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PRELIMINARY ASSESSMENT OF THE FATIGUE ENDURANCE BEHAVIOUR OF THIN SECTION TUBULAR WELDMENTS MANUFACTURED FROM AUSTENITIC STEELS AT 525°C

Colin Austin[1], Simon May[1], Steve Jacques[1], and Andrew Wisbey[1]

[1] Amec Foster Wheeler, Clean Energy, Birchwood Park, Warrington, Cheshire. WA3 6GA UK

ABSTRACT

It has been recognised that the mechanical performance of welded 316H stainless steel can vary significantly, dependent on the material section size, weld geometry and other parameters. As part of the continual development, enhancement and validation of the UK high temperature structural integrity assessment code, R5, the performance of thin section welded 316H structures have been targeted for investigation. Thus, thin section 316H tube material, TIG welded with 316L filler to produce one or two weld beads, have been evaluated in the present work.

Two different weld configurations have been manufactured and coupon test pieces have been extracted for evaluation of the mechanical properties. These have consisted of a 2-pass butt TIG weld between two 316H plates (6mm thickness) and butt TIG welded 316H tubes (4mm wall thickness). In addition to these coupon tests, whole tubes, containing a central butt weld have been produced and tested at the service temperature to provide validation information for the analysis procedure. The work reported here will focus upon the experimental work performed, for example the production of small scale weld extract test pieces and a successful large scale tube validation test piece.

The test data described here concentrates on the low cycle fatigue behaviour at a typical service temperature of 525°C. This work has shown that the welded tube validation tests display significantly lower lives than the coupon tests and potential reasons for this difference are suggested.

INTRODUCTION

There are many Advanced Gas-cooled Reactor (AGR) components which are manufactured using thin section 316H austenitic steels joined by 316L TIG butt welds containing one or two beads through-thickness, especially within the boiler units. It is possible that the mechanical behaviour of such thin section welds can differ from those seen in typical thick section welds for these materials. The structural integrity assessment of these welds under reactor service conditions is covered by the assessment code R5/VOL2-3[1] and here the fatigue behaviour of these welded joints and their constituent materials is of particular interest. Thus thin section parent tube material has been studied, along with the performance of weldments in this material, to derive appropriate material properties for this material condition.

The tubes in AGR plant have wall thicknesses between 4 mm and 7 mm thick and to manufacture fatigue test pieces from this material and the appropriate weld material has required some test piece design development to accommodate relatively small test piece diameters and limited material availability. In addition, it was required to undertake some validation structural fatigue tests of whole tubes, containing weldments, and again these have required development to enable successful strain controlled testing at 525°C in laboratory air.

MATERIALS

Tube and Weldment Materials

The tubes were manufactured by Sandvik but supplied by EDF Energy and were manufactured from austenitic stainless Type 316H steel (cast 509885) and have a wall thickness of 4 mm with an outer diameter of 38 mm. The chemical composition of the tube is shown in . The tube dimensions are identical to the dimensions of the AGR boiler tube geometry, as shown in Figure 1 which shows a typical length of the butt welded tube.

Table 1. The chemical composition of the 316H Sandvik parent tube and the weld metal deposited for the 2 -pass longitudinal welds.

Element	C	Cr	Ni	Mo	Mn	Cu	N	Si	S
Parent tube	0.05	16.85	11.23	2.04	1.55	0.33	0.049	0.53	0.0053
2-pass weld	0.021	18.03	11.11	2.35	1.72	0.14	N/A	0.27	N/A

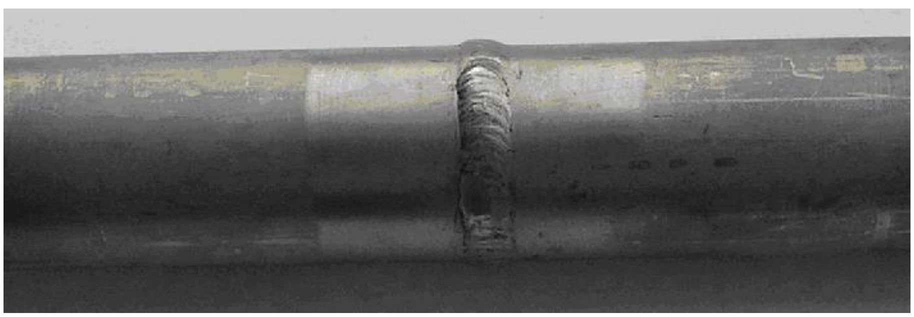

Figure 1. Sandvik tube, showing butt weld.

The butt welds in the 4mm thick tubes were produced by Doosan-Babcock using two TIG Type 316L weld passes and, as on the AGR plant, remained in the undressed condition for validation weldment testing. Tube extract specimens were also manufactured from this material, as explained below.

The butt-welded tubes were post weld heat treated (PWHT) for 15 minutes at 1050-1070°C, and cooled by quenching in cold nitrogen gas to a temperature of <300°C. The tubes were then allowed to cool in free air. Parent tube specimens tested within this programme received the same PWHT process as the weldment specimens.

Two Pass (2-pass) TIG Weld Material

The welds used to join the Type 316H tubes in plant (e.g. for joints within the boilers) consist of 2 weld beads of Type 316L TIG filler. To evaluate the weld material alone, the cylindrical butt welded joints described above are clearly impractical to cut weld only material from. However, to reproduce these material conditions as closely as possible it was necessary to produce straight longitudinal butt welds (still comprising 2 beads (2-pass) between type 316H plates of equivalent thickness to the tubes.

The 2-pass welds were produced between two 6 mm thick plates, which was chosen to replicate some of the thicker wall tubes used. A ‘V’ weld geometry was used, with a 35° angle preparation and a 2 mm gap between the plates. A 6 mm thick backing plate, made from the same material, completed the weld set-up.

After performing several trials using 1.6 mm and 2.4 mm diameter type 316L weld filler wire, hardness and micro-structural examinations revealed that the 2. 4mm wire properties best replicated the in-service welds. The 2.4 mm diameter type 316L filler wire was supplied by Doosan-Babcock. The chemical composition of this weld material can be seen in and it is worth noting that the carbon content was considerably lower at 0.021wt.% than the parent tube material above (0.05wt.%). After manufacture, the welds were examined both visually and by radiographic techniques to determine the location of any weld defects so that this material could be avoided during specimens manufacture. The weld material from these longitudinal weld beads was extracted for testing. These welded plates are shown in Figure 2.

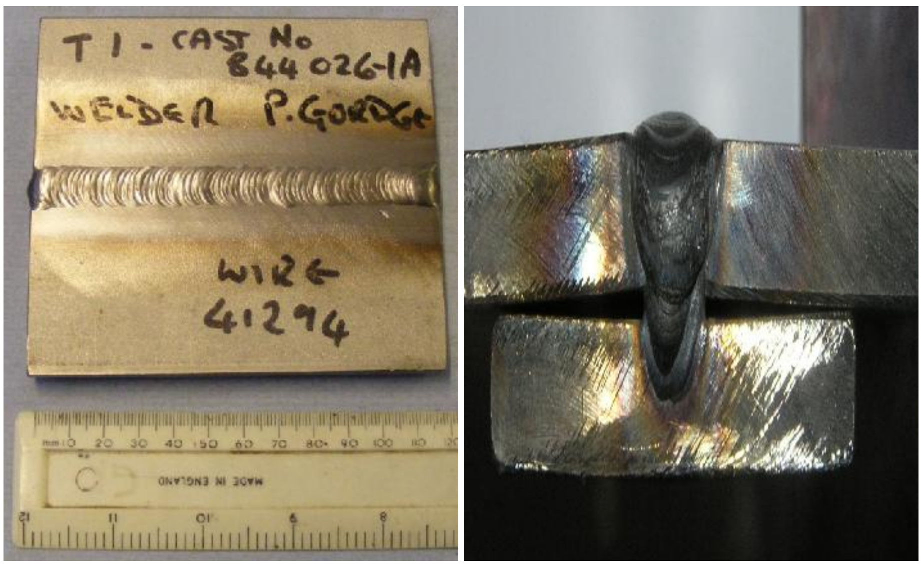

Figure 2. Top and side view of welded plates, simulating tube butt welds.

SPECIMEN MANUFACTURE

Type 316H Tube Extract/Cross-weld Specimens

Uniaxial LCF test specimens were manufactured from the 4 mm wall thickness Sandvik tube materials described above. To determine the properties of the parent tube material longitudinal sections were cut and similarly samples were extracted across the butt welds to enable the cross-weld properties to be evaluated.

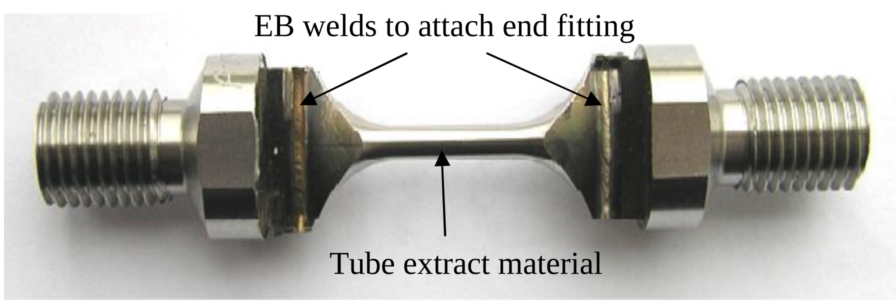

Figure 3. Tube extract test specimen after final machining, showing the location of the EB welds to attach end fittings.

A standard test specimen design could not be used due to the thin tube section thickness of 4 mm; thus a bespoke specimen design was developed. The thin section tube extracts were electron beam (EB) welded onto cylindrical end pieces of 316 material. These EB welds were examined metallographically on sections cut from trial samples and radiography was also applied to all test samples to assist in determining the integrity of these EB welds. Once confidence had been gained in the specimen manufacturing method, then the final assemblies were machined into fatigue test specimens, including the threaded ends to permit location into the test frame loading bars. An example is shown in Figure 3 and the circular machined gauge length (diameter ~3.5 mm) of the tube extract material can be seen. These are considerably smaller than conventional test piece designs.

Type 316L 2-Pass Weld Specimens

Miniature fatigue specimens were also manufactured from the two pass (2-pass) weld material produced from the joining of the 6 mm thick plates, described above. Coupons of the weld material were cut from the longitudinal welds, ensuring that the weld material was central within the coupon, as the intention was that the final specimen gauge length would only include this weld material. As with the tube extract specimens above, EB welding was used to attached 316 end pieces onto a machined cylinder of the 2-pass weld material. The specimen design ensured that the EB weld was positioned within the transition radius of the specimen and well away from the test gauge length. The final test diameter was 5 mm and the gauge length was 12 mm. An example of a final machined LCF specimen is shown in Figure 4.

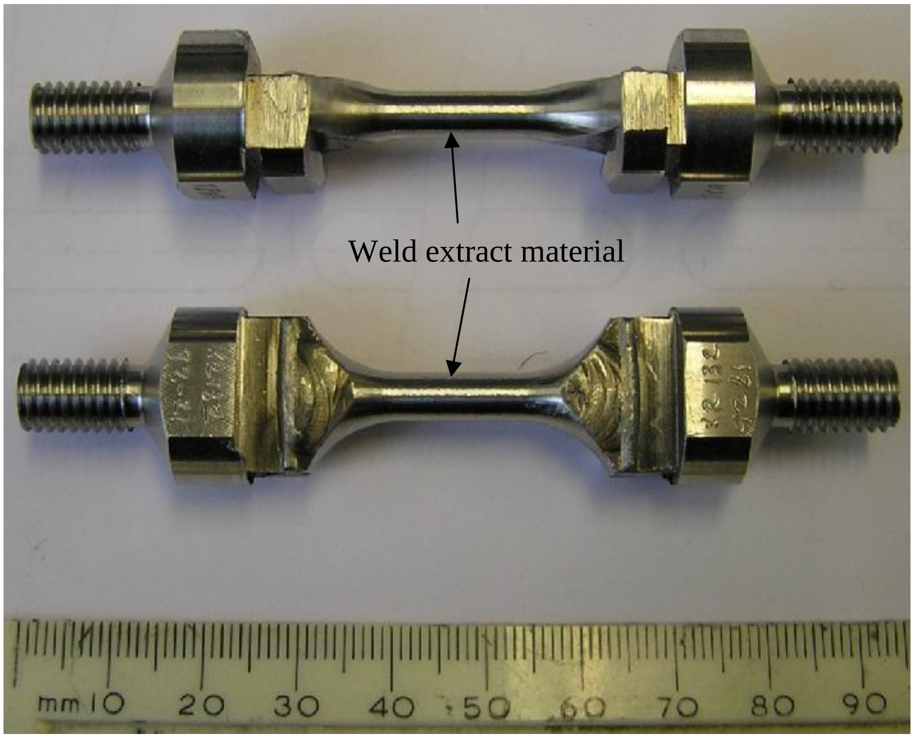

Figure 4. Two pass weld material specimen, extracted from longitudinal welded plates.

After final machining, the specimens were all solution annealed in vacuum using the same heat treatment conditions used for the tube material described above.

Validation Test - Tube Weldment Specimens

Alongside the coupon test pieces above that have been produced for testing, it was determined that some structural tests to validate the assessment methodology developments were also required. The test pieces take the form of whole tubes and incorporating a central butt weld, as described above. The tubes were approximately 300 mm long, with the weld located at the centre of its length. Typically, the weld width was 8 mm. This is shown in Figure 1.

To permit location into the test machine loading bars, adaptors were welded to the ends of the tube sections. These cylindrical adaptors were machined from sections of Type 316 steel and welded to the tube using a modified TIG technique incorporating Type 316 filler. Once welded, the adaptors were threaded in order to locate and fix the specimen in the test frame before testing. The threads were machined such that they were parallel with the central weld and concentric to each other to maintain the alignment. There was considerable development in the test specimen fixturing to ensure that test failures occurred in, or around the central weld, rather than the end fixture welds. The requirement to place the test specimen in compression during the fatigue tests led to concern that buckling could become a significant problem and hence considerable effort was spent modelling the test specimens and simulating varying degrees of misalignment between the ends of the welded tubes (the tubes were almost always misaligned to some degree after the central butt welding process). This work indicated that buckling was unlikely to be a problem for the strain ranges that were envisaged.

METHODS OF TEST

Parent Tube, Cross-weld and 2-pass Weld Extract Tests

The low cycle fatigue tests on the coupons extracted from the thin section tube and the 2-pass longitudinal plate weld were performed in strain control using the recommendations within BS 7270:2006[2]. Tests were carried out at 525°C, all at a constant strain rate of 0.04%.s^{-1}. The tests were performed between total strain ranges (TSR.) of 1.5% and 0.4%, each with a mean strain of zero (R=-1). The tests were initially loaded in the tensile direction. Strain control and hence specimen extension was monitored by a direct reading MTS side-loaded axial extensometer which was spring loaded onto the specimen gauge length. Calibration of the extensometer followed the requirements of BS 9513:2002[3]. The extensometer was air cooled with a test gauge length of 12 mm.

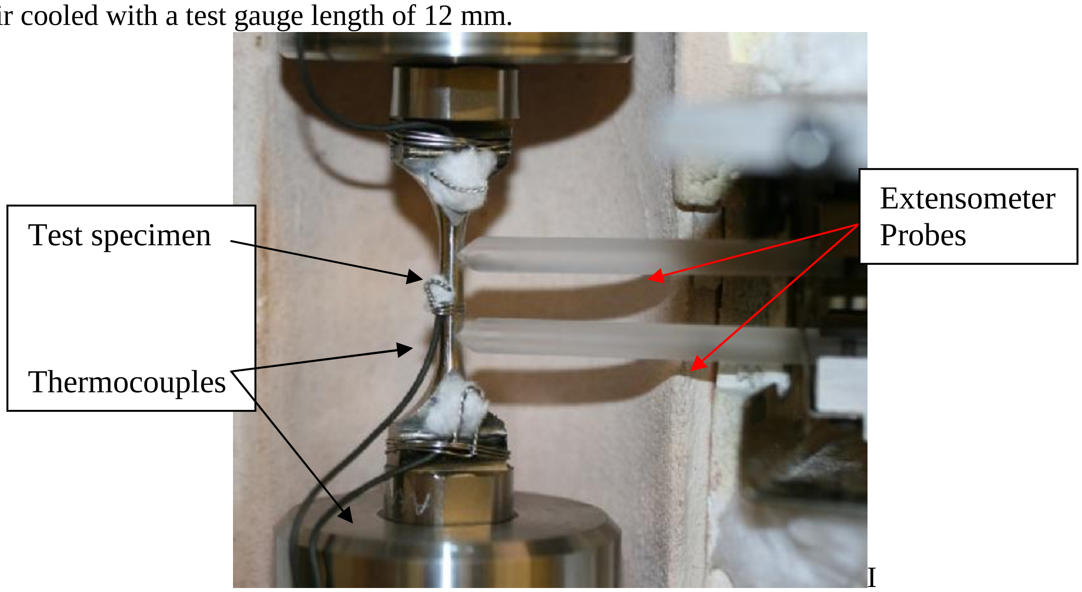

Figure 5. A typical LCF test arrangement, showing the location of thermocouples and the extensometer. This sample is parent tube material.

All loads were measured using a calibrated (to BS EN ISO 7500-2[4]) load cell. A typical test set-up is shown in Figure 5 and the insulating fibrous material over the ends of the thermocouples can be seen, avoiding direct heating of the thermocouple tip by the furnace.

Validation Weldment Tests

Low cycle fatigue (LCF) tests, under strain control, were also required on the structural validation tests, using the whole tube specimens described above. Due to the non-standard nature of these test specimens, the test arrangement and procedure has been specifically developed for these tests. However, it is based on the guidelines in the strain controlled axial fatigue standard used above, i.e. BS 7270:2006[2] and the same standards for calibration of the load cell[4] and extensometer[3] were used, as with the more conventional coupon testing, described above.

The major issue with the development of these tests has been obtaining reliable strain control. However, this has been achieved using a creep style (i.e. drop-leg) axial extensometer and using a single displacement transducer to measure the extension. Locating lugs for the extensometer were spot welded equi-distant either side of the weld. The whole weld width of 8 mm, was centralized between the lugs for the extensometer probes and a total gauge length of 20 mm initially was obtained, although this was extended to 30 mm to improve strain control after the first few tests. Hence there was approximately 6 mm or 11 mm of parent tube material on each side of the weld and within the extensometer gauge length. The general test arrangement can be seen in
Figure 6.

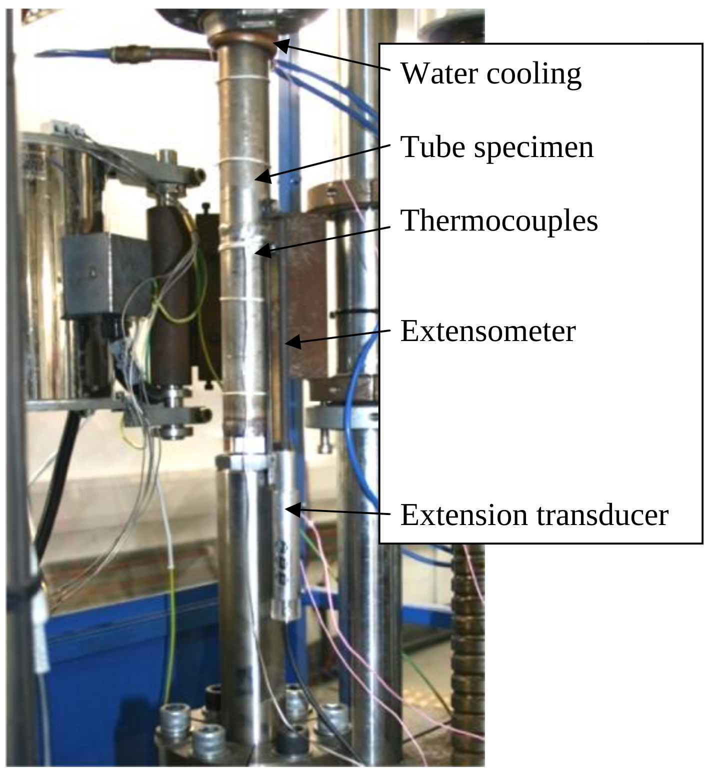

Figure 6. General test arrangement for the structural tests on whole welded tubes.

The displacement transducer was air cooled and attached to the specimen using arms that allowed the transducers to be located away from the furnace. The arms of the extensometer were attached to the tube surface at a position which is 90° around the circumference from the plane containing the maximum misalignment angle of the section. This was done to ensure that axial strain alone is measured, i.e. without any bending strain (it is worth noting that the axial misalignment due to welding of the tube was measured for each sample). The working range of the LVDT was +/- 2.5 mm with a working gauge length of up to 30 mm.

The fatigue tests were carried out at 525°C, with a constant strain rate of 0.04%.s^{-1}, similar to the more conventional coupon tests. The tests were performed over total a total strain range (TSR) between 1.5% and 0.4%, each with a mean strain of zero (R=-1).

The tests were initially loaded from zero stress and zero strain in the tensile direction and continuously cycled using a triangular waveform until failure, as indicated by an approximately 90% reduction from the maximum applied load. None of these validation tube weldment specimens were taken to complete separation to avoid damage to the extensometer or test machine.

RESULTS & DISCUSSION

All of the fatigue endurance data obtained from the parent tube material, the cross-weld tube extracts (only 2 off tests), the extracted weld material from the plate samples and the structural validation tube tests are summarised in Figure 7. In addition, the best estimate mean and lower bound fatigue endurance curves for 316L and 316H from the literature[5] have also been plotted to compare with the experimental data shown here (although it should be noted that this data has been derived from other test temperatures and interpolated for 525°C). This literature data is a compilation of fatigue test data that was assembled for the European Fast Reactor collaboration originally. A fatigue failure criterion of a 10% reduction in maximum tensile cyclic stress has been used (using the method described in BS7270:2006[2]), as this eliminates some of the variability associated with the final failure stages of a fatigue test, leading to sample separation.

The literature endurance curves have been compensated for the reduced test specimen diameters used here in the tests, using the methodology in R5 Vol 2/3[1]. The procedure adjusts the base line endurance curve by removing the nucleation cycles to provide the crack growth cycles. These growth cycles are then adjusted to compensate for reduced material thickness. The thickness compensated endurance curve is then generated by taking the sum of the adjusted growth cycles with the nucleation cycles.

Despite the very small diameter and relatively long length of some of the coupon tests, the majority of tests failed within the gauge length and have been included in the data shown in Figure 7. However, two tests were lost to buckling and were thus considered invalid.

As may be anticipated the parent 316H tube material, extracted from the 4 mm wall thickness tubes, gave the highest fatigue lives from the coupon tests (i.e. using standard LCF testing procedures), although at the lowest strain range tested (0.4% total strain range) the parent data overlapped that from the weld material extracted from the 2-pass longitudinal welds. Clearly with the limited number of tests available at present care must be taken when interpreting the differences in fatigue life for the different material conditions. The parent 316H tube data was found to agree closely with the literature for 316H material[5], which had been extracted from a range of wrought product forms, e.g. bar and forged material (i.e. significantly thicker section than the 4 mm thick tube). This suggests that there isn't a large effect of section thickness on the fatigue life of wrought material, once specimen size effects have been accounted.

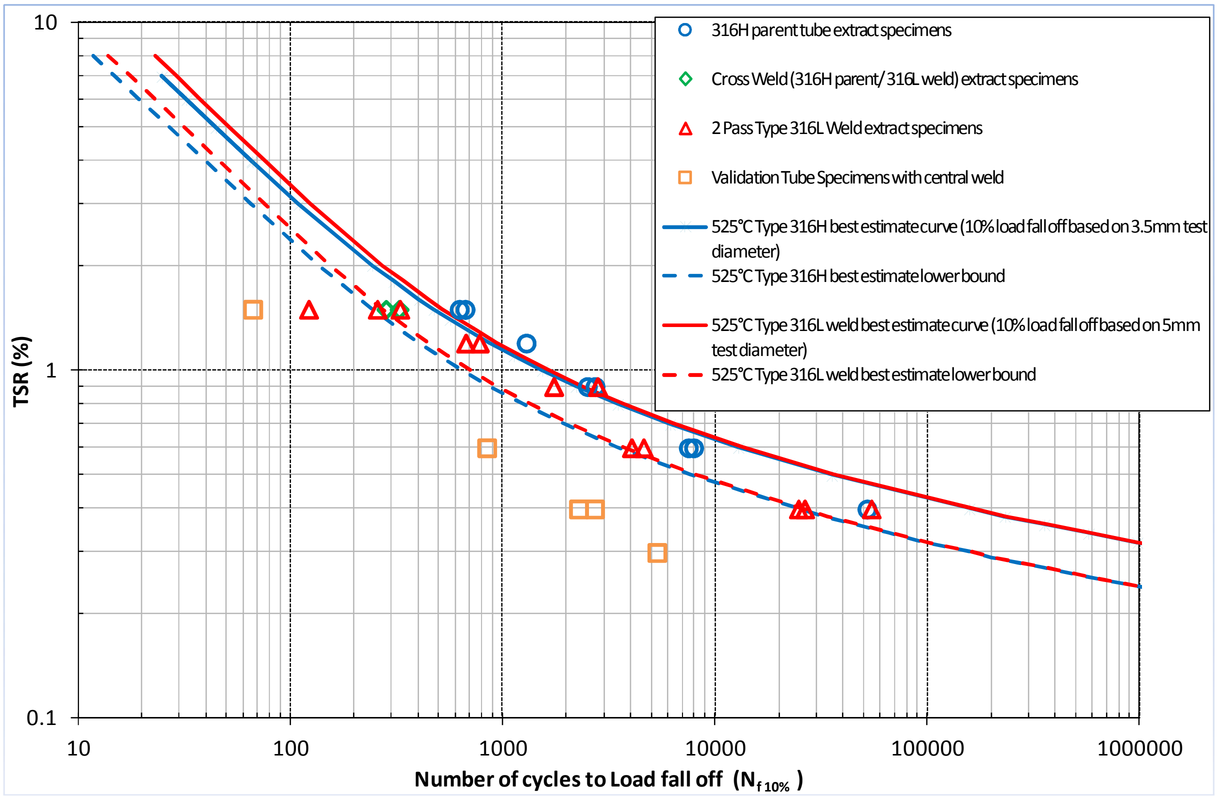

Figure 7. The total strain range and number of cycles to failure (life to 10% reduction in stress - $N_{f10\%}$) for the various 316 weld and parent tube tests conducted.

The apparent reduced fatigue life of the 2-pass weld extract specimens, compared to the parent tube is perhaps unsurprising given the increased likelihood of defects (hence crack initiation sites) in the weld material. However, it should also be noted that there is also a significant difference in the chemical composition of the two materials, with the parent tube showing almost double the carbon present, compared with the weld (). The two coupon tests on specimens extracted across the tube welds (i.e. cross-weld samples) gave lives that were very similar to the weld only material and this again seems consistent with the expected behaviour. Clearly there is a need to consider weld material properties separately from parent tube when undertaking any form of structural integrity assessment.

The miniature tube (parent & cross-weld) and 2 pass weld extract specimens used in this study were all manufactured with a turned finish with a nominal roughness average of 0.4 µm (Ra), typical of plant situations. However, the surface roughness was not measured on individual specimens and thus any variation in surface finish may contribute to some variation in fatigue life[6]. In contrast, the weldment tube validation tests were tested with an undressed weld and all failures occurred at the transition between the weld and parent tube. This is probably unsurprising given the stress concentration at this position and thus providing an early crack initiation site. The tube extract cross welds, which were machine turned, cracked in a similar location relative to the weld and it is thought that there may be a relatively soft HAZ, which may promote provide a crack initiation site, however, this requires confirmation.

The endurance of the weldment tube validation test data is significantly less than the lower bound curve predicted for Type 316 steels from the literature[5] and a progressive, almost linear, increase in fatigue life with reducing T.S.R. is observed. This trend is observed even at the lowest T.S.R. of 0.3% which, unlike all other data shows no exponential increase in fatigue life. The data suggests that all of the endurance consists almost entirely of crack propagation, with little or no crack initiation phase. This could be due to the effect of the weld itself, but the effects of misalignment (due to welding), surface finish and a different specimen set up to the miniature specimen test should also be considered. It will clearly be important to understand all of the potential causes of reduced fatigue life for plant components, when using coupon test data to predict plant component life.

Table 2. Summary of tensile properties of the tube and welded 316 at 525°C.

Material Condition	0.2% Proof Strength MPa	UTS MPa	Elong^{n} to failure %	Reduction in area %
Parent tube (4 mm)	137	379	28	51
Cross-weld in tube	116	375	-	-
2-pass weld only	119	394	28	46

A summary of the tensile data for the various test arrangements evaluated is shown in
and this suggests that the parent tube offers the highest proof strength of the different 316 conditions, although the 2-pass weld extract specimens showed the highest UTS.

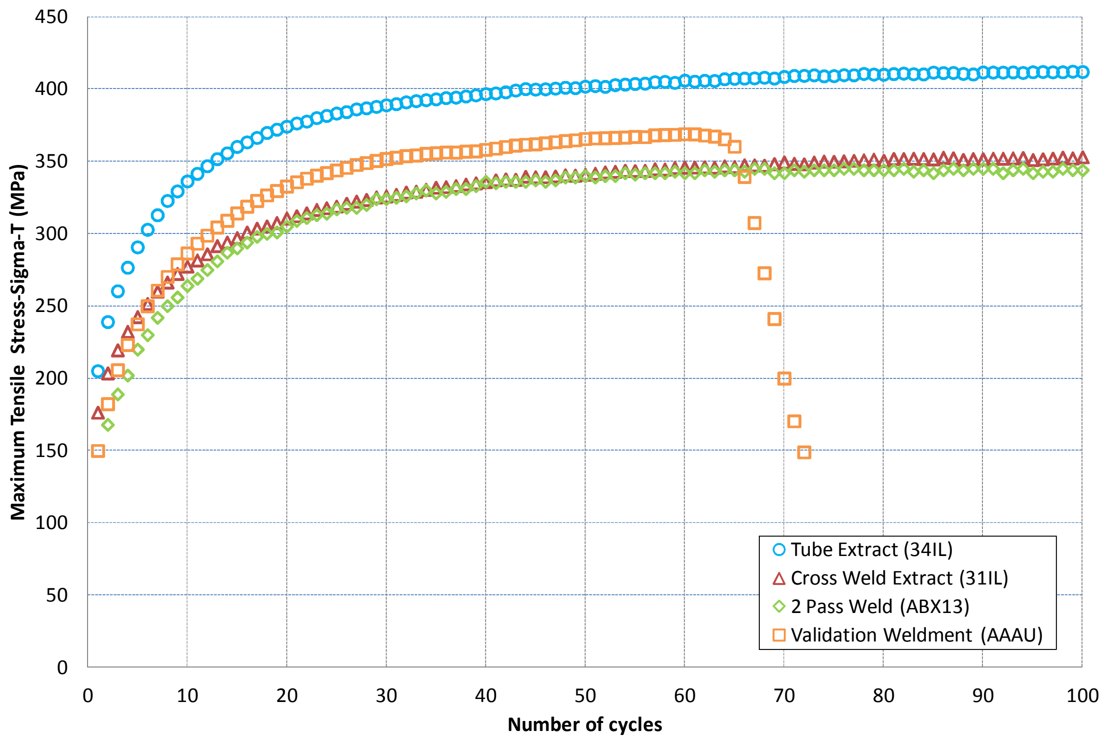

Figure 8. The peak cyclic tensile stress for the first 100 fatigue cycles for tests performed at a total strain range of 1.5%, showing the difference in response of the four different specimen sources.

The peak cyclic tensile stresses that were measured during fatigue tests at a 1.5% total strain range can be seen in Figure **8**. This shows that all of the materials examined undergo cyclic hardening, which after peaking slowly reduces and this is consistent with other work on this

material[7]. The parent tube undergoes the largest level of hardening of any of the samples, consistent with the high 0.2% proof strength of this material (
). Whilst the cross-weld tube and 2 pass weld extract specimens gave very similar levels of cyclic hardening, again consistent with their almost identical tensile 0.2% proof strengths (
). Similar hardening behavior was seen at all of the strain ranges tested.

SUMMARY

Thin section 316H tube material, some containing welds, have been evaluated under elevated temperature fatigue conditions. This has required the development of novel, non-standard test piece designs, including structural tests of whole tubes containing a weldment. Strain controlled fatigue tests have been performed and this has showed the reduced life of weld containing test pieces, compared with parent. The structural tests showed a further reduction in life and appeared to show a change in the overall behavior with no tendency towards a fatigue limit at lower strain ranges. It is thought that this may be associated with the retention of the weld cap on these structural tests and the resultant stress concentration feature. There is a clear requirement to understand the features which contribute to the fatigue life of plant components when using standard coupon test data within assessments.

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