 20% over the same stress range.

At the start of the programme blocks of heat treated material were exchanged. The specimens were manufactured in the workshops of the laboratory which was to test them, to designs which had previously been used in that laboratory (Nikbin et al, 1977; Ellison and Harper, 1978). These test-piece geometries are shown schematically in Fig. 1. All the specimens had side grooves cut in them to ensure plane strain conditions, promote flat fractures and control the direction of crack growth. Both deep and shallow side grooves were used as indicated in Fig. 1.

Different methods of starting the crack were employed. Saw cuts, electric discharge machining, fatigue precracking and naturally grown creep cracks were all used and not found to affect significantly the subsequent creep crack propagation. Crack length was measured optically (Nikbin et al, 1976) to an accuracy of better than 1 mm or by a DC electrical potential technique (Harper and Ellison, 1977) with a sensitivity of 0.2 mm.

The displacements required for the evaluation of C* were measured in all cases by LVDT's mounted outside the furnaces. For the DCB and CT test-pieces, the displacement was measured along the loading line at the pins. In the case of the SENB specimens the crack opening displacement was measured, and from this the bending rotation, θ, of the specimen was calculated.

All the tests were carried out at a temperature of 565 °C. This temperature was maintained within ± 1 °C for the SENB specimens, and for the CT and DCB specimens, it was held to within ± 3 °C.

Towards the end of the testing programme checks were made of the reproducibility of results between the two laboratories. Each institution made two CT specimens of its own material to its standard design. One of each pair of specimens was tested in each laboratory under identical loads. From these tests any differences in experimental techniques or data handling could be detected.

RESULTS

The results of the repeatability tests showed no systematic differences between the two laboratories. Examples of creep crack growth rate, $\dot{a}$, plotted against K, σ_{ref} and C* are presented in Figs. 3 to 6. Figure 3 indicates that different trends are obtained with K for each geometry for the ½ Cr steel. Generally the CT and SENB specimens showed a steeper dependence on K than the DCB test-pieces. Similar features were demonstrated with the 1 Cr material. Comparison of growth rate with σ_{ref} for the 1 Cr steel is presented in Fig. 4 which also indicates different responses for each test-piece shape. Comparable behaviour was again shown by the other material.

The dependences of crack growth rate on C* are shown in Figs. 5 and 6 for both steels. There is a closer correspondence in behaviour for each geometry than was demonstrated with K or σ_{ref}.

DISCUSSION

Most individual investigations of creep crack growth reported in the literature have been limited to one or two geometries. These investigations tend to indicate that the stress intensity factor is more successful in correlating crack propagation in highly constrained brittle materials where little relaxation of the elastic stresses at the crack tip is possible by creep, whereas reference stress is more appropriate to the low constraint high deformation circumstances.

The results of the present investigation on a much wider range of test-piece geometries do not support the previous observations. It has been found that K was no more successful in correlating the data on the brittle ½ Cr steel than it was in describing the behaviour of the 1 Cr material which had a ductility ten times greater. Similarly σ_{ref} was no better in characterising the crack growth in the ductile 1 Cr steel than it was in describing the response of the ½ Cr material. Examples of the correlations are shown in Figs. 3 and 4. It can be seen that the slopes of the data are so steep that extrapolations from one specimen geometry cannot be used to predict reliable estimates of growth rates in other geometries. Furthermore, different rankings are predicted by the K and σ_{ref} characterisations. Figure 3 shows that faster cracking rates are obtained for the SENB than the DCB specimens at the same K whereas the reverse is true at the same σ_{ref} (Fig. 4).

The variation of crack growth rate with C* for both materials is shown in Figs. 5 and 6. In each case the rankings are the same with the more deeply side-grooved DCB and CTS specimens cracking faster at the same value of C* than the less constrained shallow grooved CTS and SENB specimens. All the results can be covered by a much narrower scatter band than those required for the K and σ_{ref} plots. Within the scatter bands the results from each test tend to vary linearly with C*. In addition a favourable design point here is that the C* correlation has a much lower slope ($\simeq 0{\cdot}8$) than for the K and σ_{ref} plots. However, in some tests, a change of slope in the $\dot{a}$ v C* plot was observed, the gradient being steeper at lower crack growth rates. These observations are all in agreement with previous work (Nikbin et al 1976, 1977; Harper 1976).

Extrapolation between the different test piece geometries using the C* parameter is possible because of the reasonable scatter in results compared with the K and σ_{ref} correlations.

Although it is admitted that the methods of estimating C* presented here are only approximate and that further work is required to produce more accurate determination of the parameters involved, C* seems to provide the most reliable method at the present time of predicting crack growth rates of bodies operating in the creep range.

It has been argued (Freeman and Neate, 1978) that reference stress can be used to predict the rupture lives of cracked specimens. To examine this possibility further, failure lives have been included for the cracked test-pieces in Fig. 2. It can be seen that the data do not correlate with the plain bar results for either the ½ Cr or 1 Cr steels although closer agreement is obtained with the more ductile 1 Cr material as may be expected. Although σ_{ref} has been adapted for cracked bodies, it is essentially a parameter for estimating creep deformation rates in constrained circumstances. It is strictly therefore only relevant when failure occurs by net section rupture and not by a crack growth process as occurred in these experiments.

CONCLUSIONS

This investigation of creep crack growth has covered a wider range of test-piece geometries on one material than previously reported in the literature. It has highlighted the limitations inherent in obtaining satisfactory correlations of the data. It has indicated that unsafe predictions of practical design lives can be obtained with extrapolations in terms of stress intensity factor, K and reference stress σ_{ref} for both brittle and ductile situations. Previous suggestions that K is more suitable for brittle circumstances and σ_{ref} for more ductile conditions are not substantiated.

The most satisfactory correlations of the results for both the relatively brittle ½ CrMoV steel and the more ductile 1 CrMoV steel were obtained with the creep parameter C*. Both materials showed similar trends and there was no indication of a threshold below which creep crack growth did not occur. It is argued that the C* parameter is likely to give the more reliable predictions of design lives.

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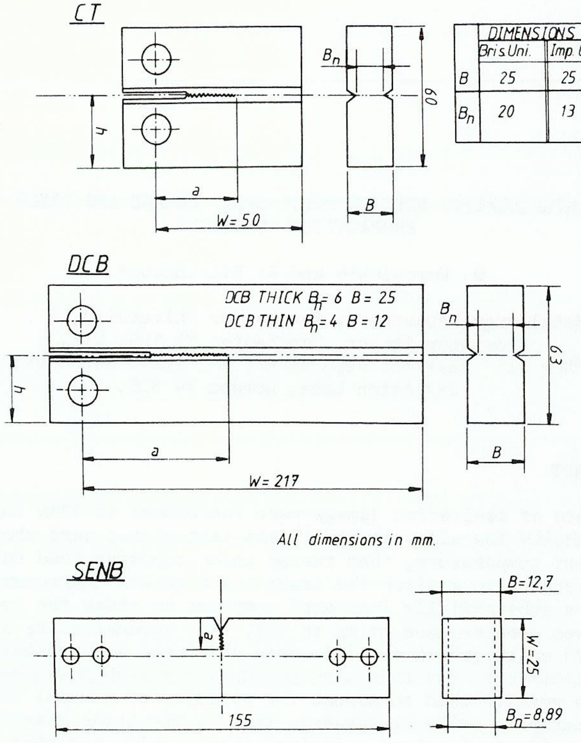

Fig. 1 Schematic of specimen geometries

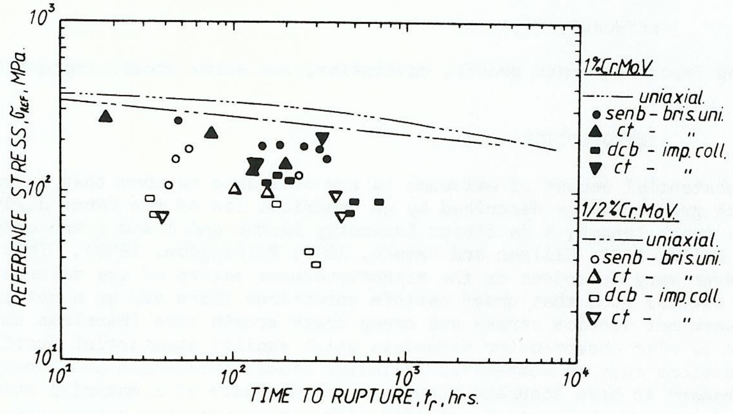

Fig. 2 Comparison of creep rupture properties of uniaxial tension and crack specimens of $\frac{1}{2}$ Cr Mo V and 1 Cr Mo V steels

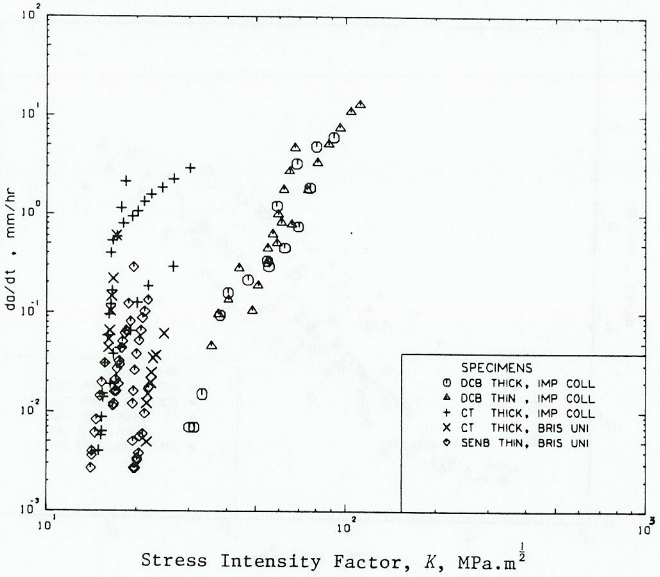

Fig. 3 Dependence of creep crack growth rate on stress intensity factor for $\frac{1}{2}$ Cr Mo V steel

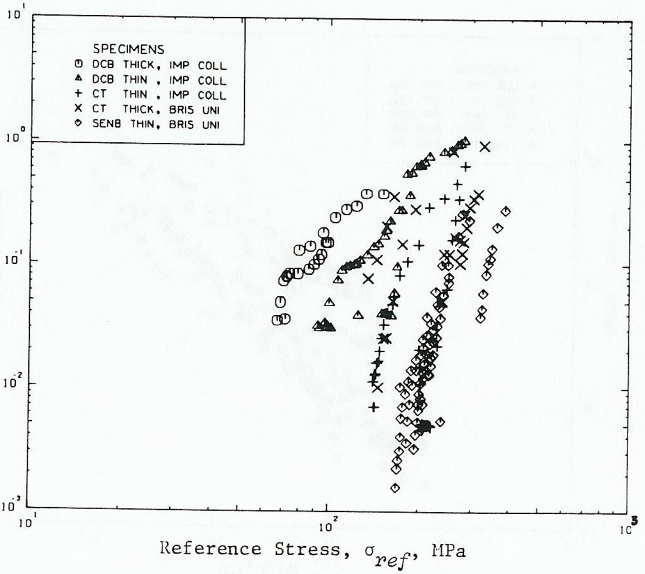

Fig. 4 Dependence of creep crack growth rate on reference stress for 1 Cr Mo V steel

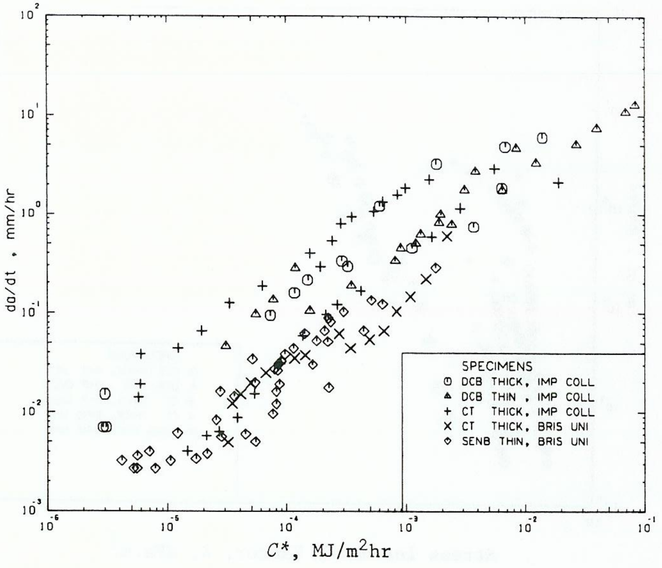

Fig. 5 Dependence of creep crack growth rate on C^* for $\frac{1}{2}$ Cr Mo V steel

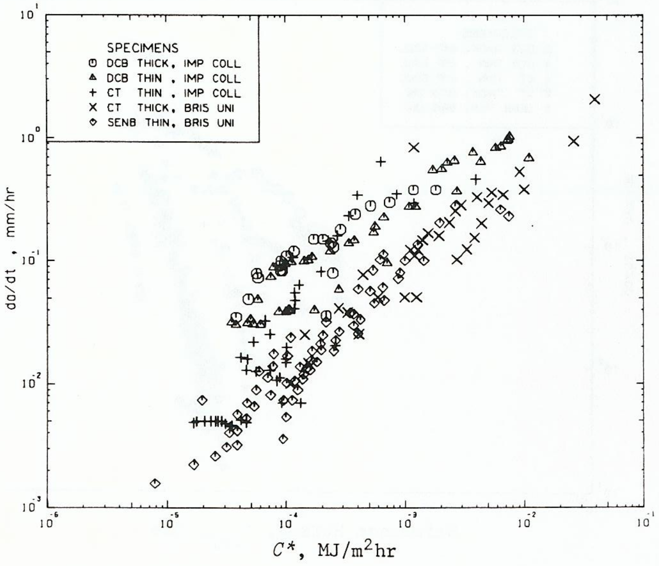

Fig. 6 Dependence of creep crack growth rate on C^* for 1 Cr Mo V steel