MATERIALS FORUM VOL. 27 (2004) 45 - 53

THE PERFORMANCE OF AN EMERGENCY COLD WELD REPAIR ON A 2.25CR-1MO LONGITUDINALLY SEAM-WELDED PRESSURE VESSEL

E. Budzakoska, D. Dunne, M. Law[1], H. Li[1], B. Small[2]

School of Mechanical, Materials and Mechatronic Engineering, University of Wollongong, NSW, 2521
ANSTO - Materials and Engineering Science, PMB1 Menai, NSW, 2234[1]
Connell Wagner –PPI, 116 Military Rd, Neutral Bay, NSW, 2089[2]

ABSTRACT

This is an overview of a current three-year project for the Cooperative Research Centre for Welded Structures entitled "Integrity of High Energy Piping". The results of a performance evaluation conducted on an emergency cold weld (controlled deposition temperbead, TB) repair applied to a 2.25Cr-1Mo steel header using the manual metal arc welding (MMAW) process are described. With repair rather than replace being a far more viable option, welding is increasingly used for performing repairs, replacements, retrofits and modifications to elevated temperature plants. However, with the considerable cost and time involved with performing conventional post weld heat-treatment (PWHT) repairs, in today's economic environment utility owners are increasingly forced to turn toward other alternatives, such as cold weld repairs. These require no PWHT and rely on a controlled deposition process – precise weld bead placement and heat inputs etc to achieve tempering of the HAZ. However, much of the research conducted on these repair techniques has used accelerated high temperature creep testing to demonstrate their integrity. How well this reflects their real-life performance is unknown. Therefore this study provides an opportunity to evaluate the effects of service exposure on the performance of an emergency cold weld repair.

Keywords: Cr-Mo steels, post-weld heat-treatment, cold weld repairs, controlled deposition (temperbead) techniques, longitudinal seam welds, manual metal arc welding process, mechanical properties

1. INTRODUCTION

2.25Cr-1Mo steel is low-carbon and low-alloy ferritic steel with excellent creep and oxidation resistance at elevated temperature used extensively in the power, chemical and oil industries as a structural steel. Power generating equipment such as steam pipes and headers are typically used under the combined effects of internal-pressure loading and high temperature exposure, conditions that cause creep damage.

Creep damage in the form of early crack formation through grain boundary creep cavitation first occurs in weldments. Therefore, weldments are the life-limiting factor in most high-temperature components operating in the creep regime.[1-4] Longitudinal seam welds are common in large high temperature steam lines, piping and other components, such as headers. These welds are the focus of much remaining life (RL) assessment research,[5-14] for two reasons. Firstly, the unfavourable orientation of the seam in relation to the hoop stress introduces the risk of catastrophic failure. This can lead to injury and/or loss of life of plant personnel, as well as considerable damage to the steam line or header body resulting in lengthy and undesirable outages. Secondly, there is a history[15,16] of catastrophic failures in the US of longitudinally seam welded hot reheat steam lines, which caused equipment damage, significant outage costs and court litigation. One failure also caused the loss of six lives and injured 10 personnel. Repairs in these components are often difficult and costly but the price of replacement is far greater, therefore while cutting costs and optimising component availability, it is very important that plant integrity is never compromised.

Welding of thick-section components introduces residual stresses in the weldment, as a result of the thermal contraction during the welding process and hence post weld heat-treatment (PWHT) is often required. PWHT relieves the material of these stresses by modifying the microstructures of the weld metal (WM) and heat-affected zone (HAZ) and provides improved mechanical properties of the weldment. However, when conventional weld repairs are not possible due to the considerable time required for PWHT and the costs resulting from this, then cold weld repairs are an alternative.[17]

Cold weld repairs are welds that require no PWHT; also referred to as non-PWHT techniques or controlled deposition techniques (CDT). These rely on controlling and maintaining precise weld bead placement and heat inputs etc to achieve tempering of the HAZ. Development of these techniques began in the early eighties and were initially trialed on carbon steels, where success was achieved in industrial applications. There is continuing work on expanding the application of these techniques to include Cr-Mo and low-alloy steels. Much of the research[18-23] conducted on these repair techniques has used accelerated high temperature creep testing to demonstrate their integrity. How well this reflects their real-life performance is unknown. However, a unique opportunity presented itself when a 2.25Cr-1Mo longitudinally seam-welded reheater outlet header operating at 540°C and a 28.9MPa hoop stress failed prematurely after 107,000hours. The unit was repaired in-situ with a cold weld repair and then returned to service for a further 5000 hours, before finally being retired when a replacement header was available. This component is therefore the subject of the present study providing an opportunity to evaluate the performance of a service-exposed longitudinal seam, cold weld repair applied to a 2.25Cr-1Mo pressure vessel.

The main objective of this study was to evaluate and characterise systematically the metallurgical and mechanical property performance of the service-exposed cold weld repair relative to both the service exposed conventional fabrication weld and parent metal.

2. BACKGROUND

The longitudinally seam welded reheater outlet header had been in service for a period of 107,000 hours at 540°C and a hoop stress of 28.9MPa prior to failure. The unit was repaired in-situ without PWHT (cold weld repair, using the MMAW process) and returned to service for a further 5000 hours, before finally being retired when a replacement header was available.

The header dimensions are OD of 756 mm, a wall thickness of 48mm, and a length of 16 m. It was fabricated using 2.25Cr-1Mo rolled steel plates (ASTM SA387 Grade 22 steel). The header was constructed in two halves each 7.5 m long, consisting of four longitudinal submerged arc (SA) seam welds at both the 12 o'clock and 6 o'clock positions and finally a circumferential girth (butt) weld joining the two halves together. The test material was machined from the retired header containing service-exposed non-PWHT temperbead (TB) repair welds.

The test material was supplied in the form of two plate segments approximately 400mm wide, 900mm long, and 48mm thick. One plate segment was sourced from the bottom right-hand side (RHS) seam-weld and the other was sourced from the top RHS seam-weld. Each plate consisted of base metal and weld metal material with the seam weld located along the centre portion of the plate. Both original SA fabrication weld metal and non-PWHT TB repair weld metal were contained in each plate. Figure 1 shows the location of the fabrication weld metal at one end and the TB repair weld at the other. The cross-sectional view of the steel plate in figure 1 for each weldment is provided in Figure 2.

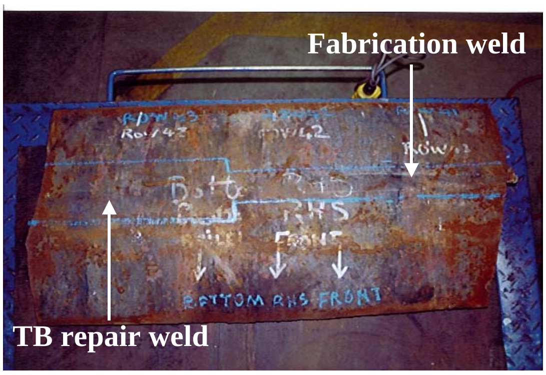


Figure 1. A plate segment showing the approximate outline of the TB repair on the LHS and SA fabrication weld on the RHS.

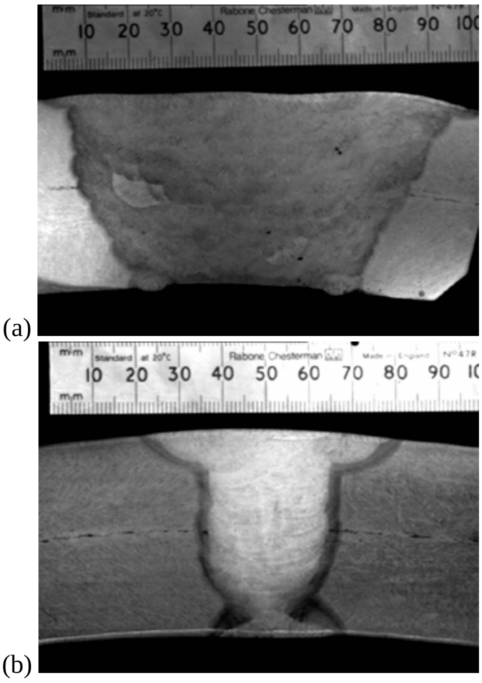


Figure 2. Shows the cross sectional view of each weldment indicated in Figure 1. (a) TB repair weld and (b) SA fabrication weld

3. EXPERIMENTAL PROCEDURES

Mechanical tests and metallurgical characterisation techniques were used to evaluate the TB repair welds in the as-received, retired condition. These mechanical property and microstructural characterisations were completed with the aim of collecting all the necessary data to enable the development of correlations that may exist between the mechanical properties and the microstructural condition of the header and repair weld. The mechanical property characterisation involved hot tensile (miniature sample), Charpy impact, hardness and creep-rupture testing, while the metallurgical characterisation consisted of compositional analysis, surface replication, conventional metallography and post-test fractography. Table 1 lists the tests and specimen locations.

Table 1. Test Schedule

Test	Location on Specimen
Chemical analysis	PM and WM
Microstructural characterisation – Metallographic replication – Conventional destructive through-wall microstructural samples	PM, WM and HAZ
Fractography	Creep-rupture / miniature tensile fracture surfaces
Hardness traverses (3): 1. Outer wall 2. Mid-wall 3. Inner wall	Fabrication weld TB repair weld
Miniature tensile	PM and WM
Charpy impact	PM and WM
Creep-rupture	PM, WM and cross-weld region

The test specimens were machined from 20mm thick slices taken from both the TB repair and original fabrication weldments. All test specimens were machined transverse to the welding direction. The 20mm thick slices taken from each weldment are shown in Figure 3, with the respective test specimen locations also indicated.

3.1 Microstructural characterisation

3.1.1 Compositional analysis

Samples approximately 25mm x 25mm x 25mm were taken from the mid-thickness of the plate from the parent metal, TB-repair and fabrication weld metals. These were then chemically analysed to determine the chemical composition in terms of average weight %.

Figure 3. Shows the preparation of test specimens from each weldment, TB repair weld LHS and fabrication weld RHS.

3.2 Microstructural examination

3.2.1 Surface metallographic replication (MR)

Replicas were taken of the parent metal, both HAZs (either side of the weld metal) and weld metal for the respective weldments investigated. These were then examined under light optical microscopy (LOM).

Prior to preparation of the destructive through-wall metallographic samples, replicas were also taken on the through-wall thickness of the plate. Again these were performed on the parent metal, both HAZs (either side of the weld metal) and weld metal for both weldments investigated. This was an additional measure taken to verify the presence of any creep damage that may have been overlooked in the surface replications.

3.2.2 Conventional metallography

Three through-wall samples (10mm cube) were taken from the outer-wall, mid-wall and inner-wall regions of the plate respectively. These were taken for the parent, weld metal and one HAZ, for each weldment supplied; the samples were then mounted and metallographically prepared for microstructural analysis. These samples were oriented in the transverse direction, perpendicular to the welding direction. Additionally, four samples were also prepared in the longitudinal direction to examine the microstructure for the presence of inclusion stringers in this orientation.

3.2.3 Post–test fractography

Post-test creep-rupture and miniature-sample tensile test specimens were prepared for fractography. This simple technique allows topographical examination of the fracture face under the scanning electron microscope (SEM). This was performed for both test specimens.

3.3 Mechanical property characterisation

Tensile testing
Miniature sample tensile specimens were tested with a 24 mm gauge length (GL) and 3 mm diameter. Specimens were machined from parent and weld metal regions in the transverse orientation. The tests were performed at room temperature (RT) and elevated temperature. Due to the smaller size test specimens utilised in this testing, minor modifications to the test methodologies specified had to be implemented.

Room Temperature
The RT miniature sample tensile tests were conducted in accordance with AS1391-1991. The tests were run in strain control with a preset strain rate of approximately 8 x 10^{-4} mm/mm/sec, as specified in AS1319-1991.

Elevated Temperature
The elevated temperature miniature sample tensile tests were conducted along the lines of AS2291-1979. Sample extension was measured by means of an LVDT (linear variable differential transmitter) mounted outside the furnace.

The elevated temperature tests were performed at 540, 580 and 610°C. During these tests, the test temperatures were continuously measured and monitored using two K-type thermocouples attached at either end of the sample GL and connected to two hand-held electronic thermometers.

Charpy-impact testing
Standard full size Charpy Vee-Notch impact tests were performed in accordance with AS1544-2-1989. A limited amount of sample material was available for these tests therefore only one test was conducted at each individual test-temperature. The tests were performed at seven different temperatures within the range –196˚C and 210˚C.

Hardness
Vickers (HV10) hardness traverses of the weldment profile (Figure 4) were performed in accordance with AS1817-1991, for each weld investigated. Three traverses were completed approximately: 2 mm in from the outer wall; at the mid-wall region approximately 5-10 mm above any impurity segregation; and 2 mm in from the inner wall. These three traverses were then averaged to give a representative hardness profile.

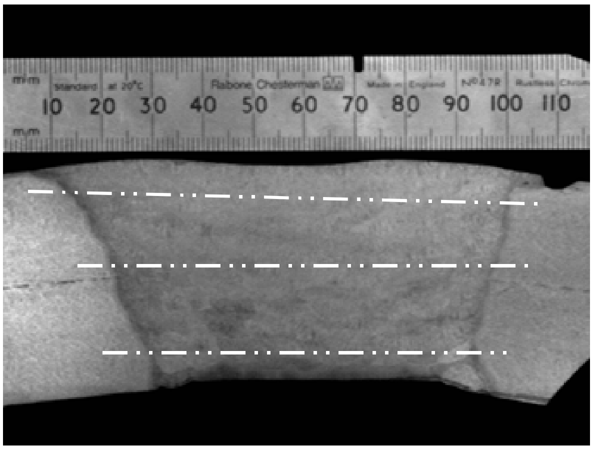


Figure 4. Shows the location of the hardness traverses

Creep-rupture testing
Standard full-size creep-rupture specimens were tested with a 40mm GL and 8mm diameter. Specimens were machined from the parent metal and TB repair weld metal as well as cross-(X)-weld regions (composite samples containing parent metal, HAZ and weld metal, with the fusion line located at the centre of the gauge length) for both the TB repair and fabrication welds. All samples were machined from the transverse direction, perpendicular to the welding direction.

The creep-rupture tests were conducted at 40MPa, which is considered a conservative stress level for headers under normal operating conditions. In order to enable an iso-stress extrapolation to be performed, the tests were accelerated using four elevated test temperatures in the range 640-685˚C.

The tests were performed in accordance with ASTM E139-83 (1990) and in an argon atmosphere, limiting oxidation of the sample during testing. The test specimens were dead-weight loaded using lever-type creep machines. Creep displacements were continuously measured across the shoulders of the test specimens until rupture, using an LVDT. This enabled a creep strain (ε) versus time (t) curve to be generated for each. During testing the temperature of both the top and bottom regions of the specimen as well as the specimen extension were continuously monitored and recorded, using a data acquisition and logging system.

4. RESULTS AND DISCUSSION

Metallurgical examination and mechanical tests were performed on the parent material, original (conventional) fabrication welds and the non-PWHT TB repair welds. Although, the properties of both weld metals will be the main focus herein.

4.1 Microstructural characterisation

Compositional analysis
The results of the compositional analyses are provided in Table 2, also included are the ASTM SA387 Grade 22 and AWS/ASME SFA A5.5 standard values for virgin base metal and weld metal respectively.

For both the TB repair and fabrication weld metals, all elements except manganese (Mn >0.85%), P (>0.015%), S (>0.013%), and Si (only marginally >0.35%), fell within the AWS/ASME SFA A5.5 weld metal specification.

Microstructural examination
The structure was found to be predominantly bainitic. Overall, the investigations revealed the microstructures to be satisfactory, with no visual evidence of creep cavitation or significant microstructural damage.

A high concentration of non-metallic inclusions is present throughout the HAZ and the fabrication weld metal. This high inclusion concentration in the weld metal generally coincides with weld metal deposited using a high acid flux 2.25Cr-1Mo sub-merged arc (SA) welding process. Two types of inclusions were identified under LOM in the HAZ microstructures; these were predominantly oxide and sulfide types.

Post–test fractography
The fractographic examinations of the parent metal and weld metal creep-rupture and miniature sample tensile specimens did not identify any anomalous structures.

The fracture morphologies of the miniature sample tensile specimens tested at 580°C for parent metal, fabrication weld metal and TB repair weld metal are shown in Figures 5. As evident in these micrographs the amount of deformation displayed by the three materials decreased in the order:

Parent > Fabrication weld metal > TB repair weld metal

Table 2. Chemical Compositions

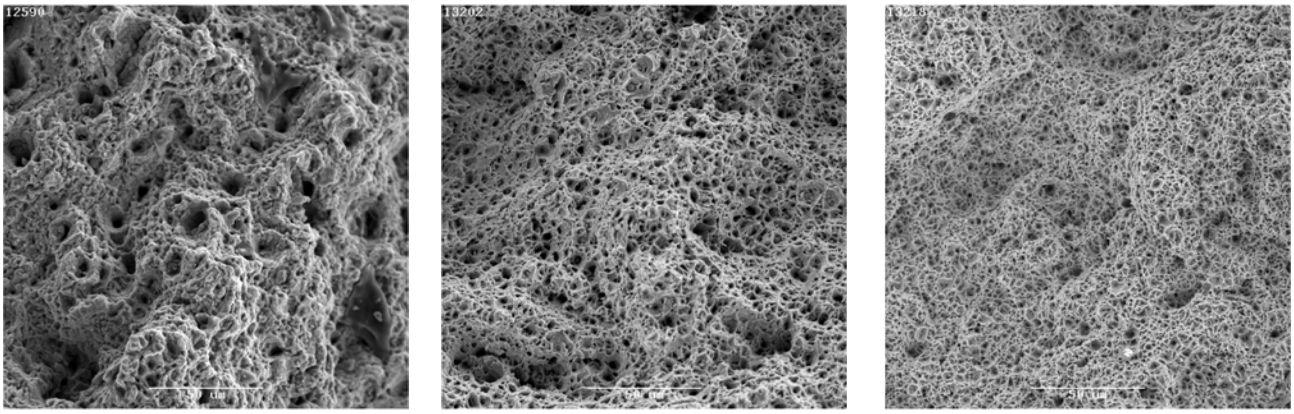
Element	Parent	ASTM SA387-78	Fabrication weld metal	TB repair weld metal	AWS/ASME-SFA A5.5
Carbon	0.135	0.15	0.045	0.07	0.08
Silicon	0.26	0.5	0.33	0.35	0.35
Manganese	0.465	0.66max	1.09	0.86	0.85
Phosphorus	0.0115	0.035	0.0205	0.0085	0.015
Sulfur	0.016	0.035	0.016	0.013	0.013
Chromium	2.24	2.62max	2.16	2.39	2.2
Molybdenum	0.93	1.15max	0.95	1.1	1.05
Nickel	0.17		0.11	0.08	
Copper	0.17		0.09	0.08	
Vanadium	0.008		0.011	0.0195	

Non-metallic inclusions were also observed throughout all of the samples. Small spherical inclusions dominated in the weld metal samples. From the fractography examinations it is clear that the fabrication weld metal contains significantly more inclusions compared to the TB repair weld.

For the weld metal samples (Figures 5b and c), failure was predominantly observed to be by nucleation /and coalescence of voids and particularly through decohesion of the particle-matrix interface. The weld metal samples were characterised by voids of a very fine scale. Considering that the inclusions present in the weld metal are predominantly spherical in shape and usually smaller than those typically found in parent metal, this observation was found to be consistent with the observed microstructure.

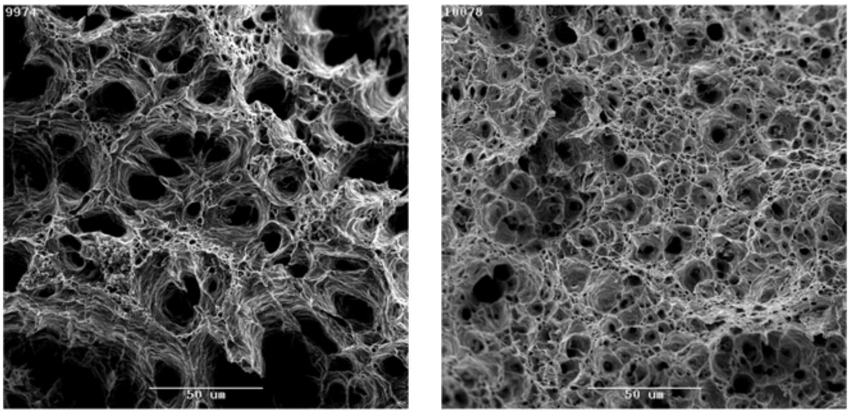
The fracture morphology of the creep-rupture specimens for both parent and TB repair weld metal are shown in Figure 6. The failure mode was ductile fracture by transgranular crack propagation.

Overall, the parent metal and weld metal microstructures appeared to be normal for steel exposed to the prescribed service conditions. Fractography of both cross-weld (composite) samples are still in progress.



(a) (b) (c)

Figure 5. Shows SEM micrographs of the fracture morphology of the miniature sample tensile test specimens tested at 580˚C. (a) Parent metal, (b) Fabrication weld metal and (c) TB repair weld metal. Electron micrographs x500



(a) (b)

Figure 6. Shows SEM micrographs of the fracture morphology of the creep-rupture specimens tested at 665°C (a) parent metal, (b) TB repair weld metal. Electron Micrographs x500.

4.2 Mechanical property characterisation

Tensile testing
Room temperature miniature tensile tests were performed to characterise the tensile properties. The elevated temperature properties were determined using a more complex, high-temperature test method. These tests were performed at 540, 580 and 610˚C.

The tensile properties of the TB repair weld metal were noticeably higher than both the fabrication and parent materials. Overall the TB repair weld properties were superior to those of the service exposed fabrication weld.

Charpy-impact testing
A limited amount of sample material was available for these tests therefore only one test was conducted at each individual test-temperature.

In general, the TB repair weldment appears to have restored notch-toughness to the degraded weldment, with the ductile-brittle transition temperature curve of the TB repair weld showing characteristics similar to the parent metal.

Hardness
Three hardness traverses of the weldment profile were performed for each weld investigated. These were completed at the outer wall; mid-wall and inner wall regions of the header cross-section. These traverses were then averaged to give a representative hardness profile. Figure 7 shows the representative hardness profiles of the TB repair and fabrication weldments taken from the bottom RHS seam weld.

The hardness values were:
Parent < Fabrication weld metal < TB repair weld metal

The following hardness observations were noted:
- The TB repair weld has a substantially higher hardness than the parent metal and the fabrication welds.
- No normalisation of the hardness properties across the parent / HAZ / weld metal zones is evident in the TB repair weld (as is the case for the parent / HAZ / fabrication weld metal). However, this may occur with prolonged service exposure.

- For both the TB repair and fabrication welds the top weld of the header was found to be marginally softer, this is probably because it was exposed to a high service temperature.

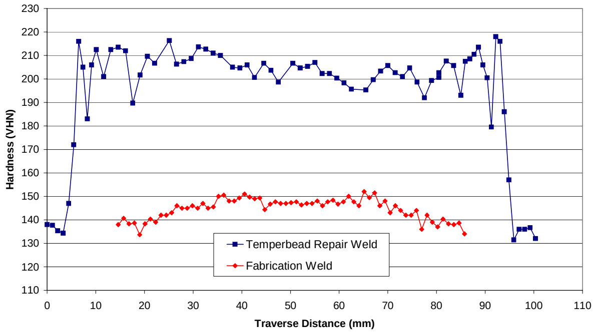


Figure 7. Shows the average hardness values for both longitudinal seam welds

Creep-rupture testing
The limited amount of test samples available for this test program i.e. one specimen per test temperature is unable to provide any conclusive information and therefore should only be used as a guide to the material's creep behaviour.

The creep rupture data generally showed the parent metal to have the highest creep ductility. Ductility decreased from parent metal > TB repair weld metal. The rupture elongation of the parent metal was more than 20% higher than that exhibited by the TB repair weld metal.

The general trend observed in most materials is for a reduction in ductility with increased test duration.[24] This trend was also evident in the current tests, where the lower the test temperature, the longer the time to rupture and the lower the rupture elongation observed.

Several studies have found non-metallic inclusions play a critical role in controlling the creep behaviour in the weld metal. In a study by Henry et al.,[24] the effect of non-metallic inclusions on the elevated temperature properties of submerged-arc (SA) weldments, as controlled by flux compositions, was investigated. The work entailed accelerated creep testing of a series of fabricated 2.25Cr-1Mo SA test welds using three different flux types, namely the acid, neutral and basic flux types. The results of this investigation demonstrated that the type of flux used in the fabrication of SA welds has a significant effect on the creep behaviour of low alloy ferritic steel weld metals. The acid flux was found to exhibit the poorest creep behaviour, with rupture strengths significantly below the minimum 2.25Cr-1Mo base metal values. The weldment fabricated using this particular flux type was characterised by a relatively high concentration of Mn-Si and Mn-S inclusions in the weld metal. The header in the current investigation was also fabricated using the SA welding process and an acid flux.

Where sulfur is present,[24,25] the bond between the matrix and particle is non-wetting (incoherent), in which case the inclusions act as pre-existing stable nuclei, effectively eliminating the nucleation stage of damage accumulation. Inclusions may be advantageous in improving the weld metal toughness by promoting the formation of acicular ferrite, however, they are detrimental as they act as nucleation sites for creep cavity initiation.

Therefore a material containing a significant number of stable cavity nuclei at grain boundaries (as in the case for weld metal with a high concentration of incoherent non-metallic inclusions) would exhibit poor creep properties.

The creep properties of the current paper are presented in the form of a ‘Temperature versus Time to rupture’ curve in Figure 8. The mean ISO (International Standards Organisation) creep data has also been included.

From this, it is evident that all regions investigated (parent, weld metal, and composite cross (X)-weld samples) demonstrated poor creep performance, falling well short of the mean ISO creep data. The creep properties of the original fabrication weldment were inferior to both the TB repair weldment and the parent metal. This creep behaviour is consistent with those trends observed for the SA acid flux fabricated test welds evaluated by Henry et al.

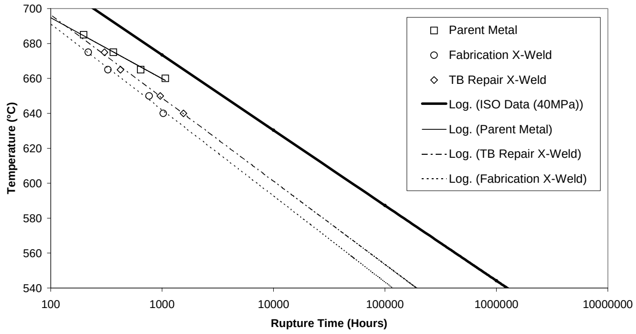


Figure 8. Temperature versus Time-to-rupture curve of the material investigated. Figure compares the creep–rupture lives of the TB repair and fabrication weldments.

5. CONCLUSIONS

In this investigation the performance of a longitudinally seam-welded emergency cold weld (TB) repair was evaluated after 5000 hours service exposure at 510˚C and a 28.9MPa hoop stress. Both the mechanical properties and microstructural condition were evaluated and characterised using an experimental procedure consisting of a series of mechanical tests and microstructural techniques.

ACKNOWLEDGMENTS

The work reported herein was undertaken as part of a Research Project of the Cooperative Research Centre for Welded Structures (CRC-WS). It was a collaboration between the CRC-WS and eleven Power Stations from South Australia, Queensland, New South Wales, Victoria and Northern Territory. The Cooperative Research Centre for Welded Structures was established and is supported under the Australian Government's Cooperative Research Centres Program.

The authors would also like to acknowledge the following people for their valuable contributions to the project:

- Dr George Collins, director of Materials and Engineering Science, ANSTO;
- Mr Andrew Croker, formerly of ANSTO;
- Graham Smith, Ted Roach and Darren Attard (ANSTO) metallography support;
- Sam Humphries, Kevin Thorogood and Dave Carr technical support in the mechanical testing and particularly Tim Nicholls for performing and maintaining the creep-rupture tests.
- Andrew Chapman, Connell Wagner PPI

REFERENCES

1. Laha, K., Rao, K.B.S. and Mannan S.L., Effects of Post-Weld Heat-Treatment on Creep Behaviour of 2.25Cr-1Mo Ferritic Steel Base, Weld Metal and Weldments. in Creep: Characterisation, Damage and Life Assessment Proceedings of the Fifth International Conference on Creep of Materials. 1992. Lake Buena Vista, Florida, USA: ASM International.
2. Croker, A.B.L., Finlay, M.R. and Law, M., Weld Repair of Creep Damaged Pressure Vessel and Piping Steels. in Welding and Repair Technology for Power Plants Second International EPRI Conference. 1996. Daytona Beach, Florida, USA: EPRI.
3. Croker, A.B.L., Harrison, R.P. and Moss, C.J., Weld Repair of Creep Damaged Steels. in IMMA Conference on "Failure, Repairs and Life Assessment of Pressure Vessels and Pipework III". 1995. Melbourne.
4. Lundin, C.D., et al., Failure Analysis of a Service-Exposed Hot Reheat Steam Line in a Utility Steam Plant. Welding Research Council Bulletin. **354**: 1-37.
5. Ellis, F.V. and Brosche, D.J., Creep-Rupture Properties of Low Carbon Virgin 2-1/4Cr-1Mo SAW Longitudinal Seam Weldments and Effect of Specimen Size. PVP - High Temperature Service and Time-Dependent Failure, 1993. **262**: 147-156.
6. Ellis, F.V., et al., Remaining Life Estimation of Boiler Pressure Parts Volume1: Identification of Relevant Damage Mechanisms. 1988, Electric Power Research Institute: California, USA. p. 1-38.
7. Le Mat Hamata, N. and Shibli, I.A., Creep Crack Growth of Seam-Welded P22 and P91 Pipes with Artificial Defects. Part I. Experimental Study and

Post-Test Metallography. International Journal of Pressure Vessels & Piping, 2001. **78**: 819-826.

8. Le Mat Hamata, N. and Shibli, I.A., Creep Crack Growth of Seam-Welded P22 and P91 Pipes with Artificial Defects. Part II. Data Analysis. International Journal of Pressure Vessels & Piping, 2001. **78**: 827-835.
9. Nakoneczny, G.J. and Schultz, C.C., Life Assessment of High Temperature Headers.
10. Nonaka, I., et al., Performance of Repair Welds on Aged 2.25Cr-1Mo Boiler Header Welds. International Journal of Pressure Vessels & Piping, 2001. **78**: 807-811.
11. Ripley, M.L., et al. Remaining Creep Life Determination of Seam-Welded 2-1/4Cr-1Mo Steel Headers. in IMMA Conference on "Failure, Repairs and Life Assessment of Pressure Vessels and Pipework III". 1995. Melbourne.
12. Viswanathan, R., Seam Welded High Energy Piping, in EEI Prime Movers Committee Meeting (18 October). 1993: Illinois, USA.
13. Viswanathan, R., Dooley, R. and Saxena, A., A Methodology for Evaluating the Integrity of Longitudinally Seam-Welded Steam Pipes in Fossil Plants. Journal of Pressure Vessel Technology, 1988. **110**(3): 283-290.
14. Wells, C.H. On the Life Prediction of Longitudinal Seam Welds in Hot Re-Heat Piping. in International Conference on Life Extension and Assessment of Fossil Power Plants. 1987: EPRI.
15. Stevick, G.R., Failure of Welds at Elevated Temperatures. Welding Research Council Bulletin, 1994. **390**: 1-39.
16. Norris, R.H. and Saxena, A., Creep Crack Growth Behaviour in Weld Metal/Base Metal/Fusion Zone Regions in Chromium Molybdenum Steels. Welding Research Council Bulletin, 1996. **416**: 1-61.
17. Mitchell, K.C., Cold Weld Repair Applications in the UK, National Power - Research and Engineering Division: Wiltshire, England.
18. Viswanathan, R. and Gandy, D.W., Performance of Repair Welds on Aged Cr-Mo Piping Girth Welds. Journal of Materials Engineering and Performance, 1999. **8**(5): 579-590.
19. Viswanathan, R. Weld Repair of Aged Piping - A Literature Review. in Second International EPRI Conference on Welding and Repair Technology for Power Plants. 1996. Daytona Beach, Florida, USA: EPRI.
20. Nugent, R.M. Automatic Gas Tungsten-Arc Welding Temperbead Technique Development. in Welding and Repair Technology for Fossil Power Plants 1994 International EPRI Conference. 1994. Williamsburg, Virginia, USA: EPRI.
21. Lau, T.W., Lau, M.L. and Poon, G.C., Development of Controlled Deposition Repair Welding Procedures at Ontario Hydro. Welding Research Council Bulletin, 1996. **412**: 35-42.
22. Gandy, D.W. and Childs, W.J., Repair Welding of SA508, Class 2 Pressure Vessel Steels Utilising the Consistent Layer Temperbead Technique. in Welding and Repair Technology for Fossil Power Plants 1994 International EPRI Conference. 1994. Williamsburg, Virginia, USA: EPRI.
23. Friedman, D.L.M., EWI/TWI Controlled Deposition Repair Welding Procedure for 1-1/4Cr-1/2Mo and 2-1/4Cr-1Mo Steels. Welding Research Council Bulletin, 1996. **412**: 27-34.
24. Henry, J.F., Ellis, F.V. and Lundin, C.D., The Effect of Inclusions, as Controlled by Flux Composition, on the Elevated-temperature Properties of Submerged - Arc Weldments. in International Conference on Weld Failures. 1988. London, UK: Cambridge.
25. Middleton, C.J., Reheat Cavity Nucleation and Nucleation Control in Bainitic Creep-Resisting Low-Alloy Steels: Roles of Manganese Sulphide, Residual and Sulfur-Stabilizing Elements. Metal Science, 1981.