CHARACTERISATION OF CREEP FRACTURE AT INTERFACES IN WELDMENTS

R A AINSWORTH
Nuclear Electric Ltd, Gloucester GL4 3RS, UK

ABSTRACT

Creep fracture of austenitic to ferritic dissimilar metal welds is described. Experimental data are reported which are used to characterise the rate of creep crack growth along the interface between the ferritic parent metal and the weld metal. It is shown that this characterisation may be in terms of the steady state creep parameter C* evaluated from experimental load line displacement rates in a conventional manner. Evaluation of C* for component assessments is discussed and illustrated by finite-element results. It is concluded that conservative assessments of creep crack growth rates in components may be made by estimating C* using reference stress methods in conjunction with creep strain data for the ferritic parent metal.

KEYWORDS

Creep crack growth, dissimilar metal weld, interface.

INTRODUCTION

In high temperature pressure retaining plant in fossil-fired and UK Advanced Gas-Cooled Reactor power stations there are welded joints between austenitic and ferritic steel components. These joints, known as dissimilar metal welds, typically contain either a nickel based or austenitic weld metal. An estimate of the time to initiate creep cracking in such welds may be based on creep rupture data from cross-weld specimens in conjunction with a life fraction rule, with an allowance for any fatigue damage in service (Ainsworth et al, 1996). However, failures in such cross-weld specimens have generally been observed to occur by cracking along the interface between the ferritic parent steel and the weld metal. There is, therefore, an incentive to augment the rupture based assessment approach with procedures for estimating the rate of interfacial creep crack growth.

In this paper, an experimental programme to measure the rate of interfacial creep crack growth in test specimens over a range of temperatures is first described. By reference to finite-element analyses for test specimen geometries, characterising parameters for interfacial creep crack growth and their determination from measurements of experimental displacement rates are then discussed. Finally, procedures for assessing creep crack growth in dissimilar metal welds in service are developed.

EXPERIMENTAL PROGRAMME

Constant load creep crack growth tests have been performed on dissimilar metal welds between a type 316 stainless steel and a 2¼CrlMo ferritic steel with both Inconel and stainless steel weld metals. Here, only the tests on the latter welds are described and in these the ferritic steel is buttered with a layer of Nb stabilised 2¼CrlMo weld metal and joined to the austenitic steel by a type 316 weld metal laid by the manual metal arc welding process. The dissimilar metal welds were tested at 530°C, 540°C and 550°C in both the virgin condition and the aged condition. The aged material was taken from an ex-service joint which had operated for approximately 100,000 hours at 540°C. Based on the approach in Ainsworth et al (1996), this period of operation corresponds to a creep life fraction of 0.16 using mean creep rupture data and 0.55 based on lower bound creep rupture data from cross-weld specimens.

Three specimen geometries were tested for the virgin joint : 19mm compact specimens (CT) with the weld fusion boundary normal to the loading direction (Fig. 1); and single-edge-notched-tension (SENT) specimens 15mm thick by 25mm wide with the weld fusion boundary either normal to the tensile axis or at the natural weld angle of 45° to the tensile axis. For the ex-service joint, only SENT specimens with the fusion boundary at 45° to the tensile axis were tested. In some cases, stainless steel extension pieces were electron beam welded to the joints to make up specimens of standard size. Initial defects were electro-discharge machined so that the crack tip was as close as possible to the coarse grained region of the heat affected zone, adjacent to the ferritic buttering layer/ferritic parent interface. For the SENT specimens with the weld interface at 45°, the defect was machined normal to the tensile axis in the ferritic parent metal but terminated at the same metallurgical region. Specimens were neither fatigue pre-cracked nor side-grooved.

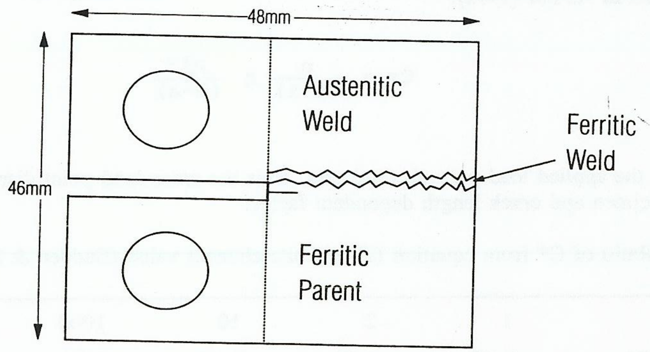

Fig. 1 Geometry of compact specimen

Test durations were generally between 1000 and 8000 hours and during each test the load line displacement increased in a manner typical of a creep test with primary, secondary and tertiary stages. Associated with this increased displacement was an increase in crack length as deduced from a direct current potential drop technique in conjunction with measurements of initial and final crack lengths. Calculations indicated that the increased displacement was predominantly due to creep rather than due to a change of specimen compliance associated with the increasing crack length. Correlations of crack growth rate with fracture characterising parameters are presented later in this paper.

Metallurgical observations of crack growth were similar in all specimens irrespective of whether the joint was virgin or ex-service and irrespective of specimen type and the orientation of the interface to the loading direction. In all cases, cracks tended to propagate along the heat affected zone associated with the ferritic layer/ferritic parent interface. Extensive creep damage was not observed in the ligament ahead of the crack with, instead, cavitation damage being confined to a small zone typically 50μm in size ahead of the crack tip. A typical micrograph illustrating the nature of the cracking is shown in Fig. 2.

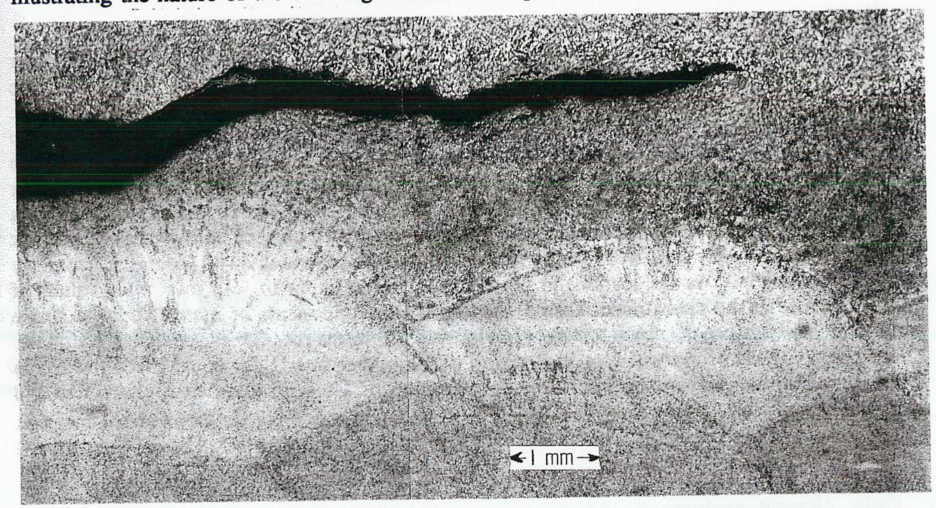

Fig. 2 Typical micrograph illustrating interfacial crack growth in virgin joint

FRACTURE CHARACTERISATION

To describe creep crack growth rates in specimens and to relate these to creep crack growth rates in components, it is necessary to have suitable characterising parameters. For cracking along interfaces, the structure of the crack tip fields has been identified for both elastic-plastic material response, as described by Shih and Suresh (1994) for example, and these depend on the material mis-match across the interface. In this section, this dependence is examined for an interface between materials of differing creep response. As this paper is concerned with dissimilar metal welds for which typical operating temperatures are such that the austenitic material creeps much slower than the ferritic steel, the extreme case of an interface between one material which deforms in creep and one which does not is also considered.

Crack Tip Fields

A crack is assumed to be located on an idealised interface between two materials, each of which is described by the power-law creep expression

$$\dot{\epsilon}^c = B\,\sigma^n \tag{1}$$

where $\dot{\epsilon}^c$ is the creep strain rate under a constant stress σ; B takes the constant values B_1 and B_2 in the two materials; and n is a constant assumed to be the same in the two materials. Without loss of generality, $B_2/B_1 \geq 1$ and materials 1 and 2 are referred to as the 'hard' and 'soft' materials, respectively.

For the linear case (n=1), the crack tip fields are described by a complex stress intensity factor and a bimaterial constant defined by the ratio B_2/B_1 (Shih and Suresh, 1994). The magnitude of the complex stress intensity factor may be obtained from a path-independent J or C* value. For the non-linear case (n>1), C* is still well defined although characterisation of the crack-tip fields also requires a mixity parameter defined in terms of the ratio of shear to opening stress at some distance ahead of the crack tip (Shih and Suresh, 1994). Therefore, an interface crack loaded at a particular value of C* will not have the same crack tip stresses as a crack in a homogeneous material loaded at the same C*. However, it will be seen below that creep crack growth rates in test specimens can be correlated with C* independently of specimen geometry and interface angle. As the loading in these specimens is likely to lead to similar values of mixity to those in the pressurised dissimilar metal weld components of interest here, a single parameter description of creep crack growth rate in terms of C* is assumed adequate. Therefore, as C* is proportional to load raised to the power (n+1) for equal creep indices in the materials either side of the interface, the variation of C* with geometry, crack size and ratio B_2/B_1 is examined below.

Finite Element Analyses

Finite element analyses for idealised bimaterial compact and single edge notch tension specimens, with the interface normal to the load direction, have been reported by O'Dowd and Budden (1996) and Budden and Booth (1996). For the compact specimen, values of C* at steady state creep conditions have been calculated for a crack length to specimen width ratio (a/w) equal to 0.5. Both virtual crack extension (VCE) and contour integral methods have been used to calculate C*, the latter approach being applied on 5 contours starting on the crack surface in material 1 and ending on the crack surface in material 2. For mis-match ratios B_2/B_1 = 10 and 1000 and for n=5, the difference between the VCE and contour integral results was at most 8% and in the remainder of this paper only the VCE results are described.

Fig. 3 shows the steady state values of C* normalised by the corresponding values for the specimen made completely of the soft material for a range of ratios B_2/B_1. It can be seen that the results reduce with increasing B_2/B_1 to a value of about 0.37 in the limit of one material being rigid ($B_2/B_1 \rightarrow \infty$). Similar results have been obtained for the SENT specimen as indicated in Fig. 3. Clearly an overestimate of C* is produced by assuming that the specimen is composed totally of the softer material.

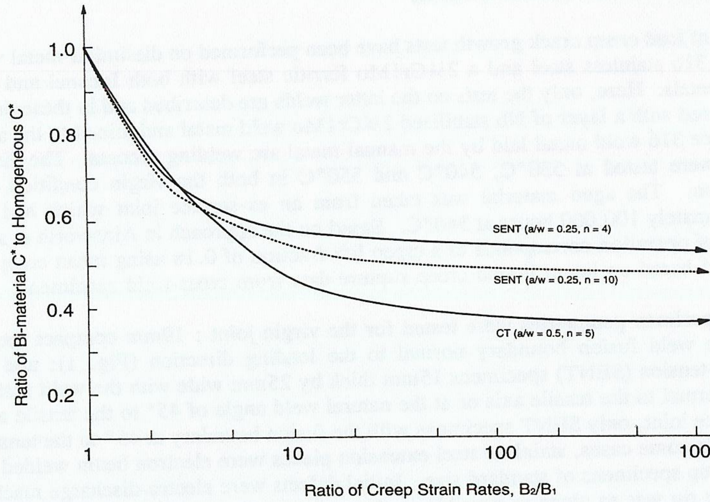

Fig. 3 Influence of creep mismatch on C*

In specimen tests, C* is generally deduced from the load point displacement rate according to the formula in ASTM (1992):

$$C^* = \frac{n}{(n+1)}\,\eta\,\frac{P\dot{\Delta}^c}{(w-a)} \tag{2}$$

Here P is the applied load per unit thickness, $\dot{\Delta}^c$ is the creep load point displacement rate and η is a specimen and crack length dependent factor.

Table 1 Ratio of C* from equation (2) to finite-element value (Budden & Booth, 1996)

B_2/B_1	1	2	10	1000	∞
$C^*_{eqn\,(2)}/C^*_{VCE}$	1.08	1.06	1.15	1.20	1.21

For the CT specimen, values of C* obtained from equation (2) and the finite-element value of creep displacement rate are given in Table 1 normalised by the finite element C* values. The factor of 1.08 at B_2/B_1 = 1 for the homogeneous specimen is probably due to the details of the modelling of the loading holes rather than any error in η. It can be seen that C* from equation (2) exceeds the VCE values. Similar results apply for the SENT specimen (Budden et al, 1995). Consequently, the use of equation (2) would be non-conservative as a means of producing materials creep crack growth data as a function of C* as it corresponds to an underestimate of creep crack growth rate for a given C*. While the factors in Table 1 could be used to modify equation (2), the differences are small and, in particular, smaller than those in Fig. 3. Therefore, use of values of C* evaluated as if a bi-material specimen were homogeneous and composed of the softer material would more than compensate for any non-conservatisms in equation (2). This is addressed further in the next section and in the following sub-section equation (2) is used un-modified to characterise the creep crack growth data obtained in the experimental programme described above.

Characterisation of Experimental Creep Crack Growth Rates

Creep crack growth rates in the experimental programme on dissimilar metal welds have been correlated with C* evaluated from the experimental load point displacement rates using equation (2). No discernible differences were obtained between data obtained on CT and SENT specimens, between tests at 530°C, 540°C and 550°C, between tests with the interface normal and at 45° to the loading, and between data on the virgin and ex-service joint. The data at 540°C are shown in Fig. 4. Tests at different load levels have led to results over a wide range of C* values. It is apparent that, apart from the 'tails' in the early stages of a test which are common in creep crack growth tests (Webster and Ainsworth, 1994), there is a good correlation between creep crack growth rate and C*.

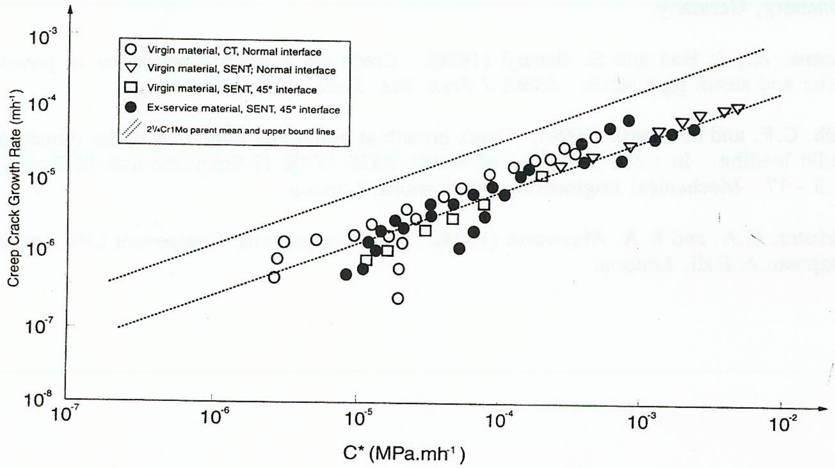

Fig. 4 Experimental creep crack growth data

Also shown in Fig. 4 are mean and upper bound lines for creep crack growth in virgin and ex-service parent 2¼Cr1Mo at 545°C from Saxena et al (1988). It is apparent that the slopes of the lines are consistent with the current data and that the data are bounded by the upper bound line. Therefore, although the cracking occurs along the interface, the interface is not particularly fragile and the corresponding crack growth rate at a given C* is not greater than would have been expected had the crack deviated into the parent ferritic.

COMPONENT ASSESSMENT METHODS

For an idealised weld in which the creep stress exponent, n, is the same in all materials, C* is proportional to load raised to the power (n+1) and consequently estimation schemes, such as those of Kumar et al (1981), may be adapted by inclusion of numerically determined factors such as those in Fig. 3. This has been pursued by O'Dowd and Budden (1996) for interfacial cracks in a similar manner to the treatment of cracks within welds away from an interface (for example, Ainsworth and Lei, 1996). In this section, these approaches are first discussed using reference stress methods, then compared with experimental and numerical results, and finally used to set out a practical defect assessment procedure for dissimilar metal welds.

Reference Stress Methods

From dimensional arguments, C* may be written

$$C^* = \sigma_{ref}\,\dot{\epsilon}^c_{ref}\,R \tag{3}$$

where σ_{ref} is a reference stress, $\dot{\epsilon}^c_{ref}$ is a corresponding creep strain rate deduced from an expression such as equation (1) and R is a parameter with dimensions of length. For homogeneous components, a convenient choice of σ_{ref} is

$$\sigma_{ref} = P\sigma_y / P_L(\sigma_y,\ a) \tag{4}$$

where P is the applied load and P_L is the corresponding limit load defined for a material with rigid plastic yield stress σ_y and for the component with crack size a. With this choice, R can then be obtained from detailed finite-element solutions, such as those in Kumar et al (1981), and is in general a function of n, geometry and crack size. However, it transpires that R is not particularly sensitive to n so that equation (3) can be generalised to non-power law creep behaviour by making suitable approximations (Webster and Ainsworth, 1994). In particular, by ensuring consistency with the elastic solution at n=1, and neglecting a factor of 0.75 in plane strain, the approximation

$$R = K^2/\sigma^2_{ref} \tag{5}$$

where K is the elastic stress intensity factor, has been shown to lead to good agreement with a range of numerical and experimental data (Webster and Ainsworth, 1994).

For defects in welds there are a number of options for using equations (3-5) which include:

(1) The length scale, R, in equation (3) can be defined as a function of the mismatch in creep properties with the reference stress defined for a homogeneous component and the corresponding creep strain rate defined in terms of one of the materials in the weld (for

induced at the external surface in an uncracked bimaterial cylinder. There is a corresponding increase in axial stress at the internal surface so that internal circumferential flaws might be expected to lead to higher values of C* than the homogeneous cylinder.

Component Assessment Procedure

From the above information it is possible to propose a practical assessment procedure for defects in dissimilar metal welds (Budden, 1995). This is set out below:

(1) Creep crack growth data should be generated using standard CT or SENT test specimen geometries with defects located on the interface as indicated in Fig. 1. The corresponding values of C* should be deduced from equation (2) with η factors for homogeneous specimens. This leads to creep crack growth data, $\dot{a}(C^*)$, of the form shown in Fig. 4.

(2) Estimate C* for a defect in a component from the reference stress method in equations (3-5) assuming the component is homogeneous and made of the faster-creeping material.

(3) Obtain the crack growth in service or remaining life by repeating Step (2) for increasing crack size in conjunction with the data from Step (1).

(4) Where the approach in Step (3) does not lead to satisfactory margins, use the results of more detailed analysis, of the type reported in this paper, to refine the estimate of C*, recognising that the minor factors in Table 1 may need to be applied to the data in Step (1) when using more accurate methods.

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REFERENCES

Ainsworth, R.A., P.J. Budden and R. Hales (1996). Assessment of the high temperature response of structures : developments in the R5 procedure. In: *Creep and Fatigue*. pp 385 - 397. Mechanical Engineering Publications, London.

Ainsworth, R.A. and Y. Lei (1996). Strength mis-match in estimation schemes. Int. Symposium on Mis-Matching of Welds, Lüneburg, Germany.

Budden, P.J. (1995). A procedure for determining interfacial creep crack growth rates in transition joints. Nuclear Electric Report ED/GEN/REP/0006/95, Gloucester.

Budden, P.J. and P. Booth (1996). Finite-element creep analysis of a bimaterial compact tension specimen. Nuclear Electric Report ED/GEN/REP/0041/95, Gloucester.

Budden, P.J., N.P. O'Dowd and E.R.J. Griffiths (1995). Finite-element analysis of a bimaterial SENT specimen under elastic-plastic loading. Nuclear Electric Report ED/GEN/REP/0005/95, Gloucester.

I. Mech. E. (1981). High temperature data for ferritic pressure vessel steels. I. Mech. E., London.

Kumar, V., M.D. German and C.F. Shih (1981). An engineering approach for elastic-plastic fracture analysis. EPRI Report NP-1931, Palo Alto.

Miller, A.G. and R.A. Ainsworth (1989). Consistency of numerical results for power law hardening materials, and the accuracy of the reference stress approximation for J. *Engng. Fract. Mech.*, **32**, 233 - 247.

O'Dowd N.P. and P.J. Budden (1996). The effect of mismatch on J and C* for interfacial cracks in plane and cylindrical geometries. Int. Symposium on Mis-Matching of Welds, Lüneburg, Germany.

Saxena, A., J. Han and K. Banerji (1988). Creep crack growth behaviour in power plant boiler and steam pipe steels. *ASME J Pres. Ves. Tech.*, **110**, 137 - 146.

Shih, C.F. and S. Suresh (1994). Crack growth at bimaterial interfaces under monotonic and cyclic loading. In : *Mis-Matching of Welds, ESIS 17* (K H Schwalbe and M Kocak, eds), pp 3 - 17. Mechanical Engineering Publications, London.

Webster, G.A. and R.A. Ainsworth (1994). High Temperature Component Life Assessment. Chapman & Hall, London.