Abstract

The steels operating at elevated temperatures are well known to be exposed to premature failure due to cracking caused by constant thermal stress, i.e. secondary creep process. Therefore, creep crack growth (CCG) tests were carried out on compact tension (CT) specimens machined from P91 weld joint at 600°C to determine its behaviour in realistic conditions. At the same time, numerical method for predicting the CCG in CT specimens by a series of incremental steady state finite element (FE) analysis were performed using Norton’s law to represent creep behaviour. Verification of the FE predictions were obtained for weld metal (WM) and heat affected zone (HAZ) by comparison with experimental results, indicating at the same time that creep crack growth rates are significantly higher for WM than for BM.

Keywords

Creep crack growth, Thermal stresses, P91 steel weldment.

1. Introduction

Steel weldment components used in power generation plants are continually exposed to high temperatures and failure processes such as creep crack growth (CCG), which can occur within the high temperature regime. Safe and accurate methods to predict CCG are therefore required in order to assess the reliability of such components, [1]. Finite element (FE) methods has been applied extensively in the study of CCG to predict the fracture mechanics parameters in estimating CCG rates, [2-6], as well as some analytical and empirical methods to predict creep strain, [7-11].

This approach is of utmost interest for critical components in thermal power plants, such as steamlines. Creep damage and crack growth is typical problem for steamlines operating at high temperatures (550 °C and higher), being heavily loaded at the same time. Remaining life of critical components, including steamline, is very important topic for many old thermal power plant, which are already operating over their design life time. Having in mind that operating parameters, like temperature and stress, directly affect the life of a steamline, it is clear that one has to pay attention to these effects, focused on different weldment region, since they are typically location where damage and crack would appear first. Therefore, our main topic here is creep crack growth rate in different weldment regions, correlated with the fracture parameter, $C^*$, to evaluate behaviour of a critical component’s regions and their residual life, as shown also in [3, 8].
It is well known that creep crack growth rates, $da/dt$, correlate very well with the creep fracture parameter; $C^*$, for homogeneous material, [2]. Experimental studies on the CCG in weldments have shown that the $C^*$ parameter can also be used for characterizing the creep crack growth in weldments. Tests have been carried out, following the ASTM E1457-00 standard [12], using compact tension (CT) specimens for P91 weldments. The experimental data obtained were used to investigate the CCG behavior of welds and to validate numerical methods used for crack growth modelling.

In this paper, creep crack growth tests were carried out on compact tension (CT) specimens machined from P91 weld joints at 600 °C. This steel is referred to as mod. 9Cr1Mo or P91 and is used for manufacturing pipes and vessels for a fast breeder reactor. This steel has found wide application in all new Japanese and European power stations for the manufacture of pipes and small forgings, [13]. It is tough, readily weldable and it has high creep strength at 600 °C and 100,000 h.

The creep damage approach can be used with finite-element (FE) analysis to predict the creep crack growth behavior of welds, [14]. However, this method demand large number of material constants, which are difficult to provide especially for the heat-affected zone (HAZ) material. Rather, a relatively simple numerical method for creep crack growth prediction has been investigated and validated using experimental results. Namely, Norton’s law, which requires only two material constants, has been used to predict the creep crack growth in CT specimens made of P91 weldments and compared with experimental data for verification.

2. Experimental Analysis

Standard creep test specimens were machined from the welded joint and from simulated HAZ materials of P91 steel. Crack growth test specimens were machined from the base metal and weldments with the notches introduced centrally, using electrical discharge method (EDM) in WM and HAZ, as shown in [14].

2.1 Test data for different temperatures

The P91 steel has been also tested at somewhat higher temperatures to find the upper limit of its applicability. Results for strain vs. time, at two different temperatures, 600 °C and 625 °C, are given in fig. 1. They clearly indicate detrimental effect of temperature, limiting P91 usage to 600 °C.

![Figure 1. Strain vs. time for different temperatures](image-url)
2.2 Test data for weldment zones

To obtain the material properties for the BM, WM and HAZ regions, tensile specimens of were machined out of the butt-welded pipe segments by EDM technique, and presented in tab. 1, together with data for Norton’s law material constants. It can be seen in tab.1 that the variation in creep properties does not follow the same sequence as the yield strength data. The creep exponent, n, is the lowest for the WM where as the HAZ has the lowest m value determined in tensile tests.

<table>
<thead>
<tr>
<th>Material</th>
<th>$R_{0.2}$ (MPa)</th>
<th>$R_m$ (MPa)</th>
<th>$E$ (GPa)</th>
<th>$D_1$</th>
<th>$m$</th>
<th>$A_1$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P91 BM-600°C</td>
<td>441</td>
<td>464</td>
<td>164</td>
<td>0.0018</td>
<td>27.73</td>
<td>1.57·10^{-45}</td>
<td>18.51</td>
</tr>
<tr>
<td>P91 WM-600°C</td>
<td>362</td>
<td>385</td>
<td>125</td>
<td>0.0015</td>
<td>23.86</td>
<td>5.99·10^{-24}</td>
<td>8.55</td>
</tr>
<tr>
<td>P91 SIM. HAZ-600°C Type IV</td>
<td>320</td>
<td>333</td>
<td>155</td>
<td>0.0016</td>
<td>17.38</td>
<td>7.16·10^{-35}</td>
<td>14.35</td>
</tr>
<tr>
<td>P91 SIM. HAZ-600°C Centre</td>
<td>293</td>
<td>317</td>
<td>139</td>
<td>0.0016</td>
<td>17.38</td>
<td>7.16·10^{-35}</td>
<td>14.09</td>
</tr>
</tbody>
</table>

2.3 Creep crack growth test

Creep crack growth tests were performed according to the ASTM standard E1457-08, [12]. The crack length and load line displacement were measured, an DC electrical current was applied to the specimen and the value of the electric potential drop was measured, determination of $\Delta a$, by using PD method compliance. The specimen used were CT25 type with $W=25$ mm, with grooves of 20% of specimen thickness, to provide a crack straight front. Compact tension CT specimen prepared for testing connected through sensors for potential current measurement of displacement and potential drop as indicated in fig. 2. The results are shown in fig. 3 for BM, WM and HAZ of P91 steel.

![Figure 2. Dimensions and arrangement of tested CT specimen.](image)

This data was used in calculating $C^*$ and for validating the finite elements damage predictions. Comparing the creep crack growth for both steels it can be seen that larger $\Delta a$ can be obtained in creep weak weldment regions relative to base metal and the gradual increase in the crack length with time while it is faster in weld metal and heat affected zone.
2.4 Weldments Test Data and Creep Behaviour

Figure 3. Creep crack growth comparison of P91 weldments.

Figure 4. Creep behaviour of P91 weldments at T= 600 °C.

The creep and creep rupture curves for the P91 weldments are shown in figs. 4 and 5, for different levels of stress.
2.5 Determination of $C^*$

The experimental $C^*$ parameter for the CT specimen is estimated from the creep load line displacement rate ($V_c$) using the equation:

$$C^*(t) = \frac{n}{n + 1} \frac{P V_c}{B_n (W - a)} \left(2 + 0.522 \left(1 - \frac{a}{W}\right)\right)$$  \hspace{1cm} (1)

where $P$ is the applied load, $W$ is the specimen thickness, $a$ is the crack length and $B_n$ is the net thickness of the side grooved specimen. Also $n$ is the creep stress exponent in the Norton creep law given by:

$$\dot{\varepsilon}_{\text{min}} = A \sigma^n$$  \hspace{1cm} (2)

The $n$ exponent values are given in table 1 for each weldment zones, having higher values for base metal, but the materials exhibit creep deformations at elevated temperature would be better presented by average creep strain rates covering all three regimes of creep as described schematically in fig. 6.

![Figure 5. Minimum creep strain rate data of P91 weldments at T= 600 °C.](image)

![Figure 6. Creep curve representing secondary creep rate and average creep rate.](image)
The average creep rate is relatively more suitable method to yield more representative deformations rates for longer times defined by:

\[
\dot{\varepsilon}_{avg} = \frac{\varepsilon_f}{t_r} = \dot{\varepsilon}_0 \left( \frac{\sigma}{\sigma_0} \right) = A_{avg} \sigma^{n_{avg}} \tag{3}
\]

The experimental data for CT specimens show the \( C^* \) parameter correlates the crack growth rate data, \( a \), and the behavior can be written in a simplified form as

\[
\dot{a} = D C^{\phi} \tag{4}
\]

where \( D \) and \( \phi \) are material constants, which are presented numerically in equations below and are fitted by \( C^* \) presentations in fig.7.

![Figure 7. Relationship between \( C^* \) and CCG rate of P91 weldments.]

Creep crack growth (CCG) rates of different weldment zones of P91 at 600°C are correlated crack tip parameter \( C^* \), show consistency in correlations after the steady state creep crack growth conditions at the crack tip have been established. Comparison of CCG rates correlations of different weldment zones of P91 steel at 600°C, directs attention to lower resistances of P91 weldment zones than that of P91 base metal. Also, figure 7 indicates bigger scatter of HAZ results compared to the BM and significantly higher crack growth rates that are represented by best fit for weldments data, tab. 2.

**Table 2. Weldments data.**

<table>
<thead>
<tr>
<th></th>
<th>P91</th>
<th>WM/BM</th>
<th>HAZ/BM</th>
<th>Eq.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM</td>
<td>( \dot{a} = 0,0284(C^*)^{0.871} )</td>
<td>( \approx 4 )</td>
<td>( \approx 6 )</td>
<td>(5)</td>
</tr>
<tr>
<td>WM</td>
<td>( \dot{a} = 0,1143(C^*)^{1.0087} )</td>
<td></td>
<td></td>
<td>(6)</td>
</tr>
<tr>
<td>HAZ</td>
<td>( \dot{a} = 0,2547(C^*)^{1.3124} )</td>
<td></td>
<td></td>
<td>(7)</td>
</tr>
</tbody>
</table>

For the same values of \( C^* \), the creep crack growth rates for weld metal and heat affected zone are higher than for base metal by a factor of \( \approx 4 \) and \( \approx 6 \), respectively.
3 Finite element modelling of creep crack growth

The method implemented in this study is the nodal release in the crack path assuming a straight-line crack path for incremental increase.

3.1 Modified nodal release method

The advantage of this method that only the material constants in Norton’s law is required to determine the creep crack growth and $C^*$ parameter, a sequence of incremental steady state finite element analysis, with increasing crack lengths to simulate continuous crack propagation. The starting constraint was applied to the $W=25$ mm and $W=50$ mm CT specimens models with initial crack length of 12.5 mm and 25 mm, respectively. As seen in fig. 8, applied in the y-direction (crack path) equally to experimental value for first step in FE model, the incremental increase in crack length is set for 0.5 mm to represent the increase in $\Delta a$.

![Figure 8. Schematic of node release modeling for creep crack growth.](image)

3.2 Finite Element Models

Creep crack growth simulations were carried out using the finite element program ABAQUS, 2D FE analyses were performed to calculate the $C^*$ for base metal, weld metal and heat affected zone.

Due to the symmetry of CT models, only one-half of BM, WM and HAZ were considered, as shown in fig. 9, the FE mesh mainly consists of 2D, (CPS8R) an 8-node biquadratic plane stress quadrilateral, reduced integration, the element size nearest to the crack front of 0.123 mm, to provide adequately accurate results.

![Figure 9. Two-dimensional FE modeling of CT specimen for creep crack growth.](image)
The procedure followed was to divide the crack front into nine cracks over 9 steps. For total \( \Delta a = 4.5 \, \text{mm} \) by increment of 0.5 mm for each crack at mesh size of 0.1 mm, calculated \( C \) integral for each step starting at step 2.

The results obtained by using described procedure are shown in figs. 10 and 11, together with the experimental results. One can see relatively large difference, especially in the case of plain strain 2D simulation. Anyhow, relatively good agreement between experimental results and 2D plain stress simulation is encouraging for further investigations.

Figure 10. Load-line displacement vs. time obtained from experimental and FE analysis.

Figure 11. Comparison of FEM calculated CCG rate vs. experimental data.
4 Conclusions

On the basis of the results shown one can conclude following:

- Temperature effect on creep strain rate is very strong, limiting P91 usability to 600 °C. Namely, at 625 °C strain rate is approximately 10 times higher than at 600 °C.
- Creep crack growth rate can be correlated with C* fracture parameter, indicating lower crack growth resistance of weldment regions as compared to the base metal.
- Having in mind the simplicity of the finite element modeling used here, the agreement between experimental results and 2D plain stress simulation is good enough. Nevertheless, more investigation is needed, including a 3D simulation to achieve better agreement with experimental results.

References


[12] ASTM E1457-00, Standard test method for measurement of creep crack growth rates in metals, ASTM 03.01, Philadelphia: ASTM 2000, PA 19103, USA.
