Creep performance of welded structures at high temperatures

M Law, W Payten

Materials Division, ANSTO, PMB 1, Menia, 2234, NSW, Australia
Email: mlx@nucleus.ansto.gov.au

Abstract

The operation of high temperature plant is often terminated by localised creep damage of welded joints. Despite its economic significance, weld performance under creep is poorly understood. The creep life of welds cannot be directly predicted by the properties of individual parts of the weld. Numerical modelling of creep processes in welded joints provides a method of predicting creep performance and life.

1 Introduction

Component failure at high temperature often results from local failure in welded joints. These weld failures occur at stresses below the apparent creep rupture strengths of the parent or weld materials (Tu¹, Egger²).

Creep is a progressive, time dependent deformation. In metals it occurs under stress at temperatures greater than approximately 0.4 of the absolute melting temperature. Typical curves of strain against time are shown in fig 1. During creep, internal damage such as precipitate evolution and other microstructural changes reduce the material strength. Rupture occurs due to loss of cross sectional area, internal voiding, and cracking.

The creep response and the time to rupture may be described as power law functions of stress, the strain rate is often described by a Norton power law,

\[ \dot{\varepsilon} = K \sigma^n \]  

(1)

In practice this is complicated by the fact that the creep response varies through time, but the Norton law provides a useful estimate of creep behaviour at low stresses, such as occur in service. Where more accurate data is required other methods may be used such as the use of a time function to modify the creep rate given by the Norton law.
A welded joint consists of a number of metallurgically distinct zones and may be considered as consisting of weld metal, unaltered parent metal, and between these, a heat affected zone (HAZ). The welding process causes local thermal gradients which modify the parent material microstructures and properties, creating a number of microstructures known as the HAZ. The area of the HAZ adjacent to the parent material known as the inter-critical HAZ (IC-HAZ) is often involved in service related creep failure.

1.1 Analytical Solutions
Analytical solutions exist for simple shapes of homogeneous composition (Bailey\(^3\)). Analysis of more complex shapes, composite structures or real world creep data requires use of numerical techniques such as finite element analysis (FEA).

2 Modelling
Modelling was undertaken to demonstrate the effect of variables on the evolution of stresses within the joint. Models were generated of girth welds in a cylindrical pressure vessel operating under internal pressure in the creep regime. The weld preparation type ("V") and weld root (5 mm), vessel dimensions, and parent material creep property remained constant. The models were axissymmetric half models of the weld, heat affected
zone (HAZ), and parent materials. The FEA model generation was automated by use of a computer macro which created and meshed the finite element model based on the weld dimensions.

A number of different variables were modelled in the study. These consisted of 5 included weld angles, 2 weld metals, 3 HAZ material properties, 2 different HAZ widths and 4 different levels of imposed axial loading. The set of cases led to a total of $5 \times 2 \times 3 \times 2 \times 4 = 240$ different conditions. The cases modelled were examined for the maximum first principal stress in each of the materials, weld metal, HAZ and parent material.

The weld was modelled with three material zones ($Tu^+$), these corresponded to the weld metal, the HAZ's, and the parent metal. The materials were assumed to deform in secondary creep according to a Norton power law. The 'n' exponent was 6 for all materials. The coefficients are given in the table below:

<table>
<thead>
<tr>
<th>Material</th>
<th>Creep rate relative to parent</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAZ</td>
<td></td>
</tr>
<tr>
<td>&quot;a&quot;</td>
<td>5 : 1</td>
</tr>
<tr>
<td>&quot;b&quot;</td>
<td>50 : 1</td>
</tr>
<tr>
<td>&quot;c&quot;</td>
<td>100 : 1</td>
</tr>
<tr>
<td>Weld</td>
<td></td>
</tr>
<tr>
<td>creep-soft</td>
<td>10 : 1</td>
</tr>
<tr>
<td>creep-hard</td>
<td>0.1 : 1</td>
</tr>
</tbody>
</table>

These relative creep rates were chosen to cover a range of possible material combinations typical of low alloy ferritic steels. The parent material properties were constant so the effect of the stress redistribution in the vessel on the weldment remained constant in all cases. All cases proceeded to a constant time which corresponded to the relaxed state for the parent material.

3 Results

Stresses tend to accumulate in the creep hard portion of the weld. The weld angle has only a small effect on weld stresses. Axial loadings had the most significant effect on the magnitude of stresses. The stresses are similar for the loadings of 0, 12.8, and 20 MPa, but rise an average of 57% for the 40
MPa axial load cases (where system loading is equal to the nominal hoop stress). These observations are supported by industry experience of failure in service associated with additional axial loading. Results are presented graphically (figs 2, 3, 4).

Fig. 2 Effect of weld angle and axial loading on HAZ stresses.

Fig 3. 80 degree weld, creep-hard weld metal, 12.8 MPa axial loading. Maximum stress is 48.3 MPa. Deformations (shown X 3) are negligible.
Fig 4. 80 degree weld, creep - hard weld metal, 40 MPa axial loading. Maximum stress is 77.4 MPa. Deformations (shown X 3) are significantly greater than in Fig. 1.
4 Life Consumption

The method used to follow life consumption under varying stresses was based on the Robinson life rule where the:

\[
\text{Life Fraction Consumed}_{\text{creep}} = \sum \left( \frac{t}{t_r} \right).
\]

(2)

The equation used to relate life to stress was:

\[
t_r = B \sigma^{-m}.
\]

(3)

The position of maximum life consumption is not apparent from an examination of the maximum stresses at any one time. In the case below (figs 5, 6) the maximum stresses are on the outer wall late in life, but have been higher in the inner wall early in life. In this case the life consumption is highest at the inner surface, an area difficult to inspect.

Fig. 5 Stresses in longitudinal weld.
It was seen in modelling that even when the "relaxed" state is reached, where the stress pattern is constant, the stress maxima which occur at material interfaces tend to increase slowly. Life consumption tends to increase rapidly through life due to its power dependence on stress. In figure 7 below the stress is uniformly increasing while the life consumed (m=5), is rapidly increasing. If a uniaxial creep test shows voiding or microstructural change at 75% of life, in an increasing stress state this 75% life consumption may not occur till 90% of life. One result of this is that methods of life assessment which rely on inspection, depending on inspection frequency, may not show degradation until near failure.
5 Conclusions

The importance of axial loadings in raising stresses was demonstrated. The highest stresses seen with additional axial loadings were more than 100% above the nominal midwall stress. As the time to failure for materials under creep follows an inverse power relationship with stress (typically with \( n = 3 \) to 7), this indicates a large life reduction for these cases. These results reflect industry experience relating type IV cracking and premature failure with additional axial or bending stresses [7].

The parameters which give the optimal weld performance (lowest peak stresses) under normal operating conditions may not provide optimal performance under the unfavourable conditions bought about by additional axial loadings.

To optimise the creep life of welds it is necessary to minimise the creep strain mismatch between the materials, minimise the width of the heat affected zone, and specify low axial or bending stresses on the pressure vessel. Inspection schedules may be designed to target welds with large mismatch between the weld components creep properties, wide heat affected zones, or are assessed as being subject to high imposed axial loadings.
Failure occurs as a result of the interaction of the global stress state and the local creep properties of welded joints. Investigating welded joints solely from either a mechanical or a material viewpoint will not provide a full assessment of joint integrity.

Life consumption modelling provides results which provide a more accurate basis for assessment than a static evaluation of stresses at any one point in time.

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8. References


4] Tu S. Wu R. Sandstrom R " Design against Creep Failure for Weldments in 0.5CR-0.5 Mo-0.25 V pipe" Int. J. Pres. Ves. & Piping. 58. 345-254. 1994