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Creep crack growth data and prediction for a P91 weld at 650 °C

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ABSTRACT

Creep crack growth tests have been carried out on compact tension (CT) specimens machined from a P91 weldment. Four of these specimens were cut from the parent material side of the weld and another seven specimens were cut across the weld. For the cross-weld specimens, starter cracks were positioned into (or close to) the Type IV region. The creep tests were carried out under constant loads, at 650 °C. The results obtained showed that, the creep crack growth rates for parent material specimens are about ten times lower than those for the cross-weld specimens and that the scatter in the data is relatively high. In this respect, the accuracy of the crack tip location, in the cross-weld CT specimens, plays an important role. Finite Element (FE) analyses were carried out, on notched bar and CT models, using damage mechanics material behaviour models. These analyses were used to estimate the triaxial stress factor, α, for the parent material (PM), the weld metal (WM) and the heat affected zone (HAZ). FE analyses were then used to predict the creep crack growth in the CT specimens. Results from the FE analyses for both the PM and the cross-weld CT specimens were in good agreement with the corresponding experimental results. The effect of the potential drop versus crack length calibration on the calculated C* values was also investigated.

1. Introduction

Creep is a potential mode of failure for steam-piping systems within fossil and nuclear-fuelled power stations (e.g. [1]). Such failures have been reported to have occurred in weldments, which consist of several distinct regions with different microstructures, i.e. the parent material (PM), the weld metal (WM) and the heat affected zone (HAZ), which are produced during the welding process (e.g. [2]). The creep damage accumulation rate is often a maximum in the region of the HAZ [3]. The HAZ region can be further divided into three distinct sub-regions, i.e. the coarse grained zone, the fine-grained zone and the intercritical zone, commonly referred to as Type IV region, [4]. The different creep deformation properties applicable to these individual zones result in the constraint of transverse deformation during long-term service. Hence, a multiaxial stress state is created [5]. The Type IV region is the weakest region and is hence often the position in which failure occurs [5].

The C* contour-integral, i.e.

$$C^* = \int_{\Gamma} W^* \mathrm{d}y - \sigma_{ij} n_j \left(\frac{\mathrm{d}\dot{u}_j}{\mathrm{d}x}\right) \mathrm{d}s \tag{1a}$$

where

$$W^* = \int_0^{\dot{\varepsilon}} \sigma_{ij} \mathrm{d}\dot{\varepsilon}_{ij} \tag{1b}$$

is commonly used to correlate creep crack growth data for isotropic materials [6]. For materials testing using, for example, CT specimens it has also been shown that, for a material obeying Norton's creep equation [7], i.e.,

$$\dot{\varepsilon}_{\min} = A\sigma^n \tag{2}$$

The C* contour-integral, [8], is related to the load-line displacement rate, $\dot{V}$, i.e.

$$C^* = \frac{n}{n+1} \frac{P\dot{V}}{B_N(W-a)} \left(2 + 0.522\left(1 - \frac{a}{W}\right)\right) \tag{3}$$

where n is the creep exponent as given in Eq. (2), P is the applied load, $\dot{V}$ is the load-line displacement rate, B_N is the side grooved specimen net section thickness, W is the specimen width and a is the crack length.

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Table 1
Chemical composition of P91 parent material and weld metal (w%).

Material	C	Mn	Si	N	Cr	Mo	Nb	Cu	V
PM	0.11	0.36	0.022	0.048	8.74	0.98	0.12	0.08	0.21
WM	0.087	1.04	0.28	0.04	8.6	1.02	0.24	0.03	0.22

It has been shown, [9], that, for 2-materials and 3-materials cross-weld CT specimens, the magnitude of the C* contour-integral, for a crack tip within the HAZ of a weld, depends on the orientation of the crack relative to that of the HAZ and on the position of the crack tip within the HAZ, i.e. along the PM–HAZ interface, along the HAZ–WM interface or at some intermediate position.

For cracks running parallel to the HAZ, the contour-integral is independent of the contour length [9] and relatively independent of position (along PM–HAZ, along HAZ–WM or intermediate). For other crack orientations, it was found that the C* contour-integral varied with both the orientation of the crack and its contour length. Also, in each case, there were differences between the actual C* contour (Eq. (1)) integral value and the value of C* calculated using the load-line displacement rate (Eq. (3)). However, since the overall load-line displacement rate, $\dot{V}$, used in (Eq. (3)) and the strain rates, $\dot{\varepsilon}_{ij}$, and displacement rates, $\dot{u}_j$, used in (Eq. (1)), to determine the C* contour-integral are similarly affected by the relative creep strengths of the component parts, the difference in the C* values (contour-integral versus values related to load-line displacement) are relatively small, particularly for the case of a crack on the PM–HAZ interface (Type IV crack). Therefore, the use of Eq. (3) to estimate C* values, for cross-weld CT specimens, is considered to be reasonably justified. Tu [10] and Davies [11] came to the same conclusion for the Type IV crack growth condition.

In this paper, the results of experimental creep crack growth tests and Finite Element (FE) creep crack growth analyses, for parent material and cross-weld compact tension (CT) specimens, are presented. Parent material compact tension specimens were cut from the PM side of a P91 weldment. Cross-weld compact tension specimens were cut from the weld so that the specimen consists of three materials, i.e. the PM, the WM and the HAZ.

2. Experimental procedure

2.1. Parent material, weld metal and test weld

P91 is a high strength, high ductility steel capable of operating at high temperatures (in excess of 600 °C). The P91 used in this study has lower creep rupture strength than the mean code data for P91 steel [12]. The chemical compositions of the P91, PM and WM, are shown in Table 1. Uniaxial, notched bar and CT specimens were cut from the parent material side of the same P91 weldment.

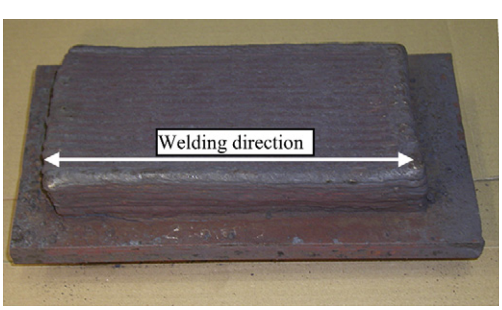

Fig. 1. A block of P91 weld metal.

Fig. 2. Section in the double-grooved weldment.

A weld block, Fig. 1, was made from the P91 weld consumable; this was subjected to a post-weld heat treatment of 760 °C for 3 h. Uniaxial and notched bar specimens were cut from the weld block in the welding direction, longitudinal, and perpendicular to the welding direction, transverse. The weld metal material properties used here are taken from the uniaxial specimens that were cut from the longitudinal direction.

A double-grooved weldment, see Fig. 2, was manufactured and then heat treated in the same way as the weld block. Notched bar, waisted, impression creep and CT test specimens were also cut from the weldment.

Electrical Discharge Machining (EDM) was used to create the starter cracks in the specimens. Tests were carried out under constant load and constant temperature, 650 °C, conditions. Variations of the load-line displacements and the crack growth rate data were determined at various times during the test.

2.2. Specimens

Standard uniaxial and notched bar specimens were cut from the PM and the WM to obtain creep strain and creep rupture data. Waisted and notched bar specimens were cut across the weld region of the weldment. These specimens were machined in such a way that, the boundary between the HAZ and PM is located in the centre section of the notch, for notched bar specimens, and in the centre of the waist, for the waisted specimens. Cross-weld notched bar and waisted specimens were used to provide material data that is related to creep rupture properties for the HAZ material. Impression creep specimens were machined from the HAZ and tested to provide steady-state creep strain data for the HAZ material. Geometries, testing conditions and results for all of the above-mentioned specimens have been reported in [12].

Creep crack growth CT specimens were cut from the PM side and across the weld of the double-grooved weldment, as shown in Fig. 3. Fig. 4(a) and (b) show the geometries and dimensions of PM and

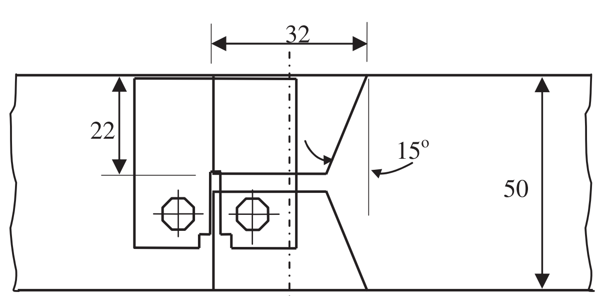

Fig. 3. Test weld and cross-weld CT specimen (dimensions in mm).