Advanced Modelling and Testing – Thick Sectioned Welded Alloy HCM2S (P23)

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by

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EXECUTIVE SUMMARY

Objectives

The principal aim of the project was to use advanced modelling and testing to extend the size range for which the HCM2S (P23) steel can be fabricated both with and without PWHT. The specific objectives were :

- To optimise the fabrication of thick section HCM2S utilising practical and efficient welding processes (MMA, FCAW).
- To thoroughly investigate the welding of HCM2S without PWHT.
- To model the weld and cross weld mechanical properties of HCM2S both with and without PWHT in order to define cross weld properties.
- To demonstrate acceptable weldment mechanical properties .
- Consequently to produce fabrication guidelines for thick section HCM2S both with and without PWHT.

Summary

This project involved the manufacture of a number of pipe butt welds between HCM2S (P23) and itself – both with and without PWHT, and also dissimilar joints with BS 3064 660 (CMV) and ASTM A 335 P91 respectively, both these alloys representing materials with which there has been identified a potential desirability to join with thick section HCM2S.

BS 3064-660 has long been employed as, inter alia, main steam pipework and has now, after many years service, been found to suffer a set of cracking problems which could be resolved by complete or partial replacement with HCM2S.

ASTM A335 P91 belongs to a family of 9% to 12% Cr martensitic steels that are presently employed in state-of-the-art supercritical boilers and will undoubtedly continue to be employed in the next generation. A commercial benefit is anticipated if HCM2S could be used to replace such martensitic steels as P91, with which it is on a par in respect to creep strength. Obviously its use would necessitate the ability to produce dissimilar and similar welds in thick section and the potential to avoid PWHT would offer an even greater advantage.

The main infill procedure used on the weldments was either manual metal arc (MMA) or flux cored arc welding (FCAW) and, for some of the combinations, more than one filler metal chemistry was used. Routine mechanical testing, including Charpy impacts, were carried out to the requirements of BS EN288 part 3 and satisfactory weld procedures qualified for each of the combinations welded.

Samples were taken from the majority of the welds both as ‘all weld’ and ‘cross weld’ test pieces and creep rupture tests carried out . All of the tests were at 575°C conducted with a range of stresses with the intention of achieving durations up to 10 khours. In parallel, modelling was carried out using neural network technology to

predict the creep rupture properties to be expected with both the PWHT and non-PWHT weldments in HCM2S.

Subsequent to this, Finite Element modelling, using data both measured and estimated, was used to evaluate and compare the change in stress distribution with time for both an as welded and stress relieved weldment.

In addition, samples of HCM2S type weld metal were thermally aged to simulate 50khrs operation at 575°C. These were then stress rupture tested to evaluate any change in the creep properties due to this ageing.

The project was successful in achieving the following deliverables:-

- Qualified welding procedures using both manual metal arc and flux cored arc welding techniques for joining thick section HCM2S to itself, CMV and P91 – all with PWHT.

- A qualified weld procedure for HCM2S at 40mm thick in the ‘as welded’ condition utilising the temper bead technique to improve properties.

- Prediction of short term mechanical properties and long term stress rupture values in HCM2S weld metal using neural network analyses techniques

- Verification by comparison that the tensile predictions and measured values were in good agreement.

- Verification that the measured stress rupture values were within an acceptable scatter from the mean of the derived values.

- Confirmation that the long term stress rupture values in the non post weld heat treated and post weld heat treated condition were similar as predicted by the neural network analysis.

- Developing a methodology to simulate accelerated long term ageing of test material using kinetic and thermodynamic models

- Estimating that the remaining life of the aged material was, by extrapolation, consistent with the design allowable stress.

- Thick section P23 was modelled by finite element analysis (FEA) to estimate residual stress and stress relaxation in creep across a weld in both the as welded and post weld heat treated condition.

- The model was used to compare the difference in effect between the code limit of 16mm and the likely practicable upper limit of 40mm.

- It was concluded that acceptable strains were developed during the life of the thick P23 weld for the non-PWHT’d condition to make it a viable option.

1.1 TECHNICAL BACKGROUND

CO_2 emissions from ageing power plant represent a major contribution to the worldwide problem of global warming. To increase efficiency and reduce emissions in new plant it is necessary to design for operation at higher temperatures and this requires the use of new alloys with improved creep resistance. Most new creep resisting steels contain high chromium levels (9 – 12%) and require sophisticated Post Weld Heat Treatment (PWHT) procedures that can be extremely difficult and expensive to perform, especially at site. Application of such PWHT is, in some cases, not desirable due to the resulting high levels of distortion, which can result in an unacceptable increase in subsequent assembly costs. In many repair/replacement applications, such steels are unsuitable for joining to existing lower alloyed steels, which suffer severe loss in creep strength as a result of the higher PWHT temperature range. However a newly derived variant of standard 2¼Cr 1Mo steel has been developed which gives creep strength close to the 9Cr (P91) steels. This steel, developed by Sumitomo has been given the designation HCM2S.

1.2 BACKGROUND TO HCM2S

HCM2S was developed some years ago(1) as an improved version of the standard 2¼Cr 1Mo alloy, primarily through the addition of tungsten at around 1½% to improve creep strength and a reduction of carbon to less than 0.10% to improve weldability/ restrict HAZ hardness in the 'as welded' condition. The intended application was for water wall tube panels in super-critical power plant where the ability to fabricate these large furnace panels complete, without the need for post weld heat treatment is of paramount importance. However it was soon recognised that the enhanced creep properties, developed by the addition of tungsten, niobium, vanadium, nitrogen and boron, were nearly equal to those of the higher alloyed T91 and it was therefore a good candidate for other applications such as superheater tubes for metal temperatures possibly up to about 575°C. Note that the upper limit is related to problems with steam side (and flue gas) oxidation rather than creep strength.

Apart from being potentially cheaper, its main advantages are that, in thin sections, it does not require either preheating or post weld heat treatment to produce acceptable microstructures and hardness. It has since obtained status in the ASME code through code case 2199-1, approved in 1999, which gave it the P number 5A (the same as standard 2¼Cr 1Mo – T22) and it was subsequently given the designation T23 in ASME IIA - SA213. Hence for manufacture to ASME I, as permitted by table PW 39, post weld heat treatment is not required up to a thickness of 16mm. When post weld heat treatment is unavoidable, it may be carried out at temperatures lower than that required for P91 thus ensuring minimal degradation of the adjoining materials in, for example, retrofit situations involving P22 or CMV.

The heavier section pipe to SA 335 i.e. P23, although also included in the code case, is not currently included in ASME IIA although it was introduced to the ASTM series of material standards in the 2003 edition. Nevertheless prior to this Innogy obtained a pipe length from Sumitomo notionally to this specification and this report details welding and testing carried out on it (Appendix 1). Note that hereafter HCM2S will be referred to by its ASTM/ASME designator – P23.

The material in this form sees a potential for application in both headers and pipework with particular interest as a replacement for BS 3604 grade 660 (CMV) in repair and refurbishment of existing power plant. Of interest also was the possibility of avoiding post weld heat treatment in thicker sections.

The following scope of work was therefore established in order to better exploit the full potential of this alloy.

- Weldability of P23 to itself both as welded and stress relieved.
- Weldability of P23 to CMV – stress relieved.
- Weldability of P23 to P91 – stress relieved.

Welding was carried out with both the more traditional TIG/MMA combination and also the higher deposition FCAW welding process and testing carried out to the requirements of BS EN288 part 3. In addition all weld and cross weld stress rupture tests were conducted at 575°C over a range of stresses for target durations up to 10,000 hours.

Selected welds were also given an ageing treatment designed to simulate mid-service history and limited cross weld stress rupture tests again carried out. The ageing time and temperature was derived using the principles of Thermocalc. Neural network technology was used to predict the creep behaviour for the P23 material both as welded and post weld heat-treated. This data, together with additional information from various sources was used to model creep behaviour with time for both an as welded component and a stress relieved component to assess the viability of avoiding post weld heat treatment on thicker section fabrications.

To aid the reader in understanding this report it is broken down into relevant sections as follows:-

- Section 2 – Welding and Weld Procedure Qualifications
- Section 3 – Neural Network Analysis
- Section 4 – Service Aged Material
- Section 5 – Stress Rupture Testing
- Section 6 – Residual Stress Modelling
- Section 7 – Discussion and Conclusions.

2.0 WELDING & WELD PROCEDURE QUALIFICATION

2.1 Introduction

A number of pipe butt welds were manufactured involving P23 to itself and also to BS 3064 660 (CMV) and ASTM A 335 P91 respectively. The main infill procedure was either manual metal arc (MMA) or flux cored arc welding (FCAW) with, in both cases, a tungsten inert gas (TIG) root being used and for the latter case, a few runs of MMA prior to infill. A summary of the material combinations, weld procedures and resultant PQRs is presented in table 2.1. In the original scope it was intended to include welds between P22 and P23 however as both materials are classified P5A in ASME IX, the welding of one should automatically qualifiy the other. Testing of the P22 type weld metal was also contained within the P23/CMV weld tests. By removing this from the scope, additional effort was able to be expended on the P23 to P91 combinations using two different weld filler chemistries matching either the lower or the higher alloy.

It should be noted that it was originally considered that T23/P23 material should be classified as group 5 in accordance with the table in BS EN288 part 3 (i.e. a Cr-Mo alloy) and is described as such on some of the weld procedures and PQRs in this report. This would have been consistent with the ASME designation P5A(2¼Cr 1Mo) denoted in code case 2199-1. However it has recently become clear that it is more likely to be denoted as group 6.2.(i..e. high vanadium alloyed Cr Mo steels) As such it may not be automatically exempt from PWHT in the same way standard 2¼Cr 1Mo is in accordance with the UK and European boiler codes BS1113 and BS EN 12952.

Two slightly different weld preparation details were utilised for the weldments – Figure 2.1 type 1 and type 2. The former was used for the majority of the TIG/MMA weld procedures and type 2, which, with a longer weld nib, has more access, was used for the FCAW welds. The type 2 was also used for the as welded P23/P23 butt to facilitate the two layer buttering employed for the temper bead technique. Specific details for each are as follows:-

2.2 P23/P23 – As welded.(test ref ZL344)

Welding process: TIG/MMA

Principal welding consumable: Metrode Chromet 23L

It was adjudged that to achieve the best possible structure and properties in the heat-affected zone of the ‘as welded’ thick section material, a temper bead technique should be employed. The priciple involved in this technique is to deposit the second layer of weld metal in such a way that it refines and tempers the coarse grained heat affected zone in the parent material caused by the first weld bead. This requires carefull heat input control of both the first and second layers welded directly on to the base material. This was achieved by the deposition of the first layer in the root and up the sidewall of the weld preparation with a 2.5mm diameter electrode. This was then followed by a second layer deposited with a 3.2mm diameter electrode. The ratio of heat input between these two layers was targeted at nominally 2:1[2] and in practice was fairly closely achieved with a range of 0.6 to 085kJ/mm measured for the first layer and 1.2 – 1.3 kJ/mm for the second. For the infill, a 3.2mm diameter electrode was used and a range of heat inputs up to 1.9 kJ/mm were recorded. All of the welding, including the temper bead layers, was carried out with the pipe axis fixed and inclined at 45° to the horizontal – termed H-L045 in EN ISO 6947 and on completion, in lieu of post weld heat treatment, a pre-heat boost to 250°C was applied to minimise the risk of hydrogen cracking. Further details are given in weld procedure A2020CC3 TM revision 1 (Appendix 2) and the mechanical test results are shown in page 2 of PQR 010907 (Appendix 3). Testing was carried out in accordance with BS EN288 part 3 and the results obtained were generally acceptable.

Note that the revision to the weld procedure was to remove 4.0mm electrodes for the infill. This was as a result of poor weld metal toughness being recorded when welding was originally carried out with this larger diameter electrode. See page 2 of PQR 001003 for detailed results (Appendix 3). This is also discussed in more detail in section 2.11.

2.3 **P23/P23 – Post weld heat treated.**(test ref PQT2)

Welding process: TIG/MMA/FCAW

Principal welding consumable: Metrode Cormet 23

After the initial TIG root and two layers of MMA, the remainder of the infill and cap was carried out in the H-L045 welding position as previously described using FCAW. On completion the weldment was stress relieved at 715°C for 3 hours. The welding details are given in weld procedure A2020CC1 FC (Appendix 2) with the mechanical test results summarised on page 2 of PQR 001002 (Appendix 3). As can be seen, adequate strength, ductility and toughness were reported.

2.4 **P23/CMV – Post weld heat-treated.** (test ref ZL308)

Welding process: TIG/MMA

Principal welding consumable: Babcock Welding Products type K

After completion of the TIG root, MMA fill procedure the weldment was stress relieved at 705°C and mechanical testing carried out to the same requirements as before. The relevant weld procedure A0520CC1 TM is presented in Appendix 2 with the test results detailed in page 2 of PQR 010707 given in Appendix 3.

2.5 **P23/CMV – Post weld heat-treated**. (test ref ZL340)

Welding process: TIG/MMA/FCAW

Principal welding consumable: Metrode Cormet 2

After completion of the TIG root, and 2 layers of MMA, infill was completed with the flux cored wire and the weldment stress relieved at 705°C. Mechanical testing was carried out to the same requirements as before with the relevant weld procedure A0520CC1 FC presented in Appendix 2 and the test results detailed in page 2 of PQR 010906 given in Appendix 3.

For the **P23/P91** weldments, as well as the use of two different welding processes for the main infill, two differing philosophies for the weld chemistry were adopted. These were to use weld metal that matched the lower alloy P23 base material – the industry 'norm', and also using weld metal matching the higher alloy P91 base material. In addition, for the first case it was decided that one weld would be made with the BWP P23 type consumable, referenced type J and one with the Metrode Chromet 23L electrode, both notionally identical. The post weld heat treatment in every case was 730°C, a compromise between temperatures appropriate for the two alloys being joined. The details for the five weldments are therefore as follows:-

2.6 P23/P91 – Low alloy weld metal (test ref ZL444)

Welding process: MMA

Principal welding consumable: Metrode Chromet 23L

Weld procedure: A1720CC1 TM (Appendix 2);

Test Results PQR 011003 (Appendix 3)

2.7 P23/P91 – Low alloy weld metal (test ref ZL443)

Welding process: MMA

Principal welding consumable: BWP type J

Weld procedure: W78576/02 (Appendix 2);

Test Results PQR 011002 (Appendix 3)

2.8 P23/P91 – Low alloy weld metal(test ref ZL445)

Welding process: FCAW

Principal welding consumable Metrode Cormet 23

Weld procedure A1720CC1 FC (Appendix 2);

Test results PQR 011004 (Appendix 3)

2.9 P23/P91 – High alloy weld metal (test ref ZL432)

Welding process: MMA

Principal welding consumable: BWP type M

Weld procedure W78576/01(Appendix 2) ;

Test results PQR 011001 (Appendix 3)

2.10 P23/P91 – High alloy weld metal (test ref ZL590)

Welding process FCAW

Principal welding consumable Metrode Supercore F91

Weld procedure W78576/03 (Appendix 2);

Test results PQR 011005 (Appendix 3)

2.11 Summary of Results

Weldability: All welds were carried out satisfactorily in the inclined 45° position. No specific difficulties were noted by the welder and all the welds were found to be defect free by both magnetic particle inspection of the surface and volumetric examination using ultrasonic technique.

Strength: In every case, failure of the cross weld tensile was located in the parent material at a stress exceeding the minimum for that material. In the case of dissimilar joints failure understandably occurred in the weaker material.

Ductility The side bends were bent over a former of diameter equal to four times the thickness of the bend specimen. In every case they were bent to 180° without any unacceptable defects being noted. Note that this is in excess of what is currently required by BS EN288 part 3, where an angle of 120° only is required.

Notch toughness For ease of comparison, the results from the tests are summarised in table 2.3. The standard 2¼Cr 1Mo weld metals have been omitted but two additional test results for Chromet 23L have been included for comparison. (see also Table 2.2)

The absorbed energy measured in the Charpy test for the stress relieved manual metal arc weld metal of the P23 type all gave values in excess of 100J at room temperature (PQT1, ZL443 & ZL444). Note that the Metrode Chromet 23L and BWP type J were essentially identical.

However in the ‘as welded’ condition poor results, an average of 12J, were obtained in test reference PQT3. This utilised 4mm diameter electrodes for the infill and low toughness was attributed to the large areas of unrefined weld metal developed at this stage. The weld procedure was therefore revised to limit the electrode to 3.2mm maximum. This resulted in a notable improvement in absorbed energy to an average of 22J. Although still relatively low, this compares favourably with manual metal arc 9% Cr weld metal – test ref ZL432, albeit tempered a little lower (730°C) than normal.

Other notable, though not too surprising results were the lower toughness exhibited by the comparable FCAW weld metals. PQT 1 c/w PQT2 ; ZL444 c/w ZL445 ; ZL 432 c/w ZL590. This is considered to be an inherent effect of a rutile based flux compared with the basic flux used for the manual metal arc electrodes.

In conclusion, nine weld procedure tests were satisfactorilly conducted involving the material combinations, welding processes and consumables detailed in the foregoing section. This enables both RWE Innogy and Mitsui Babcock to manufacture weldments in the various combinations to fully code compliant and efficient qualified weld procedure specifications.

3 NEURAL NETWORK ANALYSIS

3.1 Background

In principle the tensile properties and in particular the yield strength of ferritic weld metals can be predicted from a knowledge of the chemistry of an alloy and the application of the principles of physical metallurgy.(3) The method makes the assumption that the yield stress of a particular microstructure is contributed to by several factors :

- The intrinsic strength of iron
- Substitutional solid solution strengthening
- Interstitial solid solution strengthening
- Precipitation strengthening
- Grain size
- Heat treatment etc.

However the application of such methodologies to real welds is limited as the number of variables is far greater than implied by this approach. Simple linear regression is often employed to overcome these difficulties and such a technique will search for robust correlations between input and output parameters. For example the effect of carbon content on the yield stress may provide a good linear correlation, which would allow the prediction of yield simply from the carbon content. It should be noted that the application of such statistical techniques does not imply, nor rely on, an understanding of the underlying physical mechanisms.

The advent of digital computers has allowed the practical use of what are termed 'neural networks' which in effect are conducting regression analyses on a massive number of variables using non-linear functions. The use of very flexible functions allows the neural network to capture interactions between input variables that have an effect on the output. It may be, for example, that the effect of carbon on the yield strength becomes greater if vanadium is present. A 'paired' interaction such as that between carbon and vanadium is relatively easy to envisage but a neural network is capable of modelling multiple interactions. The process is shown schematically in Figure 3.1.

MacKay (3) has developed a treatment of neural networks using Bayesian statistics, which allows the calculation of error bars or limits of uncertainty. Whilst a mathematical description of this process is beyond the scope of the present work, the benefit of MacKay's work can be understood by the following example: Imagine a large data set of input parameters and the resultant outputs. In the example used previously yield stress would be the output and chemistry, grain size, heat treatment etc would be the input. If the model had one thousand inputs for carbon levels between zero to 0.2% then the regression equation would be well defined and the uncertainty or error in the output would be small. On the other hand, if the data set only contained one carbon content between 0.2% to 0.3%, then the regression equation in this space would have considerable uncertainty and the output could have a large error.

3.2 Modelling Results.

For the present work, three developed neural network programmes were used to predict the properties of the P23 type manual metal arc and flux cored weld metals.

The method for estimating yield and ultimate tensile stress values is described in a paper by H.K.D.H. Bhadeshia and others [3] and uses the inputs of:-

- detailed chemical analysis,
- welding heat input,
- interpass temperature,
- tempering temperature,
- tempering time.

The chemical analyses for both the MMA and FCAW weld metal deposits are given in table 3.1 and the remainder of the inputs are as detailed in section 2. The resultant estimated values are shown in table 3.2 together with hardness measurements obtained from some sample welds. As can be seen, the equivalent UTS values compare favourably with the predictions developed by the neural analysis.

However, of greater interest were the predicted stress rupture values for the weld metals calculated for both the as welded condition and the stress relieved at 715°C condition. This followed the principles outlined in another paper by Bhadeshia and others.[4] As discussed in the paper, the variables for this analysis do not require welding details but rely only on the following inputs:-

- time to rupture (input as $\log_{10}$)
- test/operational temperature
- detailed chemical analysis
- normalising temperature
- time at temperature and cooling rate
- tempering temperature
- time at temperature and cooling rate

- annealing temperature
- time at temperature and cooling rate

The output gives predicted stress to rupture for the conditions chosen.

It should be noted that the input does not rely on nor require any welding details. It has been shown by testing and validating the programme that the long term creep properties of wrought and welded steels are essentially identical. In fact the majority of the data in the programme is derived from wrought material tests.

The chemical analyses used are again as detailed in table 3.1 and a thermal cycle, considered to be representative of the welding/PWHT cycle, was applied to the normalising and tempering stages of the programme. The third stage thermal cycle was set to 300K to represent no further heat treatment. This followed the same philosophy used in the referenced work.

The results obtained are shown graphically in Figure 3.2 and some measured values, detailed more thoroughly in section 5, are shown for comparison. The predicted values and measured values show reasonably good agreement being within 20% of the mean and well above the lower bound. The amount of uncertainty was, however, considered to be quite large and it is suggested that perhaps further effort could be expended in refining the programme to accommodate the measured data.

This is discussed further in section 7.

4 SERVICE AGED MATERIAL

4.1 Introduction

Knowledge of the remaining creep life expectancy after a period of service is of obvious interest to high temperature plant owners, and in this section there is a description of the work undertaken to produce an indication of creep strength at mid-life. Mid-life, for the purposes of the present work, has been taken as 50,000 hours at 575°C, which is a typical temperature where T/P23 might be expected to be employed.

Obviously, there is a need to accelerate the ageing process to produce reasonable ageing times to suit the present programme duration and ageing temperatures were explored by modelling both kinetics and thermodynamics.

Aged specimens were subjected to creep testing.

4.2 Time – Temperature Equivalence Derivation

The concept of equivalent times at temperature is not a new one and starting from the consideration that creep and ageing processes are thermally activated, the rates of reaction may be described by the well known Arrhenius equation after the Swedish chemist who first studied reaction kinetics.

$$r = \mathrm{A}\exp\frac{-Q}{RT}$$

where r is the rate of reaction, A is a constant and Q is the activation energy of the process, R is the gas constant and T the absolute temperature.

Substitution of empirical data obtains the constants that allow the equivalence of any time at temperature.

This general approach was used by Holloman(5) who demonstrated that the approach was applicable to the stress relief of steels and made use of a slight modification to the arithmetic to produce the Holloman - Jaffe parameter:

$$P = T\,(C + \log t)$$

where T the absolute temperature, t the time and C a process constant. Whilst originally it was consistent C was indeed a constant, when related to the tempering of steel, it was demonstrated that chemical composition had an affect (e.g. Sinha(6)) on this constant.

The Arrhenius equation has also been applied to creep by replacing r by $\frac{1}{tr}$ and producing the Larson-Miller parameter.

The form of time temperature equations do not indicate the limits of applicability, and this aspect requires careful consideration. Arrhenius rate equations can be applied to many reactions but obviously lose all meaning when a derived temperature is outwith the range at which the reaction takes place. Tempering of a carbon steel would provide an example: A temperature of 800°C could be applied to the equation and a time would be derived, this would be meaningless as the equilibrium diagram indicates a phase change above 723°C.

In the case of the present programme several constraints were identified in deriving the optimum accelerated ageing temperature. Not the least of these was the duration of the programme, which indicated a temperature that would give an equivalent time in the range of 2500 to 3500 hours. There was also a desire to remain as close as possible to the assumed service temperature of 575°C.

Three temperatures were chosen at which to conduct phase diagram computations. These computations allow for all the following elements:

Fe, C, Si, Mn, Ni, Mo, Cr, V, W, Nb

and some 14 phases including the all-important VN which is considered to be the precipitate responsible for most of the creep strength of the alloy.

The three temperatures, 575, 600 and 650°C were all examined and some aspects of the results are given in Figure 4.1 (Equilibrium calculation) and Figure 4.2 (W in ferrite).

The first graph depicts the change in carbide fraction with temperature, and indicates the main precipitation to be M_6C and VN. The M_6C barely alters between the three chosen temperatures and the VN, a major contributor to creep strength, hardly alters at all.

The second graph depicts the tungsten in solid solution for the chosen temperatures where a slight increase with increasing temperature.

The general conclusion from these two graphs is that accelerated ageing temperatures up to 650°C would generally yield acceptable results, and this conclusion being based in larger part on the constant VN mode fraction. The variation of tungsten in the lattice would probably give rise to an additional solid solution strengthening effect but this would be small. Despite the expected small magnitude it was generally accepted that the closer the accelerated ageing temperature would be to the service temperature, the better.

A range of temperatures was investigated from the point of view of the desired duration and a temperature of 615°C chosen.

Application of the Holloman parameter indicates an equivalent time as 3596 hours whereas the use of Larson-Miller on neural network derived from stress rupture values yielded a time of 3,200 hours.

The welds were in fact aged at 614°C for 3208 hours. The result of the subsequent stress rupture tests are given in the next section and discussed further in section 7.

5 STRESS RUPTURE TESTING

5.1 Comparison of Results

All results from the creep testwork are given in Tables 5.1 and 5.2, which show parent and weld metal materials, welding process, references of procedure qualification tests, and the test parameters and results. All tests were conducted at 575ºC.

5.1.1 Weld metal tests

The data from the all-weld P23 weld metal tests are plotted in graphical form in Figure 5.1. It can be seen that the MMA weld metal from Metrode electrode, viz Chromet 23L, without post weld heat treatment (PWHT), gives a reasonably consistent series of test results, the longest in the series being 6904 hours. If the weld metal is given a PWHT (3 hours at 715°C) before testing, this gives a slight strengthening effect, however only two test results are available, and these, even though tested at different stresses (152 and 162 MPa) gave similar durations (2082 and 1969 hours respectively). As a comparison, an in-house test on weld metal from a Babcock J type electrode- also a P23 weld metal and very similar to Chromet 23L, given PWHT, also showed as slightly stronger than the non-PWHT Chromet 23L.

The FCAW weld metal at very high stress/low duration conditions appeared to be similar to the MMA weld metal, but further longer term results, at durations of 849 and 1527 hours, were distinctly inferior, some 20% lower on rupture stress compared with the MMA results.

5.1.2 Cross weld tests

The remainder of the tests were all of the cross weld type. For convenience in presentation and to illustrate various aspects of the results, the tests are combined into a number of groups, some tests being common to more than one group. The groups are considered below in the following order:

- All P23 weldments, viz. P23 welded to P23 with P23 consumables
- All cross welds with P23 weld metal, viz. P23 welded to P23 or P91 with P23 weld metal
- Cross welds of P23 welded to P91 with different consumables
- As above, but including P23 welds to CMV material
- Effect of ageing on P23 to P23 welds with P23 consumables

5.2 P23 to P23 welds with P23 consumables

Testing was conducted on welds made using the MMA process and Metrode Chromet 23L electrodes, with no subsequent PWHT, and on welds using the

FCAW process, Metrode Cormet 23 weld consumable, and which were subsequently post weld heat treated at 715°C for 3 hours.

The results obtained are presented in Figure 5.2. To act as some form of reference and to aid the eye when comparing results from different tests, indicative lines are shown for parent material and parent – 20% on stress. These have been constructed from average data on Sumitomo HCM2S, treated on the basis of the ISO method for determining mean creep data.

5.2 Welds with P23 consumables

All results using P23 type consumables are given in Figure 5.3. Data from the previous graph are shown, together with MMA and FCAW welded samples to P91 material. In the latter cases, all welds were given a PWHT of 730ºC for 3 hours to reduce the hardness of the P91 material at the weld.

5.3 P23 to P91 welds with different consumables and weld processes

Results from tests involving welds in the above category are shown in Figure 5.4 .Once again the figure includes results given in previous plots, but this time data from specimens of P23 welded to P91 using P91 consumables are included.

5.4 P23 to CMV welds using MBEL K type consumable.

Figure 5.5 shows the same graph as in the last section, but with the series of P23 to CMV welds, welded with a P22 type (MBEL K type) consumable also shown. As expected, these welds are considerably weaker due to the lower stress rupture strength of CMV, and the failures are in the CMV parent.

5.5 Use of ageing to validate life predictions

Part of the modelling aspects (Section 4) is concerned with simulation of service life by higher temperature ageing. An exercise was conducted on P23/P23 welds with P23 MMA welding consumable to determine the ageing conditions to simulate a 50,000 hour exposure at 575ºC. Running part of the model suggested that 3208 hours at 614ºC would be a convenient set of parameters to make this simulation. Accordingly, three welds using the MMA process were manufactured and aged according to these parameters. Since the model is based on chemistry of the materials, theoretically the welding process should not make a difference to the result, so a further three FCAW welds were also manufactured and aged at the same time and conditions as the MMA welds. The only difference was that the MMA welds did not have any PWHT after welding, whereas the FCAW welds were heat treated for 3 hours at 715ºC before ageing. After ageing, these cross weld samples were then creep tested and the results compared with non-aged results.

6 RESIDUAL STRESS MODELLING

6.1 Introduction

P23, as a recently derived variant of 2.25Cr-1Mo steel, is designed to have creep properties superior to the normal P22 material, approaching those of modified 9Cr steels, but without the requirement for post weld heat treatment (PWHT).

Currently, the application of this material is limited by welding requirements developed for P22, which require PWHT for thick sections greater than 16mm. In thick section, this material cannot be exploited until sufficient data have been obtained not just to qualify the required welding procedures but also to validate the long-term creep behaviour.

The main aim of this section of work is to compare the performance of a PWHT and non-PWHT P23 weldment under service loading conditions. This comparison is achieved using finite element (FE) analysis to model the fabrication of the weld, the PWHT (if applicable) and subsequent service loading.

6.2 Finite Element Analysis

The FE analysis involved simulation of welding, PWHT and subsequent application of internal pressure at the operating temperature. Three models have been completed. The first model assumed uniform properties across the weld, heat-affected zone (HAZ) and parent material regions for a 40mm thick pipe. In the second model, different creep properties in the weld, HAZ and parent material regions were used for a 40mm thick pipe. In the third model, different creep properties in the weld, HAZ and parent material regions were used in a 16mm pipe wall thickness.

For each of the first two models, two FE analyses were made of a thick section P23 pipe weld (360mm outside diameter and 40mm wall thickness).

The first analysis modelled the existing code requirement for such a weld where a PWHT is required. The analysis comprised three stages:

- Simulation of the weld deposition,
- PWHT of the weld
- Application of service loading conditions to the pipe weld

The second analysis modelled the case where the pipe is allowed to enter service without the normal PWHT being applied. The two stages of this analysis comprised:

- Simulation of the weld deposition
- The application of service loading conditions to the pipe weld.

In the third model, only one FE analysis was employed for the code compliant section HCM2S pipe weld (312 mm outside diameter and 16mm wall thickness) where a PWHT is not required. The analysis comprised two stages as above:

- Simulation of the weld deposition
- The application of service loading conditions to the pipe weld

The commercial FE software ABAQUS version 6.3-1 was used in the analysis. An axisymmetric FE model was used in the whole analysis with 8-noded quadratic elements.

6.2.1 Geometry

In each of the first two models, the pipe was 280mm inside diameter and 40mm wall thickness. In the third FE model, the pipe was 280mm inside diameter and 16mm wall thickness. The mesh in each model comprised three different zones. The weld metal was Chromet 23L, the parent material was HCM2S and a separate zone for the 2mm thick HAZ region.

Figure 6.1a shows a schematic representation of the FE mesh of first and second models representing the weldment and Figure 6.1b shows the FE mesh for the third model.

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6.2.2 Material Properties

In the preliminary work, material properties for the weld and HAZ regions were assumed to have identical properties to the parent material. This is represented in the first model. In the second and third model, three-zone creep property data in the weld, HAZ and parent material regions were used.

The mechanical properties included temperature-dependent data for the true stress and strain, Young's modulus of Elasticity and Poisson's ratio, and of the thermal coefficient of expansion. Parameters based on a Norton-type creep behaviour during PWHT and service loading was also used in the analysis (see section 6.2.3 below). The parent material Norton parameters were derived from P23 data supplied from within the European Collaborative Committee programme. The corresponding Norton parameters for the weld and HAZ materials were derived from work by Rayner et al (7).

The thermo-physical properties included temperature-dependent data for the thermal conductivity, density, and specific heat conductivity.

6.2.3 Constitutive Relationships

The FE analysis involved simulation of the weld, PWHT and service loads. The weld simulation process was carried out using elastic-perfectly-plastic constitutive model. This was implemented directly in ABAQUS by providing temperature-dependent true stress and strain data in tabular form.

The PWHT and service loads were modelled using viscoplastic material relationships based on Norton-type creep strain law. Based on the available creep data at 575 ^{o}C, this law was defined as:

$$\dot{\varepsilon} = A\sigma^{n} \quad \text{..........(1)}$$

where A and n are constants. Tables 6.1 and 6.2 show values of the constants A and n used in the two models analysed. For the first model, uniform cross-weld creep properties were assumed as shown in table 6.1. In the second model, different creep property data were used across the three zones as given in table 6.2

In the second and third model, the values of the constants A and n for the HAZ and weld regions were determined by scaling the values for the parent material with corresponding values reported in the work by Rayner et al [(7)].

6.2.4 Simulation of the Weld

The simulation of the weld and PWHT involved thermal/stress analyses. The weld was simulated using idealised weld beads comprising 36 bead lumps for the first and second models and 23 bead lumps for the third model. Element removal/reactivation was invoked directly in each model using appropriate ABAQUS 6.3-1 commands to simulate the weld bead deposition. The user subroutine DFLUX was used to simulate thermal analysis during the welding process.

6.2.5 Simulation of the PWHT

The PWHT cycle included heating the weld area from room temperature to a soaking temperature of 715 ^{o}C at a rate of 100 ^{o}C/hr, followed by a soaking time of 3 hours and then subsequent cooling to room temperature at a rate of 100 ^{o}C/hr. Nodal temperatures were saved at each stage of the welding and PWHT processes. The nodal temperatures were then used as loading in the subsequent stress analysis.

6.2.6 Service Loading

During service, the FE model of the weldment in model 1 and model 2 was subjected to an internal pressure of 16.62 MPa at the operating temperature of 575 ^{o}C together with an end pressure loading of 25.45 MPa. In model 3 an internal pressure of 7.19 MPa and end pressure loading of 29.74 MPa were applied to the weldment during service at the operating temperature of 575 ^{o}C. A creep analysis was performed under these conditions in each model.

6.2.7 Boundary Conditions

The pipe was fully restrained at one end during welding, and during subsequent application of the service loading.

6.3 Results

In all the FE analyses, the results represented by the line plots were obtained at the following positions through the pipe wall thickness:

1. at the dead centre line of the weld in the weld region;

2. at 1mm from the weld fusion line in the HAZ region and

3. at 5mm from weld fusion line in the parent material region.

Figures 6.2 –6.13 show the predicted FE strain and stress results based on model 1 (with uniform cross-weld creep properties) while Figures 6.14 – 6.25 show the corresponding predicted FE results based on the model 2 (with three-zone cross-weld creep properties) Figures 6.26 – 6.37 show the predicted FE strain and stress results based on model 2 and model 3 (with three-zone cross-weld creep properties).

6.3.1 Model 1 – With Uniform Cross-Weld Creep Properties

Figures 6.2a-c show contour plots depicting the distribution of total axial strain, axial stress and von Mises stress respectively at the end of the welding process. It can be seen from Figure 6.2a that the retained total axial strain in the weld region is mainly compressive after welding. Figure 6.2b shows that the residual axial stress after stress is compressive on the inner surface and up to the middle region of the pipe near the weld area. Figure 6.2c shows that the Mises stress is predominantly higher in the weld region compared to the remainder of the parent pipe material region.

Figures 6.3a and b show contour plots of the axial creep strain without and with PWHT respectively at the end of service load after allowing the component to creep at 575 ^{o}C under internal pressure of 16.62 MPa for 5 x 10^{8} seconds (approximately 16 years) using the creep law defined in equation (1) above. Figures6.4, 6.5 and 6.6 show contour plots corresponding to axial stress, equivalent creep strain and von Mises stress. It can be seen from Figure 6.4 that the axial stresses with and without PWHT were the same at the end of service.

Figures 6.7- 6.12 show line plots depicting the evolution of axial creep strain and axial stress with and without post-weld heat treatment at different regions on the inside, in the middle and on the outside surfaces of the pipe during the application of the service loads.

Figures 6.7 and 6.8 show line plots depicting the axial creep strain and axial stress histories in the parent material (5mm away from the weld fusion line) respectively. It can be seen from Figures6.7a-c that for the post-weld heat-treated pipe, the axial creep strain evolution remains mainly tensile throughout the thickness of the pipe for the duration the service loads at temperature. For the non-post-weld heat-treated pipe, the axial creep strain remains compressive on the inner pipe surface and tensile in the middle and on the outer surface of the pipe.

Figures 6.8a-c show line plots depicting axial stress relaxation during service loading of the pipes with and without prior post-weld heat treatment. It can be seen that an initially tensile axial stress relaxes to a lower tensile steady state value while an initially compressive axial stress relaxes to a tensile steady state value in both pipes. At any point through the pipe wall, the axial stresses in both pipes converge towards a single tensile value. It can also be seen that axial stress relaxation to a steady value is much quicker in the post-weld heat-treated pipe than in the non-post-weld heat-treated pipe.

Figures 6.9 and 6.10 show line plots depicting the evolution of axial creep strain and axial stress in the heat-affected zone (1mm away from the weld fusion line) respectively. The figures also indicate that distribution of the strain and stress in the heat-affected zone is very complex. Figures 6.9a-c show that in the non-post-weld heat-treated pipe, the axial creep strain remains compressive on the inside and in the middle region of pipe and tensile on the outer surface of the pipe during the application of service loads at temperature.

Figures 6.10a-c also show that the initial axial stresses (prior to the application of service loads at the operating temperature) are compressive on the inside and in the middle regions of the pipe and tensile on the outside pipe surface. The initial creep strains for non-PWHT pipe are zero prior to the application of the service loading conditions.

For the pipe subjected to prior PWHT, Figures 6.9a-c show that the initial axial creep strains are compressive on the inside surface and in the middle region of the pipe and tensile on the outer surface of the pipe. The corresponding initial axial stresses were tensile on the inside surface and in the middle of region of pipe and compressive on the outer surface.

Figures 6.11 and 6.12 show the evolution of axial creep strain and axial stress respectively in the weld (along the weld centre line radially). The pattern of strain and stress distributions are similar to those in the heat-affected zone, as shown in Figures 6.9 and 6.10.

Figures 6.13a-c show the distribution of axial creep strain through the pipe wall thickness in the parent material, heat-affected zone and weld centre line respectively at the end of service loading with and without prior post-weld heat treatment.

6.3.2 Model 2 – With Three-Zone Cross-Weld Creep Properties

Figures 6.14 – 6.25 show the predicted FE results based on model 2 with three-zone creep properties defined in the parent, HAZ and weld regions given in table 6.2, corresponding to Figures 6.2-6.13 of model 1 with uniform cross-weld creep properties.

6.3.3 Model 2 and model 3 – With Three-Zone Cross-Weld Creep Properties

Figures 6.26 – 6.37 show the predicted FE results based on model 3 with model 2 results included for comparison. Please note that the graph legends in Figures 6.31 – 6.37 are defined as follows:

- ***Model 2 - pwht***: this refers to FE results based on model 2 where PWHT and service loading were considered
- ***Model 2 - npwht***: this refers to FE results based on model 2 without PWHT and where service loading was considered
- ***Model 3 - npwht:*** this refers to FE results based on model 3 without PWHT and where service loading was considered

7.0 GENERAL DISCUSSION & CONCLUSIONS

7.1 Welding & Procedure Qualification

Satisfactory weld procedure tests were carried for all of the combinations welded. Welding on all was carriied out in the most onerous H-L045 welding position The 'as welded' P23 exhibited relatively low toughness values – the optimum condition being when the electrode size was restricted to 3.2mm to maximise the grain refinement. For this test weld it was also elected that a temper bead technique be applied on the weld preparation surface to refine and temper the coarse grained heat affected zone of the parent material. This required careful heat input control between the first two layers of weld metal deposited and also resulted in a slightly larger weld volume. The HAZ Charpy results (Appendix 3 – ZL 344) demonstrated the benefits achieved.

7.2 Neural Network Modelling

The results from the yield stress and ultimate tensile stress analysis were considered to be in good agreement with the observed values.

The mean of the stress rupture estimates were quite close to the measured values when it is considered that ± 20% is typical scatter. However the upper and lower bound values showed a high level of uncertainty and it is felt that further refinement of the model may be necessary to improve this.

7.3 Stress Rupture Testing

<u>All-weld metal tests with P23 consumables</u> (Figure 5.1)

Although the graph suggests a slight improvement of the creep rupture strength of the MMA weld metal due to PWHT this is not considered to be significant and the differences are well within the typical scatter for this type of test. This is also consistent with the predictions of Bhadeshia described in section 3. Perhaps of more significance is the poorer FCAW results at the longer times/lower stresses which indicate inferior long term properties with this welding process, albeit that none of the tests went to long durations in creep terms.

<u>P23 to P23 welds with P23 consumables</u> (Figure 5.2)

At lower times/higher stresses, the MMA produced welds with no PWHT were slightly superior to the FCAW welds with PWHT, but this early advantage disappeared at longer times leaving both types of weldments showing behaviour close to the parent – 20% line.

The positions of the final fractures in these specimens were examined by sectioning the broken specimens longitudinally, metallographically mounting and polishing, and examining in the optical microscope. The highest stress MMA specimen failed through the parent material after 1919 hours, but final fracture in the remaining two MMA specimens was through the weld metal. In contrast, the highest stress FCAW specimen failed (703 hours) through the weld metal, and the remaining two FCAW specimens mainly through the Type IV position.

It is instructive to consider the position of the parent material failure with respect to the parent and parent – 20% lines constructed for guidance. In the present case, the failure indicates an approximate strength of parent – 15%. One other test specimen also failed in the parent material (a P23 to P91 weld with P91 consumable); this is included in later results but it is pertinent here to record that it failed in approximately the parent – 5% position in the plotted data. When it is considered that the thick section material is likely to be somewhat weaker than thin section, due to the different cooling rates from temperature etc., the indications from the above are consistent with the position of the two guidelines constructed on the graphs.

Welds with P23 consumables

It can be seen immediately from figure 5.3, that most of the results lie close to the parent – 20% line, with little difference in their behaviour. The exceptions are the P23 to P91 welds using the FCAW process, which are notably weaker than the other tests.

Failure positions in the latter cases were in the weld metal for the two lower stress tests, and at the fusion line with the P91 material for the lowest stress test. In contrast, the failures in the P23 to P91 welds using MMA were all at the fusion line with the P91 material.

P23 to P91 welds with different consumables and weld processes

In figure 5.4 the colour coding is such that welds made using the P91 consumables are shown in red/orange, and those using P23 consumables in blue, and this makes it immediately apparent that welds with P91 consumables are notably stronger. Not a lot of difference is observed between the FCAW and MMA results with P91 consumables, but as noted previously the FCAW welds with P23 consumable are significantly weaker.

Whereas, as indicated previously, the failure positions on cross welds with P23 type consumables were all in the weld metal or at the P91 fusion line, the type IV position was predominant in weld with P91 consumables. In the MMA welds, the highest stress sample broke at the fusion line and Type IV region of the P23, with the other two specimens being mainly Type IV failures. The FCAW welds failed either in the parent P23 or a mixed P23 fusion line/Type IV position failure. This is a general indication of the weaker P23 type material.

It is also perhaps worthy of note that fusion line welds always occurred at the 9Cr/2Cr junction and always in the weaker 2Cr type material. This is undoubtably due to carbon migration across the interface further weakening the lower alloyed material.

It is not immediately apparent, however, why the welds with the higher alloy weld metal should be better than the P23 type weld metal. This is contrary to normal fabricational practices and this interesting finding may warrant further investigation.

Use of ageing to validate life predictions

The results are summarised in Table 5.1 and Figure 5.6. Both the MMA and FCAW welds without ageing are close to the Parent – 20% line, and ageing effectively reduces the strength below this line. The MMA is affected significantly more strongly than the FCAW; some of this effect may possibly be due to the fact that the FCAW weld was given PWHT before ageing. There is a shift of failure position in the FCAW tests from the Type IV position into the weld metal.

To determine if in fact the ageing treatment has changed the properties in line with what was predicted, a construction was made on the graph to extrapolate and anticipate behaviour (Figure5.7). The ASME allowable stress for P23 at 575ºC is approximately 68 MPa, and this is indicated by the horizontal line. The MMA and FCAW welds sit approximately on the parent – 20% line, and the extrapolation of this intersects the ASME allowable at around 85,000 hours, which might then appear to be the approximate life of the welds without ageing, at a stress of 68 MPa. If the aged FCAW and MMA weld results lines are also extrapolated to intersect the ASME allowable, then the intercept times are found to be approximately 40,000 and 30,000 hours respectively. The shortfalls on the 85,000 hour life without ageing are therefore respectively 45,000 and 55,000 hours. Given the small number of specimens tested and the approximations made, these values are certainly of the same order as the 50,000 hours targeted by the heat treatment calculated by the modelling.

<u>Creep Rupture Life Comparison</u>

The stress rupture predictions obtained from the neural network analysis predict a marginal difference between the as-welded and stress relieved, and this is depicted in figure 3.2 which also contain the all weld stress rupture experimental data. In general, bearing in mind the limited quantity of the data, the stress relieved and as-welded experimental results agree with the prediction.

Of course the error bands predicted for the stress rupture results are enormous, and are associated with the restricted nature of input data, reflecting the difficulties, time, effort and expense associated with the procurement of large data sets in creep.

Figure 7.1 contains three further lines and these represent three different, but valid, assessment methods applied using the detailed procedures in the European Creep Collaborative Committee Working Group 1 Volume 5 rules on the Sumitomo data set comprising around 180 stress rupture points as reported in ECCC document AC/WG3A/8 (8).

The three methods used:

- Standard ISO method
- Larson Miller equation
- PD 6605

It is beyond the scope of the present document to discuss the assessment lines in detail but they are introduced to underscore the difficult nature of creep predictions. Even with a data set extending to 20,000 hours it can be seen that extrapolated predictions vary enormously. Predictions for 140 MPa, for example vary from 8000 hours to 100,000 hours. Viewed in this light and accepting such variations from data extrapolation, the neural network predictions which start from a chemical analysis has an understandably large scatter. At this stage in the development of the neural network analysis in the creep field, the process can only be of commercial/industrial use in the prediction of general trends.

7.4 Residual Stress Modelling

Both the PWHT and non-PWHT FE analyses were run under service conditions for 140,000 hours in models 1 and 2. At the end of this period the axial stresses in both the PWHT and non-PWHT welds had relaxed to the same level (Figures 6.4, 6.8, 6.10 and 6.12 for model 1 and corresponding Figures 6.16, 6.20, 6.22 and 6.24 for model 2), with the stresses at mid thickness being greater than those on the inner and outer surfaces but still only of the order of 20MPa.

In model 3, non-PWHT FE analysis was run under the similar service conditions for 140,000 hours, since there is no ASME code requirement for post weld heat treatment of a weld up to the 16mm wall thickness. At the end of the service period the axial stress in the 16 mm wall thickness pipe model had relaxed to a slightly higher level (Figures 28, 32, 34 and 36) compared to the corresponding results for the 40mm wall thickness pipe weldment model, with the stresses at the mid and outer thickness being greater than those in the inner surface (of the order of 40 MPa)

At the end of the service period the creep strains in the non-PWHT weld were greater than those of the PWHT weld at the middle and outside surfaces of the pipe in model 1 (Figures 6.7, 6.9 and 6.11) and in model 2 (Figures 6.19, 6.21 and 6.23).

At the inside surface of the pipe the reverse occured in model 1 with the PWHT creep strains being greater than those of the non-PWHT weld (Figure 6.9a). The maximum creep strains were approximately 0.1% (at the inner surface) and 0.5% (at the outer surface).

In model 2, however, the non-PWHT creep strains at the inside of the pipe were greater than those of the PWHT weld in the weld and HAZ regions but reversed in the parent material. The maximum creep strains were approximately 0.3% (at the inner surface) and 0.4% (at the outer surface).

In model 3 (16mm thick), the creep strains at the end of the service period in the non-PWHT weld were greater than those of the non-PWHT weld in model 2 on the inner and outer surfaces of the pipe but lower at the mid thickness of the pipe.

The maximum creep strains in model 3 (16mm thick) were approximately 0.2% (at the inside surface) and 0.4% (at the outer surface). There is therefore little difference between the responses of the 16mm (model 3) and 40mm (model 2) weldments without PWHT.

The cross-weld and all-weld uniaxial creep tests had elongations to rupture generally in the range 2 – 5%. These take no account of any reductions in ductility due to triaxial effects. Even allowing for this, it looks promising that a non-PWHT weld would be acceptable for service.

No specific results were available to estimate the failure ductility for each of the three zones. Use of the elongation measurements from the uniaxial creep rupture tests gives an indication of failure ductility but is likely to overestimate the failure ductility in the HAZ. Use of zone-specific data and failure ductilities should be used in any assessment of a non-PWHT weld's suitability for actual service.

A paucity of data for the P23 at PWHT temperature (715 ^{o}C) resulted in the creep law derived at 575 ^{o}C being used. To compensate for this the soak time was extended based on the Holloman parameter. It is likely that this approach may underestimate strains generated during PWHT giving a reduced level of strain at the end of the service period compared to the non-PWHT weld.

Currently, HCM2S weldments are limited by code requirements to sections of up to 16mm without PWHT. The comparative exercise presented in this report has indicated that the service performance is similar for a 16mm and 40mm thick pipe. HCM2S welds may therefore be acceptable for service up to thicknesses of 40mm. Further work based on some suitable form of monitored plant validation should be considered. Note that 40mm is considered to be the likely upper limit of application of this material and is of the same order as currently permitted for carbon manganese steels in most fabrication codes.

In summary, the outcome of the numerical analyses reported here indicates that the use of thick-section HCM2S welded joints up to 40mm thick in the non-post weld heat-treated condition is viable. Further consideration should be given to plant demonstration of thick-section as-welded HCM2S joints.

7.5 Conclusions

7.5.1 Viable qualified weld procedures have been developed for joining thick section HCM2S (P23) to itself and to other pipe materials using combinations of both tungsten inert gas(TIG)/manual metal arc(MMA) and TIG/MMA/ Fluxed cored arc welding processes:-

- P23/P23
- P23/grade 660 (CMV)
- P23/P91

7.5.2 The temper bead technique was successfully employed in the non- heat treated version of the thick section P23 to P23 joint.

7.5.3 Neural network analyses programmes modelling UTS and stress rupture have been employed and the ability to use such programmes imparted to Mitsui Babcock.

7.5.4 The UTS programme gave satisfactory predictions of UTS for P23 weld metal based on UTS/hardness correlations.

7.5.5 Stress rupture predictions gave wide scatter bands within which the experimental results fell.

7.5.6 The stress rupture results also fell within the –20% scatter of the predicted mean.

7.5.7 The analysis predicted PWHT'd and non-PWHT'd rupture lives as very similar and the experimental results generally support this though it is recognised that the data is limited and that the FCAW weld metal may be slightly inferior.

7.5.8 Kinetic and thermodynamic models have been employed to calculate a time at temperature to allow accelerated ageing of test material to represent 50,000 hours at the service temperature.

7.5.9 Stress rupture values for "service aged" welds have been derived.

7.5.10 Modelling of 16mm and 40mm thick weldments using finite elements has been achieved and the resultant creep strains from both PWHT'd and non-PWHT'd welds have been computed.

7.5.11 In the non-PWHT'd condition, the resultant strains after 140,000 hours were less in the 40mm case compared to the 16mm case.

7.5.12 The strains in every case were estimated as very low and negligible in comparison to uniaxial rupture ductilities.

7.5.13 It is concluded that the welding of thick section P23 without post weld heat treatment has been demonstrated as viable and a methodology to verify this for any particular joint configuration using FEA has been developed.

7.6 Future Work

7.6.1 It is recommended that further investigation be carried out on the creep behaviour of P23/P91 weldments to confirm the suggestion that improved performance is obtained with the higher alloy filler metal. The influence of, for example, carbon migration may play a significant role.

7.6.2 It would be beneficial to incorporate the current data into the creep based neural network analysis to further refine and improve its capabilities.

7.6.3 Consideration should be given to the use of full scale feature tests (pressure bottle) or ‘in plant’ demonstration to underwrite the derived acceptability of 40mm thick as welded P23 joints.

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Summary details of welding tests.

Ref	Base metal 1	Base metal 2	Filler	Main process	PWHT	WPS	PQR	Creep test?
ZL344	P23	P23	Chromet 23L	MMA	No –250°C	A2020CC3 TM	010907	Yes
PQT2	P23	P23	Cormet 23	FCAW	715°C	A2020CC1 FC	001002	Yes
ZL308	P23	CMV	Babcock K	MMA	705°C	A0520CC1 TM	010707	Yes
ZL340	P23	CMV	Cormet 2	FCAW	705°C	A0520CC1 FC	010906	No
ZL432	P23	P91	Babcock M	MMA	730°C	W78576/01	011001	Yes
ZL443	P23	P91	Babcock J	MMA	730°C	W78576/02	011002	No
ZL444	P23	P91	Chromet 23L	MMA	730°C	A1720CC1 TM	011003	Yes
ZL445	P23	P91	Cormet 23	FCAW	730°C	A1720CC1 FC	011004	Yes
ZL590	P23	P91	SupercoreF91	FCAW	730°C	W78576/03	011005	Yes

Table 2.1

Additional tests referred to in report

PQT1	P23	P23	Chromet 23L	MMA	715°C	A2020CC2 TM	001001	Yes
PQT3	P23	P231	Chromet 23L	MMA	No –250°C	A2020CC3 TM	001003	No

Table 2.2

Weld metal Charpy – room temperature

Ref	Type	Make	Process	PWHT	1	2	3	ave
PQT1	HCM2S	Chromet 23L	MMA	715°C	129J	121J	115J	122J
PWT3	HCM2S	Chromet 23L	MMA (4mm)	No	19J	8J	8J	12J
ZL344	HCM2S	Chromet 23L	MMA(3.2mm)	No	25J	12J	30J	22J
PQT2	HCM2S	Cormet 23L	FCAW	715°C	114J	34J	54J	67J
ZL443	HCM2S	BWP J	MMA	730°C	126J	126J	114J	122J
ZL444	HCM2S	Chromet 23L	MMA	730°C	125J	122J	126J	124J
ZL445	HCM2S	Cormet 23	FCAW	730°C	47J	50J	69J	55J
ZL432	9Cr	BWP M	MMA	730°C	28J	10J	32J	27J
ZL590	9Cr	Supercore 91	FCAW	730°C	9J	11J	12J	11J

Table 2.3

	2.5mm Chromet	3.2mm Chromet	4.0mm Chromet	1.6mm Cormet 23
C%	0.05	0.05	0.04	0.05
Mn%	0.57	0.54	0.57	0.66
Si%	0.14	0.23	0.21	0.31
S%	0.01	0.01	0.01	0.008
P%	0.01	0.01	0.01	0.014
Cr%	2.1	2.2	2.2	2.22
Ni%	0.77	0.76	0.74	0.03
Mo%	0.11	0.20	0.19	0.10
W%	1.43	1.55	1.50	1.42
V%	0.21	0.28	0.28	0.24
Nb%	0.02	0.03	0.03	0.02
B%	0.001	0.0011	0.0011	0.002
N%	0.015	0.020	0.023	0.011
Al(tot)	<0.02	<0.02	<0.02	<0.02
Co%	<0.02	<0.02	<0.02	0.03
Cu%	0.04	0.04	0.04	0.03
O%	0.045	0.045	0.045	0.057
Ta%	0.02	0.02	0.02	0.02

Table 3.1 : Chemical Analyses of weld deposits

Material	Heat treatment	yield	UTS	HV	Equiv UTS
FCAW	none	790	838±83	----	
	715	572	642 ± 74	210	680
	730	532	611 ± 78	220	700
MMA	none	745	896 ± 79	330	1065
	715	530	610 ± 90	225	710
	730	500	580 ± 103	220	700

Table 3.2 : Resultant estimated UTS Values

All tests at 575°C Stress in MPa, Estimate & actual life in hours

Process	Mat/WM/Mat	PWHT	Ref.	Stress	Estimate	Actual	El%	Consum	PQR No.	Failure position
FCAW	P23/P23/P23	715ºC	PQT2	143	2000	703	4.57	Cormet 23	001002	Weld metal
FCAW	P23/P23/P23	715ºC	PQT2	120	5000	5056	9.4	Cormet 23	001002	Some WM, most TP IV
FCAW	P23/P23/P23	715ºC	PQT2	100	16000	13060	1.61	Cormet 23	001002	TP IV
MMA	P23/P23/P23	None	ZL344	143	2000	1919	16.77	Chromet 23L	010907	Parent
MMA	P23/P23/P23	None	ZL344	120	10000	5591	1.05	Chromet 23L	010907	Weld metal
MMA	P23/P23/P23	None	ZL344	106	16000	9492	3.89	Chromet 23L	010907	Weld metal
FCAW	P23P23/P91	730°C	ZL445	152	2000	663	7.4	Cormet 23	011004	Weld metal
FCAW	P23P23/P91	730°C	ZL445	112	10000	3510	6.51	Cormet 23	011004	Weld metal
FCAW	P23P23/P91	730°C	ZL445	106	5000	3583	2.09	Cormet 23	011004	Fusion line with P91
MMA	P23P23/P91	730°C	ZL444	152	2000	1224	3.27	Chromet 23L	011003	Fusion line with P91
MMA	P23P23/P91	730°C	ZL444	135	3000	2334	1.68	Chromet 23L	011003	Fusion line with P91
MMA	P23P23/P91	730°C	ZL444	120	10000	5611	1.73	Chromet 23L	011003	Fusion line with P91
FCAW	P23/P91/P91	730°C	ZL590	152	2000	2874	17.63	BWP 41B	011005	Parent HCM2S
FCAW	P23/P91/P91	730°C	ZL590	135	5000	4690	6.32	(Supercore	011005	Stepped FL and Type IV in HCM2S
FCAW	P23/P91/P91	730°C	ZL590	120	10000	10240		F91)	011005	Still under test
MMA	P23/P91/P91	730°C	ZL432	152	2000	1637	19.5	M type	011001	FL and Type IV region of HCM2S
MMA	P23/P91/P91	730°C	ZL432	135	5000	5879	2.32	M type	011001	Some 2¼Cr FL, most TP IV
MMA	P23/P91/P91	730°C	ZL432	125	10000	13057	4.48	M type	011001	Some 2¼Cr FL, most TP IV < 009
MMA	P23/P22/CMV	705°C	ZL308	152	1000	41	15.98	2¼Cr	010707	CMV parent
MMA	P23/P22/CMV	705°C	ZL308	90	1000	2017	15	(MBEL	010707	CMV parent
MMA	P23/P22/CMV	705°C	ZL308	80	5000	4899		K type)	010707	CMV parent

WM : Weld Metal FL : Fusion line

Table 5.1 :Stress rupture test details and results – Cross weld tests at 575ºC

Process	Mat/WM/Mat			PWHT	Ref.	Stress	Estimate	Actual	El%	Consum	PQR No.	Failure position
	Aged 614ºC for 3208 hours											
FCAW	P23	P23	P23	715ºC	PQT2	130	5000	1195	4.56	Cormet 23		Weld metal
FCAW	P23	P23	P23	715ºC	PQT2	120	2000	1966	4.98	Cormet 23		Weld metal
FCAW	P23	P23	P23	715ºC	PQT2	110	5000	3731	2.72	Cormet 23		Weld metal
MMA	P23	P23	P23	None	ZL344	130	5000	812	4.77	Chromet 23L		Weld metal
MMA	P23	P23	P23	None	ZL344	120	2000	1137	5.67	Chromet 23L		Weld metal
MMA	P23	P23	P23	None	ZL344	110	5000	2505	3.09	Chromet 23L		Weld metal
	All weld metal tests											
FCAW		P23		715ºC	PQT2	280	1000	8.5	12.56	Cormet 23	001002	
FCAW		P23		715ºC	PQT2	200	2000	312	4.92	Cormet 23	001002	
FCAW		P23		715ºC	PQT2	130	5000	849	1.51	Cormet 23	001002	
FCAW		P23		715ºC	PQT2	120	10000	1527	2.42	Cormet 23	001002	
MMA		P23		None	ZL344	210	2000	117	3.02	Chromet 23L	010907	
MMA		P23		None	ZL344	175	2000	551	0.22	Chromet 23L	010907	Thread failure outside g/l
MMA		P23		None	ZL344	130	5000	3126	2.44	Chromet 23L	010907	
MMA		P23		None	ZL344	110	10000	6904	4.52	Chromet 23L	010907	
MMA		P23		715ºC	ZL344	152	1000	2082	3.9	Chromet 23L		
MMA		P23		715ºC	ZL344	162	500	1929	1.76	Chromet 23L		

g/l : gauge length

Table 5.2 : Stress rupture test details and results : Aged material and all-weld tests at 575ºC

Material Region	A	n
Parent material	8.414×10^{-32}	11.5
HAZ	8.414×10^{-32}	11.5
Weld material	8.414×10^{-32}	11.5

Table 6.1: Definition of Norton-type creep law constants A and n for model 1

Material Region	A	n
Parent material	8.414×10^{-32}	11.5
HAZ	4.574×10^{-29}	7.91
Weld material	1.565×10^{-30}	10.3

Table 6.2: Definition of Norton-type creep law constants A and n for models 2 & 3