REMAINING CREEP LIFE ASSESSMENT OF WELDS IN STEEL PRESSURE VESSELS

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The remaining life of welded pressure vessels subject to creep is often limited by the life of the welds. Results from miniature specimen post-exposure creep tests on weld metal, HAZ and parent materials from a longitudinal weld in a thick-walled (99 mm) $2^1/_4$Cr1Mo steel header are presented. The remaining life of the weld is estimated using three creep data analysis methods on measured HAZ and weld metal creep properties. The weld metal has the poorest creep properties suggesting it is life limiting. Norton and θ-projection analyses of the weld component materials enable constraint effects to be taken into account. This is expected to give a more realistic estimate of remaining life than by using simple extrapolation of isostress creep results from cross-weld samples.

INTRODUCTION

The remaining life (RL) of large welded components subject to creep is often limited by the life of the welds. This is particularly important for longitudinally seam-welded pressure vessels such as boiler headers, steam pipes and chemical reactor vessels where the welds experience the full pressure-induced hoop stress. These vessels were usually designed on the basis that, provided the welds were subjected to 100% inspection, they were assumed to be as strong in creep as the parent metal (1). However, experience (failures of headers and steampipes) and direct measurement of creep rates has shown that the creep strength of weldments is generally less than that of the parent material. Estimating the RL of welded vessels then often becomes a matter of estimating the remaining creep life of the welds. This is difficult because:

- welds are heterogeneous and the various zones, ie. weld metal and different regions of the heat affected zone (HAZ), have different creep properties;
- weaker, faster-creeping weld zones are constrained by adjacent, stronger zones and so off-load stress onto the stronger zones (2) – conventionally-sized specimens containing welds cannot reproduce such constraint and so creep data may be specimen-size dependent (3);
- welds are invariably subjected to a multiaxial stress state and almost all creep

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data for remaining life studies are from uniaxial creep tests;

- cracks can nucleate and grow in very small specific zones of the weld and the remaining life is then governed by the creep crack growth rate (1).

Current methodologies for dealing with the first two aspects of this complexity are applied here to creep results on material taken from a welded boiler header. These creep studies and the development of the analysis methods formed part of a recent three-year project at Ansto funded by the NSW electricity utility, Pacific Power.

CREEP TESTING

Samples were removed from a $2^1/_4$Cr1Mo steel longitudinally seam-welded final superheater outlet header which had dimensions 508 mm OD and 99 mm wall thickness and had run for 120,000 hours at nominal conditions of 540°C and 17.24 MPa pressure. The samples, which were ≈38 mm long x 20 mm wide x 7 mm deep, were removed in the tangential direction across the longitudinal weld from the hottest part of the header. Miniature creep specimens (2 mm diameter x 10 mm gauge length) were prepared from the samples and tested in vacuum creep rigs as previously described (4). The small specimen size enabled creep specimens containing only weld metal, only HAZ material, or only parent metal in the gauge length to be made. Hardness measurements were made and the samples were also metallographically examined before and after creep testing.

RESULTS AND ASSESSMENT

The microstructures were coarse-grained ferrite/bainite, typical for the material in the normalised and tempered condition and the submerged arc weld (SAW) in the welded and post-weld heat treated condition. The microstructures were only slightly degraded, with evidence of some spheroidisation and secondary carbide precipitation.

1. Analysis of creep data. It is generally accepted that, currently, the most reliable method for remaining creep life assessment is temperature-accelerated isostress creep testing and the present data are shown in this form in figure 1. The data show little scatter, despite the large grainsize (ASTM 0) and small specimen gauge diameter. This has enabled good curve fits ($r > 0.97$) to be made to enable extrapolation to the operating temperature for a RL estimate. The ISO 40 MPa mean line for $2^1/_4$Cr1Mo steel is also shown; it shows even the weld metal to have near-new creep properties.

The creep data have also been assessed using the Norton equation and the θ-projection method. The Norton type rupture life over limited ranges of stress and temperature can be represented by:

$$t_f = B\sigma^{-m} e^{Q/RT}$$

where t_f is the rupture life, B is a constant, m is the stress index, Q is the creep activation energy, R is the gas constant, and T is the absolute temperature. Rupture data were plotted on log t_f vs log stress axes and regression fits to the data used to determine B, m and Q.

The θ-projection method fits equations of the form:

$$\varepsilon = \theta_1\left(1 - e^{-\theta_2 t}\right) + \theta_3\left(e^{\theta_4 t} - 1\right)$$

to the creep curves. The resulting θ_is were used to determine the equations relating the θ-coefficients and the rupture strain, ε_f, to stress and temperature, ie.

$$\log \theta_i = a_i + b_i\sigma + c_i T(\mathrm{K}) + d_i \sigma T(\mathrm{K})$$

for i = 1, 2, 3 and 4, and

$$\varepsilon_f = a' + b'\sigma + c'T(\mathrm{K}) + d'\sigma T(\mathrm{K})$$

Having determined a, b, c, etc. by regression analysis, these equations can then be used to estimate the rupture life and creep curve at any temperature and stress.

2. Isostress tests on weld material. In the present work the small sample size meant that the creep properties of weld metal, parent metal and HAZ could be determined independently. This obviates the problems of constraint effects and specimen size (3), cross-weld specimens behaving as a series of parent, HAZ, and weld metal units (5), and the resulting conservative prediction of RL (2). Additional creep tests at 50 and 60 MPa on parent and HAZ material were done to enable determination of the stress variation for a full Norton and θ-projection analysis. The times to rupture at 40 MPa and 540°C (nominal operating temperature) and 580°C (mean maximum stub temperature) predicted by the three analysis methods are shown in table 1. For comparison, predictions for new base material are also shown.

3. RL estimation taking account of stress redistribution. A conservative analysis of the results of table 1 would assume the predicted lifetime of the vessel to be governed by the creep properties of the weld metal. However, Coleman and Parker (2) showed

TABLE 1 – Estimates of time to rupture at 40 MPa

		Time to Rupture (h)		
Temp (°C)	Material	Iso-stress plot	θ-projection	Norton eqn
580	New parent	1.5×10^5 (ISO)	2.6×10^5 (NRIM)	–
540	New parent	1.5×10^6 (ISO)	3.3×10^6 (NRIM)	–
580	parent	1.0×10^6	5.8×10^5	1.9×10^6
540	parent	1.3×10^7	†	5.6×10^7
580	HAZ	1.0×10^5	8.9×10^4	1.5×10^5
540	HAZ	7.8×10^5	†	6.4×10^5
580	weld	8.3×10^4	†	1.1×10^5
540	weld	6.4×10^5	†	1.4×10^6
640	weld	3.8×10^3	3.5×10^3	3.8×10^3

† θ-projection not possible due to ductility trough in strain-to-failure data

that the combined effects of constraint, and different creep properties in different components of the weld, caused stresses in weldments to be redistributed – regions of low creep strength shed load to regions of higher creep resistance and the actual stress experienced by the weaker weld zones may be considerably less than expected. Accordingly, the predicted life based on the properties of the weakest zone may be conservative.

Van Zyl (6) has presented an alternative analytical method which does not require the complex 3-D elastic-plastic finite element analysis used in (2) for estimating the extent of stress redistribution. The method uses the Kachanov-Rabotnov-Cane equation in differential form to assess the RL of welds, ie.:-

$$\dot{\varepsilon}t = \varepsilon_s\left(\frac{t}{t_f}\right)\left(1-\frac{t}{t_f}\right)^{\frac{\varepsilon_s}{\varepsilon_f}-1} \qquad (1)$$

where ε_s is the simplified Monkman-Grant constant, t_f is the rupture life; t is the service life and ε_f is the rupture strain. Van Zyl assumes that the parent metal and the weld components creep at the same rates (it is generally observed that vessels expand symmetrically) – thus the weld components which have the poorer creep properties must then be subjected to a lower stress, ie. the off-loaded stress. Accordingly, the numerical value of equation 1 is determined for the parent metal using measured or literature-derived creep data. This value is set equal to equation 1 for the weld components for which the unknown t/t_f can be solved by iteration, thereby making possible the calculation of t_f and σ_c, the off-loaded stress.

The Van Zyl (6) analysis has been applied to the results to assess the extent of stress redistribution in the welds and its predicted effect on time to rupture, as shown in table 2. The results suggest that large reductions in the stress and corresponding increases in predicted time-to-rupture are expected.

DISCUSSION

The use of special techniques to enable removal of samples from longitudinal welds and of miniature creep specimens tested in vacuum with creep strain measurement has meant that a relatively large amount of creep data can be obtained. Thus the creep behaviour of the weld and parent material has been well-defined and current assessment methods can be applied and compared.

The isostress, θ-projection and Norton methods all give comparable results which, for this example, predict times to rupture of the order of the header design life at its operating conditions. The θ-projection and Norton analyses were limited by the lack of data at different stresses for the weld metal. However, the stress variation terms in these two analyses may be estimated from a database of similar results. Generally they have the advantage over the isostress method that they can make predictions over ranges of stress as well as temperature. This enables the results to be applied to regions of localised higher or lower stresses, such as occur in weldments due to stress redistribution, or to assess the effect on RL of changes in operating temperatures and pressures.

TABLE 2 – Stress redistribution in a weldment due to creep (after Van Zyl)

Material Parameter	Parent		Weld		HAZ	
Stress exponent, m	6		4.1		4.1	
Monkman-Grant const., ε_s	0.0780		0.126		0.156	
Norton pre-stress coeff't, B	6.73E-13		1.40E-11		1.66E-11	
Activ'n energy, Q (kJ/mol)	452		367		376	
Service life consumed, t (h)	120,000		120,000		120,000	
Rupture strain, m/m, ε_f	0.4		0.2		0.4	
Temperature (°C)	540	580	540	580	540	580
Unrelaxed stress (MPa)	**40**	**40**	**40**	**40**	**40**	**40**
Unrelaxed time to rupt, t_f(h)	1.80E7	7.84E5	1.43E6	1.12E5	6.44E6	4.75E5
Unrelaxed life fraction, t/t_f	0.01	0.15	0.08	1.07	0.02	0.25
Relaxed stress (MPa)	**40**	**40**	**19.2**	**22.7**	**26.3**	**30.5**
Relaxed time to rupt., t_f (h)	1.80E7	7.84E5	2.90E7	1.15E6	3.59E7	1.45E6
Relaxed life fraction, t/t_f	0.01	0.15	0.004	0.10	0.003	0.08

The θ-projection method gives a more accurate description of the creep curve than the Norton method and has the added benefit that it can be used to predict times to given strains. However, a problem found with the method is its inability to cope with the existence of ductility minima in the creep data. A ductility minimum was found for both parent and weld material. The occurrence of such minima is well documented (7) and means that the θ-projection coefficients need to be determined from data beyond the minimum strain to enable predictions out to long times.

CONCLUSIONS

1. The removal of samples from welds and determination of their creep properties enables a direct measure of the state of the material. The scatter in the creep data are minimal despite the coarse grain size and the relatively small gauge diameter.
2. The various creep data analysis methods give similar results, although the Norton and θ-projection methods are more useful because they can be used over a range of stresses as well as temperatures.
3. Remaining life estimates based on weld metal or HAZ creep measurements are likely to be conservative. Taking constraint effects into account gives lower stresses and longer predicted times to failure.

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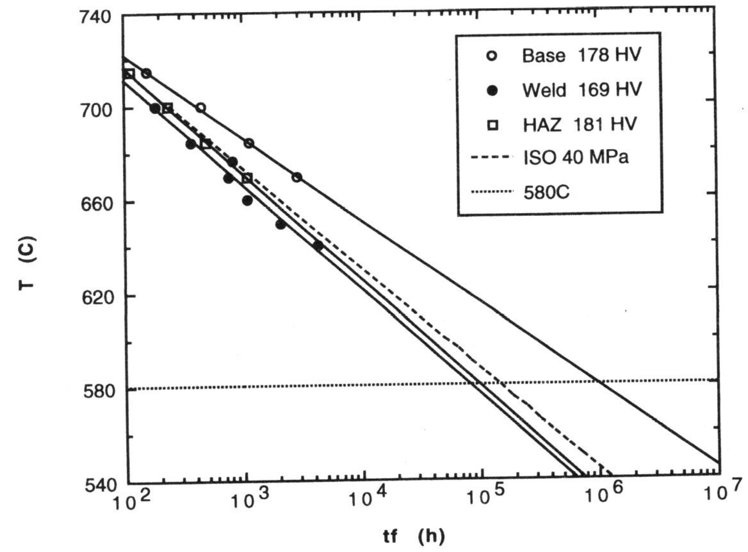

Figure 1 Isostress plot (40 MPa) showing results of miniature specimen vacuum creep tests.