Effect of residual stress on high temperature deformation in a weld stainless steel

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Keywords: Neutron diffraction, 347 stainless steel, VAMAS TWA 31, creep crack initiation, FE-modelling, Compact Tension (CT) specimen.

Abstract.

This paper considers the measurement of residual stresses induced by mechanical loading in a weld Type 347 stainless steel. The work is based in part on an ongoing Round Robin collaborative effort by the Versailles Agreement on Materials and Standards, Technical Working Area 31, (VAMAS TWA 31) working on ‘Crack Growth of Components Containing Residual Stresses’. The specific objective of the work at Imperial College London and HMI, Berlin is to examine how residual stresses and prior straining and subsequent relaxation at high temperature contribute to creep crack initiation and growth for steels relevant to power plant applications. Tensile residual stresses have been introduced in the weld by pre-compression and neutron diffraction measurements have been carried out before and after stress relaxation at 650 °C. Significant relaxation of the residual stresses has been observed, in agreement with earlier work on a stainless steel. Preliminary results suggest that the strains local to the crack drop by over 60% after 1000 h relaxation at 650 °C for the weld steel. The results have been compared with finite element studies of elastic-plastic pre-compression and stress relaxation due to creep.

Introduction

Structural integrity assessment in the current codes for design and assessment of high temperature components are conservative in their treatment of weldments as they do not take full advantage of recent advances in mechanistic understanding of the deformation and failure processes involved. A collaborative effort under the auspices of the Versailles Agreement on Materials and Standards VAMAS Technical Working Area TW31 has been initiated, starting Sept. 2005, to consider the pre-standardisation needs for the methodology of testing and analysis of weldments. This pre-standardization effort will make use of available information and data from the planned Round Robin tests to develop recommendations on weldments testing and analysis procedures. The present paper is part of the ongoing Round Robin effort in the modelling and residual stress measurements for this collaboration.

Welds are usually the weakest link in components, where failure due to creep and/or fatigue is more likely to occur, compared to the homogenous parent material regions. Residual stresses invariably arise during fabrication and repair of components, particularly when components are joined by
welding and can occur during service (e.g. un-planned overloads). Post weld heat treatment (PWHT) can reduce the magnitude of residual stresses, but not completely remove them. Furthermore, PWHT is expensive and can lead to excessive distortion or material sensitisation. Therefore it is important to identify the role of residual stresses and stress relaxation on creep crack initiation and growth in weld components.

**Specimen Geometry**

In the current work the effect of residual stress on deformation and failure in the high temperature (creep) regime of a stainless steel weld material is being examined. For this investigation a Compact Tension (CT) specimen was used, taken from a heat treated stainless steel MMA weld (see Fig. 1). AISI Type 347 material is a stabilised austenitic stainless steel, widely used in high temperature plant applications by the power and petrochemical industries. This type 347 weld metal typically has 5–10% delta ferrite, and a columnar grain structure. Residual stresses have been introduced into the specimen by compression following the technique described in reference [1]. Results are presented here for the case when the maximum pre-compression ($\Delta$ in Fig. 1) is approx. 2 mm, leading to a plastic zone size ($r_p$ in Fig. 1) of approx. 4 mm ahead of the notch (as predicted by finite element analysis).

![Figure 1](image.png)

Figure 1. (a) Method of insertion of residual stress field and region of residual stress measurement, $P =$ applied load, $\Delta =$ load line displacement, $r_p =$ size of plastic zone; (b) Specimen dimensions and location of residual stress measurement.

**Residual Strain Measurements**

Residual stress measurements have been made at ENGIN-X at ISIS, UK, SALSA at the ILL, France and Stress-Spec at the FRM-II, TUM, Germany on the specimen in the plastically compressed condition. Measurements have subsequently been made following a 1000 hour heating at 650 °C (the operating temperature of the material) on ENGIN-X. A summary of the experimental parameters used are shown in Table 1. The specimen demonstrated high hkl 200 texture and in some places difficulty in measurement due to grain size effects. This was observed clearly on the 2-D detector on Stress-Spec. It was observed in the ISIS measurement that the hkl 200 plane gave the strongest reflections (in all three orthogonal measurement directions). Previous work has suggested that the hkl 200 plane is susceptible to the development of intergranular strains and thus has not
been widely used in the measurement of residual strains [2]. However other recommended reflections such as the hkl 311 and 111 planes provided a poor diffraction response.

Table 1. Summary of neutron strain measurement parameters.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Gauge volume [mm$^3$]</th>
<th>hkl</th>
<th>Wavelength [nm]</th>
<th>Scattering angle 2-theta [$^\circ$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISIS ENGIN-X</td>
<td>2×2×2</td>
<td>Rietveld</td>
<td>Full spectrum</td>
<td>90</td>
</tr>
<tr>
<td>ILL SALSA</td>
<td>1×1×1</td>
<td>200</td>
<td>0.176</td>
<td>71.2</td>
</tr>
<tr>
<td>FRMII/TUM Stress-Spec</td>
<td>2×2×2</td>
<td>200</td>
<td>0.203</td>
<td>68.8</td>
</tr>
</tbody>
</table>

A comparison of the bulk strain calculated from an ENGIN-X Rietveld analysis is compared to the 200 and 311 single peak fits in Fig. 2. It is seen that within experimental uncertainty there is excellent agreement between the measurements, suggesting that in this case the hkl 200 plane appears not to experience significant intergranular strains. Note that one would also expect to see elastic anisotropy between the hkl 311, Rietveld and hkl 200 strains (i.e. normally the hkl 200 is the most compliant plane whereas the 311 and Rietveld represent strains nearer to the bulk response of the material), although this was not perceivable in the current set of measurements.

Figure 2. Comparison of strain in the $\varepsilon_{22}$ direction, derived from single and Rietveld peak fits from ENGIN-X. Specimen measured following pre-compression at room temperature

Figure 3 shows the residual elastic strain distributions in two orthogonal directions at the centre of the specimen along the measurement line defined in Fig. 1(b). As expected, the highest strain is normal to the plane, $\varepsilon_{22}$, the peak is approx. 3000 $\mu\varepsilon$, tensile. There is some variation between the measurements at the three institutions but these generally fall within the quoted experimental scatter (typically $\pm$ 150 $\mu\varepsilon$). The measured peak strain is similar to that presented for pre-aged parent 316H stainless steel from Turski et al. [4] (see Fig. 3a) measured using high energy X-rays. This investigation used an identical specimen geometry and the maximum displacement was approx. 2.3 mm [5]. The strain measurements in [4] obtained using neutron diffraction are somewhat lower, perhaps due to the larger gauge volume used and differences in elastic modulii. Also included in the
figures are the residual elastic strains predicted from finite element (FE) analysis. The finite element prediction is based on an isotropic material with Von-Mises flow behaviour and isotropic hardening. Further details of this analysis are available in [3]. Good agreement can be seen between the neutron and FE predictions. However, there are discrepancies in the measurements and predictions close to the notch root in the $\varepsilon_{22}$ direction. This difference may be partly due to the steep strain gradient predicted by the FE model or to the isotropic strain hardening assumption assumed in the model. The neutron measurements have a relatively large gauge volume compared to the extent of this strain gradient; hence an averaging affect is seen.

![Graph](image)

**Figure 3.** Strain measurements from neutron diffraction following pre-compression (a) Strain normal to the notch plane, $\varepsilon_{22}$ (b) Strain parallel to the notch plane, $\varepsilon_{11}$

Following precompression the specimen has been placed in a furnace at 650 °C and maintained at temperature for 1000 hours to represent typical service conditions for the material. Figure 4 shows the effect of a heat treatment on the residual elastic strain distribution normal to the notch, which is a measure of the stress relaxation. These measurements have been taken at ENGIN-X. It is clear that...
the strain at the notch has been significantly relaxed. A similar relaxation in strain was observed for
the type 316 H stainless steel in [4], though the exposure time and temperature was different.

![Graph of Relaxation of strain normal to the notch plane, $\varepsilon_{22}$, following exposure
to 650 $^\circ$C at 1000 hours.](image1)

Figure 4. Relaxation of strain normal to the notch plane, $\varepsilon_{22}$, following exposure
to 650 $^\circ$C at 1000 hours.

![Graph of creep strain with and without pre-compression in a specimen, subsequently loaded at 20 kN.](image2)

Figure 5. A comparison of the finite element predictions of the creep strain with and without pre-compression in a specimen, subsequently loaded at 20 kN.

**Effect of residual stress and strain on creep deformation**

The measurements shown in Fig. 4 illustrate the relaxation of residual stress when there is no additional (primary) load. If a specimen containing residual stress is maintained at temperature with no primary load the residual stresses will relax to zero due to creep as the elastic strains in the specimen are converted to creep strains. It is also of interest to consider the case when the residual
stress field interacts with a primary load. The numerical studies indicate that introduction of a residual stress leads to an acceleration of the evolution of creep strain during the early stages of loading. Fig. 5 shows a typical finite element prediction for the creep strain evolution for a constant primary load of 20 kN applied in the opposite direction to the load \( P \) in Fig. 1(a) at the operating temperature. The strain shown is the equivalent (Von Mises) creep strain in the most highly strained element ahead of the notch with and without pre-compression. The analysis assumes that the material exhibits primary-secondary creep response in the creep regime (further details of the material behaviour are in [3]). It is clearly seen in Fig. 5 that there is an initial amplification of creep strain rate due to the residual stress field, although at longer times, the predicted creep strain levels in the specimens are similar. The large amount of creep strain accumulated in the early stages of creep \((t < 1000\) hours) in Fig. 5 may be significant when the time to crack initiation is considered.

Discussion and Conclusion

Residual strains due to pre-compression of a notched (CT) type 347 weld stainless steel have been measured by neutron diffraction at three facilities. Comparison of the measured residual strains has been made with results from FE predictions and good agreement has been achieved. Similar relaxation behaviour has been observed with previous analysis [4] on a pre-aged parent 316H material which was exposed at 550 °C for 4600 h. In both cases there was a substantial drop over 60% in strain local to the crack tip following high temperature exposure. Finite element analysis has shown that such a residual stress field can lead to a significant enhancement in creep rates during the early stages of component life. The significance of these effects on the time to crack initiation in components containing residual stress fields is under investigation.

Acknowledgements

The authors would like to thank the local contacts at ISIS (Ed Oliver, Javier Santisteban), FRMII, TUM (Michael Hofmann) and ILL (Thilo Pirling and Darren Hughes of Fame 38) for the valuable assistance and the institutes for the provision of neutron beamtime. Thanks are also due to Dave Gladwin of British Energy who carried out the pre-compression tests. Helpful discussions with John Bouchard and Manus O’Donnell of British Energy are gratefully acknowledged.

References