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Residual stresses in arc and electron-beam welds in 130 mm thick SA508 steel: Part 1 - Manufacture

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ABSTRACT

In this study we aim to determine how the choice of welding process might impact on the through-life performance of critical nuclear components such as the reactor pressure vessel, steam generators and pressuriser in a pressurised water reactor. Attention is devoted to technologies that are currently employed in the fabrication of such components, i.e. narrow-gap variants of gas-tungsten arc welding (GTAW) and submerged arc welding (SAW), as well as a technology that might be applied in the future (electron beam welding). The residual stresses that are introduced by welding operations will have an influence on the integrity of critical components over a design lifetime that exceeds 60 years. With a view to making an assessment based on residual stress as pertinent as possible, weld test pieces were manufactured with each process at a thickness that is representative for such components, i.e. 130 mm. In Part 1, the manufacture of the welds is documented, together with the underpinning rationale, so that the value of the resulting measurements (which are presented in Part 2) will be maximised.

1 Introduction

After a hiatus spanning more than two decades, the prospect of a new nuclear build programme in the United Kingdom has stimulated interest in reviewing the manufacturing technologies that are available [1]. Over that time, the most significant changes in the landscape, in the context of fabricating components in the primary circuit of a light water reactor, have related to advancements in narrow-gap (NG) arc welding technologies, and the potential for applying electron beam (EB) welding to large components outside of a vacuum chamber [2]. In other countries, narrow-gap variants of arc welding technologies
such as gas-tungsten arc welding (GTAW) and submerged arc welding (SAW) have already been applied in the manufacture of nuclear pressure vessels [3], but EB welding does not yet appear to have been utilised in a civil reactor, despite attracting the interest of some fabricators [4]. Given that incremental changes in manufacturing practice have already been adopted in some quarters, and that further changes are likely to be considered in the near future, it would seem appropriate to assess how the choice of welding process might influence the performance of critical nuclear components over a design lifetime that is typically 60 years or more.

One of the parameters that can have an influence on the through-life integrity of nuclear components is residual stress [5-7]. Residual stresses can be additive with operating stresses, they can increase the driving force for the propagation of cracks [8], and they can contribute to the initiation of cracks even in the absence of operating stresses [9]. The residual stresses that are associated with ferritic steel welds often receive less attention than, for example, the dissimilar metal safe-end welds at nozzle-to-pipe transitions [10, 11], owing to the fact that ferritic steel welds are subjected to a post-weld heat treatment (PWHT) procedure. However, levels of residual stress in the order of 100 MPa can persist after PWHT [12, 13], and this might be significant towards the later stages of the design life of a critical component, since the ductile-to-brittle transition temperature can increase during the life of a reactor [14], potentially leading to situations in which upper shelf toughness cannot be guaranteed. Furthermore, in situations where weld repairs are carried out, it may not be feasible to carry out PWHT, and in those situations safety assessments must be carried out based on as-welded stress levels.

In this study, the authors have designed and manufactured weld mock-ups for the purpose of comparing the residual stresses that are generated with three welding processes, namely NG-GTAW, NG-SAW and EB welding. The first two of these processes are both currently employed in the manufacture of primary components in pressurised water reactors (PWRs), while EB welding will be considered for application in the not-too-distant future. In each case, the base material was SA508 Grade 3 Class 1 steel, which is widely used for primary components in civil PWRs, and the thickness of the welds was 130 mm – a value that is representative of the wall thickness of such components. It is hoped that the data that have been generated in this study will serve as a valuable reference for welding engineers and structural integrity professionals, and also as suitable benchmarks for the validation of weld
modeling frameworks, for many years to come. If the utility of this work is to be realised, it is of vital importance that the provenance of the weld test pieces is thoroughly documented. Accordingly, this article (Part 1) describes the design and manufacture of the weld mock-ups, together with the rationale that influenced manufacturing decisions, and the residual stress measurements are presented in an accompanying article (Part 2).

2 Materials

2.1 Base Material

The base material was sourced in a sufficient quantity to provide for all of the weld mock-ups in this study. It was extracted from a single prolongation ring forging that was contiguous with a dome, with the parent component being manufactured from SA508 Grade 3 Class 1 steel. The chemical composition for the base material is listed in Table 1. Prior to the extraction of the test pieces for this work, the parent component had been subjected to a quality heat treatment that involved austenitisation at 874°C ± 13°C for 6.5 - 7 hours, followed by water quenching for 3.5 hours until the component reached a temperature of 9°C, and subsequent tempering at 642°C ± 7°C for 9.5 - 11.5 hours. For the tempering operation, the heating rate was 23°C/hour while the cooling rate after the hold at 642°C was 13°C/hour. The room-temperature mechanical properties listed on the mill certificate include a 0.2% proof stress of 456 MPa, an ultimate tensile strength (UTS) of 610 MPa, and an elongation of 27%.

In all cases the welds were made between two flat plates that had been extracted from the forged ring. The dimensions of the plates were 575 mm × 165 mm × 130 mm, and butt welds were made so that the final dimensions of the joined test pieces were approximately 575 mm × 330 mm × 130 mm. A schematic representation of the manner in which plates were extracted from the parent component is given in Figure 1, which also shows the nominal dimensions of the final welds.

It was recognised that the residual stresses that arise in a weld between two flat plates will differ significantly from those between two solids of revolution. However, it was not feasible to join two solids of revolution using the laboratory equipment that was available for this work. While the possibility of joining cylindrical components with a smaller diameter was considered, it was not possible to procure such components in SA508 Gr. 3 Cl. 1 steel. On
this basis, it was judged that a suitable approach would involve using steel that is relevant to primary components in civil nuclear reactors, and extracting rectangular test pieces. The resulting test pieces would still provide an invaluable comparison between the welding processes, and they could serve as benchmark specimens for the validation of finite element models, which could ultimately be applied to relate the residual stresses in a butt-welded flat plate to those that would arise in a full-sized cylindrical component.

![Figure 1: Schematic representation of the manner in which 12 rectangular blocks were extracted from a prolongation ring in a larger component (left), and the final dimensions of the test pieces after welding (right).](image)

### 2.2 Filler Materials and Flux

An S3-1Ni-0.25Mo filler wire (AWS A5.23:ENi5) with a diameter of 1.2 mm was employed for the GTAW test piece. An SDX S3Si-EH12K filler wire (AWS A5.17:EH12K) with a diameter of 2.4 mm was used for the SAW test piece, in conjunction with SWX 150 flux (AWS A5.17:F7A8-EH12K). The chemical composition for each of these wires is listed in Table 1. The EB weld was autogenous.

In choosing the filler wires, care was taken to ensure that the copper concentrations were below 0.1 wt.-%, since copper is known to exacerbate irradiation embrittlement [14]. A wire without a copper coating was procured for GTAW whereas, for SAW, it was not feasible to procure a wire that was not copper coated without purchasing a quantity that greatly exceeded what was required for this study. However, owing to the larger wire diameter...
used for SAW, the overall copper concentration in the wire was lower than it was for GTAW in spite of the presence of a copper coating.

| Materials/Elements     | C   | Si  | Mn  | Cr  | Co  | Ni  | Mo  | S   | P   | Cu  | Fe  |
|------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| SA508Gr.3Cl.1          | 0.16| 0.27| 1.43| 0.23| 0.004| 0.77| 0.52| 0.002| 0.005| 0.04| Bal. |
| SDX S3Si-EH12K (NG-SAW)| 0.08| 0.37| 1.48| 0.012| -  | 0.037| 0.003| 0.005| 0.008| 0.054| Bal. |
| EF3N (S31Ni1/4Mo)     | 0.10| 0.20| 1.47| 0.03 | -  | 0.88| 0.25| 0.005| 0.006| 0.075| Bal. |

### 3 Welding Set-Up

#### 3.1 Welding Position

When an arc welding process was applied, all weld passes were made in the 1G welding position (i.e. with the torch vertical). The 2G welding position was employed for EB welding (i.e. with the beam horizontal), as this greatly reduced the likelihood of the weld pool sagging excessively, or even falling through to the bottom of the chamber, owing to the hydrostatic pressure associated with a 130 mm high column of liquid metal.

#### 3.2 Tack Welding

The plates being joined using the EB welding process were fixed relative to one another by tack welds located at either end of the weld seam. These tack welds spanned the entire thickness of the specimen at each end. For the arc welds, tacks at both ends of the plates were also utilized, and run-on and run-off tabs were subsequently tack welded to the ends of the samples. Some method for fixing the plates in position prior to welding was required and, although tack welds will themselves introduce residual stresses, the authors are of the view that these effects will have been confined to the ends of the test pieces, and then ameliorated by the subsequent welding process. Furthermore, the run-on and run-off tabs for the arc welds were left in place during subsequent residual stress measurements on the
grounds that removing them might have led to a small reduction in restraint, and hence some relaxation in residual stress.

### 3.3 Provision of Restraint

A customized restraint rig was designed and manufactured for the arc welds in order to mitigate what is sometimes referred to as “butterfly distortion”. This term refers to the angular distortion that takes place when multi-pass welds are made from one side only, and it is associated with progressive closure of the weld groove. The restraint rig that was employed is represented schematically in Figure 2. It can be seen that the rig comprised two king plates that were held in position relative to one another by a series of tubes, on either side of the rig, that were orientated parallel to the welding direction. It was possible to adjust the distance between the king plates simply by sliding one of the plates along these tubes. The restraining action was applied using four hydraulic cylinders, which were located in each corner of the rig. These cylinders would push a backing plate, together with the assembly that was to be welded, upwards until the assembly came into contact with the upper “fingers” of the king plates. It can be seen that there was a gap between the fingers of the king plates at the top of the rig. This gap was designed to be large enough for both the GTA and submerged arc welding heads to pass through, so that the weld length was not directly limited by the distance between the king plates.

The restraining forces that were applied to the weld test pieces could be documented by recording the pressure of the hydraulic oil, and noting the cross-sectional area of the rams. The oil pressure was recorded for each pass in both the GTAW and SAW test pieces. A small amount of additional restraint would also have been applied indirectly, since the run-on and run-off tabs were bolted to the backing plate in order to prevent the groove in these tabs from closing as weld passes were deposited. However, the restraint arising from these tabs is expected to be insignificant in comparison to the restraint applied by the rig, since the tabs were bound to the test pieces only through tack welds and through the weld metal ligaments at either end of the joint. The overall set-up for the production of the arc welds is shown in Figure 3 and, amongst other features, the run-on tabs are highlighted.
Figure 2: Schematic representation of rig used to prevent butterfly distortion for the weld test pieces made using GTAW and SAW.

Figure 3: Photograph of the GTAW test piece mounted within the restraint rig prior to welding.
3.4 Preheat and Interpass Temperature

Preheating was achieved by placing resistance-heating blankets on the top and bottom surfaces of the plates to be joined, and the temperature of the plates was monitored by observing the output from thermocouples that were spot welded to the surfaces of the test plates. In order to enable preheating blankets to be positioned underneath the weld, the test piece was placed on support bars, with a 30 mm × 30 mm cross-section, that ran along the length of the specimen on either side, as shown in Figure 4. A backing bar with the same cross-section was also manufactured to provide support for the test piece in the vicinity of the weld centerline. However, a slot was machined in the backing bar, to coincide with the weld centerline, and to provide for the supply of a backing gas, which protected the weld root from oxidation.

The GTAW and SAW test pieces were preheated in a range between 160°C and 175°C. An interpass temperature in the range between 150°C and 165°C was maintained between subsequent weld passes. Since each of these welds took several days to manufacture, at the end of each day the test piece would be allowed to cool to ambient temperature, and preheating would be repeated the following morning prior to the resumption of welding.

A preheat temperature of 104°C ± 5°C was applied to the EB weld. This was achieved by rastering the electron beam over the surface of the test pieces prior to welding. It can be argued that it is not necessary to preheat EB welds in the same way that is often necessary for arc welds, on the basis that EB welding is a fluxless process and welding is carried out in a vacuum, so it is clearly less likely that problems associated with moisture and subsequent hydrogen cracking will occur. However, in this study the primary objective was to compare the performance of alternative welding processes, and such a comparison is aided by eliminating variables to the greatest extent that is feasible. On this basis, preheating was also carried out for the EB weld.
Figure 4: Schematic representation of the support bars and backing bar that were used to create cavities for heating blankets underneath the test piece.

4 Design of Joints

4.1 Weld Groove Configurations

A square-butt weld configuration was employed for the EB weld. This process is autogenous and it was possible to join plates with a thickness of 130 mm in a single pass. In contrast, it was necessary to design grooves for the arc welding processes, and several factors had to be considered in this process. Among these were the configuration of individual weld beads (i.e. weaving vs. stringer beads), and the manner in which individual beads would be stacked in the process of filling the groove. These factors are critical because they both influence the extent to which the weld groove is likely to close as weld beads are deposited, through butterfly distortion, noting that excessive distortion in thick narrow-gap welds could result in the welding torch being trapped in the weld groove.

For the GTAW test piece, a single weld pass was deposited in each layer of weld metal within the joint. In order to bridge the gap between opposing sides of the weld groove it was necessary to employ a weaving motion, i.e. the tungsten electrode oscillated from one side of the weld groove to the other as the welding torch translated along the length of the weld. This oscillation was achieved using a welding torch fitted with a swiveling electrode holder, as shown in Figure 5. One of the benefits of employing such a weaving motion is that it reduces the likelihood of lack-of-fusion defects at either side of the weld groove, since the
arc impinges directly on each wall of the groove for part of the weaving cycle. The filler wire was delivered using a hot-wire feeder that concurrently oscillated in a manner that was synchronised with the tungsten electrode. The details of the weaving parameters are described in the next section.

No weaving motion was employed for submerged arc welding. Instead, two weld beads were deposited in each layer of weld metal within the joint, and the consumable wire electrode was tilted to ensure that adequate melting of the groove wall was achieved in each weld pass. Within each layer of weld metal, the first weld pass would involve tilting the electrode so that it was typically 5 degrees off vertical, and tilting towards the groove wall on one side of the joint. The deposition of the second pass in that layer would then be applied with an equivalent tilt towards the opposing groove wall. Again, the motivation for such a deposition strategy was to reduce the potential for lack of side-wall fusion.

![Photograph of welding torch that was used to manufacture the NG-GTAW weld test piece, showing the swiveling electrode holder and swiveling wire feed guide that enabled a weaving motion to be employed.](image-url)

**Figure 5:** Photograph of welding torch that was used to manufacture the NG-GTAW weld test piece, showing the swiveling electrode holder and swiveling wire feed guide that enabled a weaving motion to be employed.

The process of choosing the final dimensions for the weld grooves was based on experimental trials. Welding experiments were firstly carried out at a thickness of 30 mm,
and these experiments have been described elsewhere [13]. With a view to identifying suitable weld groove geometries for joints in 130 mm thick steel, preliminary welding trials were also undertaken at an intermediate thickness of 80 mm. In the first instance, grooves were machined in a cheaper, structural grade of 80 mm thick mild steel (S275). The authors were initially of the view that trials on a structural grade of mild steel would be adequate for the purpose of determining suitable weld groove geometries. However, it soon became evident that such trials would only be of value if they were carried out on a steel that had a similar chemical composition, a similar yield stress, and a similar hardenability to SA508 Grade 3 steel, since solid-state phase transformations are known to affect the extent to which butterfly distortion will occur [15]. As a result, further trials at a thickness of 80 mm were carried out using A533 steel, which has the same nominal chemical composition as SA508 Grade 3 Class 1 steel, and is subjected to the same heat treatment, with the principal difference between the steels being that A533 steel is produced in the form of a plate. Some details of these trials on 80 mm thick arc welds have already been reported [16].

The final weld groove geometries are represented schematically for each process in Figure 6. Since the EB weld employed a square-butt weld configuration, no weld groove was required. It can be seen that the SAW test piece involved the use of a smaller groove angle than was needed for the GTAW test piece. This is related to the fact that the GTA welding procedure employed a weave configuration, with a single pass being deposited in each layer of weld metal. Such a deposition strategy would have led to a high value for the weld heat input, and hence a greater degree of butterfly distortion, thereby requiring the compensation offered by a larger weld groove angle.
**Figure 6:** Schematic representation of the final weld groove geometries for a) the 130 mm thick GTAW test piece; b) the 130 mm thick SAW test piece; and c) the EB weld, which was a square-butt joint welded in the 2G welding position.

5 **Welding Parameters**

A brief summary of the welding parameters that were used in the manufacture of each test piece is given in Table 2, while detailed summaries are given for GTAW in Appendix 1 and for SAW in Appendix 2. It can be seen that, for the arc welds, the table includes a range of values in many cases. This is not a reflection of the variability that was seen within individual weld passes, but rather a reflection of the adjustments that were made, from one pass to the next, as the weld groove was filled. It should be noted that direct current (DC) was used in all cases, i.e. there was no current pulsing.

| Table 2: Typical parameters employed in the manufacture of the 130 mm thick joints.* |
|-------------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Process | Current (Amps) | Voltage (Volts) | Type of Pass | Bead Type | Welding Speed, \( v \) (mm/min) | Wire Feed Speed (mm/min) | No. of passes | Heat Input (kJ/mm) |
| NG-GTAW | 175 | root | | | 75 | 500 | 1.4 |
| | 190-220 | 10-12 | hot | weaving | 75 | 500-600 | 73 | 1.6-1.8 |
| | 325-450 | | fill | | 55-65 | 800-2100 | | 2.7-5.3 |
| NG-SAW | 300 | root | | | 340 | Auto | 1.4 |
| | 300 | 27-29 | hot | stringer | 375 | Auto | 104 | 1.3 |
| | 350-370 | | fill | | 375 | Auto | | 1.5-1.9 |
| EB | 0.3 | 150000 | full thickness | | 100 | N/A | 1 | 27 |

* Full details are given in Appendices 1 and 2.
The nature of the weaving motion for GTAW is represented schematically in Figure 7. In this figure, the path that was traversed by the tungsten electrode is shown, as it would have appeared when viewed from directly above the test piece and the welding torch. The parameters for oscillation varied significantly as successive weld passes were deposited. For example, for the root pass, the oscillation width, $2w_s$, was 1 mm. For the hot passes, this increased to values in the vicinity of 12 mm, whereas for later filling passes the oscillation width was in excess of 20 mm. It was necessary to make minor adjustments as the weld groove was gradually filled, in order to accommodate distortion. In all cases the velocity associated with swiveling, $v_s$, was 900 mm/min. The dwell distance, $d$, arose due to the electrode dwelling for a time, $t_d$, at the extremes of oscillation, while the welding torch translated at a constant velocity, $v$. The wire feeder oscillated in a manner that was synchronised with the oscillation of the tungsten electrode.

In the manufacture of the GTAW test piece, welding grade pure argon was used as both the shielding gas and the backing gas. The backing gas was directed along a channel that was machined into the backing bar, flowing at approximately 20 l/min, and it was employed for the first 6 weld passes. The flow rate for the shielding gas was between 5 and 15 l/min. The tungsten electrode was lanthanated (1 wt.-%) and had a diameter of 3.2 mm. The tip of the electrode was ground so that it was a truncated cone, where the included angle of the cone was 60 degrees, and it had a flat tip with a diameter of 1 mm. The hot-wire feeder employed a current in the range between 50 and 75 Amperes.

In comparison to the GTAW procedure, the procedure for SAW was straightforward, since the torch did not swivel during welding. After a root pass that was coincident with the weld centreline, two stringer beads were deposited in each subsequent layer of weld metal. In all cases, the welding torch was tilted by an angle of 5 degrees towards the near wall in an effort to ensure adequate side-wall fusion. A ceramic backing strip was employed to support the root pass and ensure that the root bead had an acceptable profile. Since the molten metal was protected on the top side by welding flux, no shielding or backing gases were employed. The welding flux was removed after each weld pass, and the bead surface was inspected and cleaned with a wire brush. The contact tip-to-work piece distance was 25 mm for all weld passes. A detailed summary of the welding parameters for individual weld passes in the case of SAW is given in Appendix 2.
The EB weld was made at TWI Ltd., and was witnessed by team members from The University of Manchester. Since the process is autogenous and since it involves only a single weld pass, lack of fusion defects are normally less of a concern than they are with arc welding processes. Welding was carried out with the effective minimum beam diameter being 2.5 mm, and with the focal position residing 2.6 mm below the surfaces of the plates that were closest to the electron gun. An effective beam diameter of 2.5 mm was produced owing to the beam oscillating in a circular motion at a frequency of 140 Hz, with the circle having a diameter of 2.5 mm. The chamber pressure was $3 \times 10^{-2}$ mbar, as there was a small flow of helium into the chamber (0.3 l/min) to mitigate the potential for widening of the beam in a rough vacuum.

![Diagram of welding process]

**Figure 7:** Schematic representation of the weaving of the tungsten electrode in GTAW. The torch underwent linear translation at speed, $v$, while the tungsten electrode swiveled about the axis of the torch, from one side to the other, at velocity $v_s = 900$ mm/min. For a given weld pass, the dwell distance, $d$, is retrievable by dividing the dwell time, $t_d$, by the welding speed, $v$. Values for all parameters are listed in Appendix 1, for each weld pass. Note that the oscillation width, $2w_s$, differs from the width of the weld groove.
6 Instrumentation

Each specimen was instrumented with thermocouples and strain gauges. In all cases, k-type thermocouples were attached to the surface of the specimen using a spot welder. Buried thermocouples were not used, because the authors were of the view that the difficulties associated with achieving a reliable junction at the bottom of a deep hole would raise doubts about the accuracy of the measurements. In contrast, when thermocouples are attached at the surface of the specimen, one can visually inspect the junction to assess its quality, and it is also possible to measure its exact location. However, noting the thickness of the joints, the authors decided that it was essential to attach thermocouples to both the top and bottom surfaces of the plates. The details of the thermocouple arrays for the GTAW and SAW specimens are given in Figures 8 and 9.

![Figure 8: Schematic representation of the thermocouple arrangement for the GTAW test piece.](image-url)
Figure 9: Schematic representation of the thermocouple arrangement for the SAW test piece.

The thermocouple arrays for the EB weld are shown in Figure 10. Eight thermocouples were used in total, with four being on the top surface of the weld, and four being on the bottom surface of the weld. The same thermocouple arrangement was used on both the top and bottom surfaces of the weld test piece.

Figure 10: Schematic representation of the thermocouple arrangement for the EB welded test piece.
Strain gauges were attached to the GTAW and SAW specimens. These welds were both made using a large number of weld passes, all applied from the same side of the test piece. They were also manufactured in a restrained state, with the restraint released when welding was complete. Both welds had significant potential for butterfly distortion, which would be resisted by the restraint system, thereby generating stresses in the plates that would be released when the restraint was removed. It was judged important to track the development of strain, both during the welding process and as the restraint was removed. This information would aid subsequent efforts to model the welding process. The strain gauge locations for each of the joints are shown in Figure 11, with the locations for the reference positions “R3” and “R4” being shown in Figures 8 and 9. As was the case with the thermocouple arrays, the gauges were placed symmetrically about the weld centreline, thereby ensuring redundancy. The gauges were oriented to capture both longitudinal and transverse strains. Strain gauges were not attached to the EB weld. This was welded without any external restraint [17], and the single pass keyhole weld was not expected to develop significant surface strains remote from the weld line as the weld fusion zone was expected to have an approximately constant width through the thickness.

**Figure 11:** Schematic representation of the strain gauge locations on the GTAW and SAW specimens. The fiducial points, R1 through to R4, are defined in Figures 8 and 9.
During the manufacture of the arc welds, strain gauges were also attached to the king plates on the restraint rig, so that the bending moments in the king plates could be recovered. The dimensions of the king plates are shown in Figure 12. The king plates had a thickness of 90 mm, and strain gauges were attached at the mid-height and mid-thickness positions on both sides of each king plate, as shown in Figure 12.

![Figure 12: Schematic representation of king plates in restraint rig with strain gauge positions highlighted.](image)

For the arc welds, thermal transients were recorded using a Measurements Computing USB-2416 data logger with 16 channels, together with Trace DAQ Pro software, at a frequency of 3 Hz. The output from the strain gauges was recorded with a Vishay data logger together with the Strain Smart System 8000 software package (version 5.1) at a frequency of 10 Hz for the duration of welding. The output from the pressure transducer was recorded at a frequency of 3 Hz. Manual measurements of the groove gap at the start, middle and end positions along the weld, as well as of the distance between the R3 and R4 fiducial points, were made prior to welding and after every weld pass. Further to the manual measurements, in-process distortion measurements were performed for both arc welds. Using a Creaform HandySCAN 700 handheld laser scanner, the three dimensional (3D) surface profile of the welded plate was captured after each pass. The time in-between the passes was constrained by the inter-pass temperature requirements. So, when time
allowed, scanning would include the full configuration (Figure 20a-b), including the restraint rig, otherwise the scanning focused on capturing information from the test piece. VXElements v5.1 software was used for retrieving data during scanning. Geomagic Control 2014 was used for post-processing of the point-clouds.

![Figure 13: Laser Scanning Images: (a) Full NG-GTAW set-up at the completion of welding; (b) full NG-SAW set-up at the completion of welding; (c) NG-GTAW plate after removal from](image-url)
restraint-rig; (d) instrumentation of NG-GTAW test piece; (e) cross-section of NG-GTAW test piece prior to commencement of welding; (f) cross-section of NG-SAW plate after pass 104.

Scanning at a resolution of 0.050 mm and a volumetric accuracy of 0.020 mm allowed fine details to be captured, including the locations of the reference points and the punch marks, as well as the locations of the thermocouples and strain gauges. The resulting three dimensional (3D) models constitute a valuable record of the set-up, including details such as the existence of insulating pads, the presence of run-off/run-on tabs and their distortion relatively to the test piece.

For the EB welds, distortion was measured using both digital techniques to reveal the shape of the entire plate, and calliper measurements between the fiducial reference marks (locations shown on Figure 10) to reveal the transverse and longitudinal contraction in the weld region. The overall shape measurements were made with a combination of a conventional coordinate measuring machine (CMM) at TWI, and a Creaform HandySCAN 700 handheld laser scanner at The University of Manchester.

The butterfly distortion angles, corresponding to a cross-section at the mid-length position of the welded test pieces, were obtained from the 3D models (as shown in Figure 20) and are presented in Table 3. The EB weld was associated with the lowest level of distortion, followed by the NG-SAW and then by the NG-GTAW test pieces, respectively. The overall levels of distortion are not excessive, given the size of the test pieces.

Table 3: Butterfly distortion angles for test pieces manufactured with each welding process.

| Butterfly angle (degrees) | NG-SAW | NG-GTAW | RPEB |
|---------------------------|--------|---------|------|
|                           | 1.87   | 3.65    | 0.08 |

Photographs of the completed arc welds are shown in Figure 14. The run-on and run-off tabs are labelled in the figure. It can be seen that these tabs were prepared with through-
thickness holes that enabled the tabs to be bolted to the support plate that was underneath the weld test piece. This ensured that the run-on and run-off tabs did not close excessively during the manufacture of the test pieces.

Figure 14: Photographs of 130 mm thick specimens after the completion of welding with a) the GTAW and b) the SAW processes.

7 Measured Thermal Transients

A subset of the thermal transients that were recorded during the manufacture of the NG-SAW joint is plotted in Figure 15. This test piece comprised 104 weld passes, and the figure includes data that were recorded in the first three passes and the last two passes. The maximum elevation in temperature diminished during intermediate passes, since thermocouples were attached only at the surface of the test piece. A high degree of symmetry can be observed in the thermal transients that were recorded for the first pass, which is unsurprising, since this pass was aligned with the centreline of the weld. It is also reassuring, since it indicates that reliable temperature data have been obtained.

It should be recalled that, with the exception of the first pass, the deposition sequence for the NG-SAW joint was asymmetric, since it involved two passes per layer, with one pass being deposited in each side of the groove. Nevertheless, when the results for passes 2 and 3 are compared, a high degree of symmetry can still be observed, albeit with the peak temperatures being recorded in different thermocouples. The symmetry is less striking for passes 103 and 104, but it must be recalled that these were capping passes, for which the deposition of filler material is constrained by the weld groove to a lesser degree. Furthermore, there is still significant symmetry between the results for passes 103 and 104.
if one focuses on the plots corresponding to thermocouples that were further from the weld.

**Figure 15:** Measured thermal transients for the NG-SAW 130mm weld, passes 1, 2, 103 and 104.

Three plots for the NG-GTAW joint are shown in Figure 16, corresponding to passes 1, 4 and 71, while Figure 17 shows the corresponding results for the EB weld. Although only one pass was deposited in each layer with the GTAW process, there is still an inherent source of asymmetry associated with the weaving of the tungsten electrode. Nevertheless, it appears that a very high degree of symmetry was achieved (Figure 16). Symmetry is also evident in the case of the EB weld, as one would expect (Figure 17). It is worth pointing out, however, that there is also an inherent source of uncertainty in surface temperature measurements for the EB weld since, when welding in the 2G position, gravity will act to pull the free surface of the molten pool downwards, thereby increasing the surface temperatures that are measured on the lower side of the weld.
One feature of the plots is that the cooling rates that were recorded during EB welding are noticeably lower than those that were recorded for the arc processes. This is undoubtedly related to a change from three-dimensional heat transfer (arc welding), to two dimensional (in plane) heat transfer, since full penetration EB welding effectively involves a line source of heat moving through a plate. However, a further significant contribution to the reduction in cooling rate would have been associated with the weld cooling down in a vacuum, as opposed to cooling in air. The complete set of thermocouple data that were recorded in this work have been archived, and can be accessed through the authors upon request.

Figure 16: Measured thermal transients for the 130 mm thick GTAW test piece, for passes 1, 4, and 71.
Evolution of Restraining Pressure and Weld Distortion

During the manufacture of the GTAW and SAW test pieces, the restraining pressures that were applied by the restraint rig were monitored and recorded for every weld pass. Manual measurements of the contraction of the weld groove were also made, by recording the distance between the groove walls at the top surface of the test piece after each pass was completed. Finally, the distortion of the test piece was captured for each pass in three dimensions using the hand-held laser scanning system.

As can be seen in Figure 18a, the groove gap prior to the commencement of welding in the GTAW specimen was 32 mm. However, this gap reduced to less than 22 mm by the time welding was completed, i.e. when the thickness of the weld metal ligament reached 130 mm. Similarly, the groove gap prior to the commencement of welding in the SAW specimen was just over 27 mm, and this reduced to approximately 22 mm by the time the weld was completed. Figure 18 also shows the variation in the pressure of the hydraulic oil that was recorded as each weld pass was deposited. The restraining force in each of the four rams can be recovered by noting that the rams were designed to transfer 100 tons force (996 kN) when the oil pressure is 10,000 psi (69 MPa). Thus, for every psi of pressure, each of the
rams exerts a force of 99.6 N on the work piece. This would equate to a restraining force in each of the rams of 399 kN when the oil pressure reaches 4000 psi.

Figure 18: Groove gap at the top surface of the test piece as a function of the thickness of the weld metal ligament for a) GTAW and b) SAW.

In Figure 18 it is evident that the oil pressure followed a pattern in which it gradually rose as successive passes were laid down, but there were also some significant drops at specific points in the deposition sequence. One case that needs to be noted is for the GTAW test piece when 47 mm of weld metal had been deposited. At this location, the tungsten electrode melted and needed to be replaced. Consequently, there was a significant delay between the pass that was in progress at the time the damage occurred, and the next pass, since the welding torch needed to be repaired. In the intervening time the restraining force was removed, and it was re-applied many days later, when welding re-commenced. It can be seen that there is a corresponding drop in the groove gap at this location, for reasons that are not immediately clear. In the case of the other prominent dips, the oil pressure was reduced manually, since the maximum allowable stress on the king plates arose when the oil pressure reached 4000 psi (28 MPa). It is notable that in those cases the corresponding changes in the groove gap at the top of the test piece were much smaller.

The distances between pock marks at positions R3 and R4 (see Figs. 5 and 6) were also measured on the GTAW and SAW specimens after each weld pass was deposited. The measured values are plotted for each test piece as a function of the thickness of the weld metal ligament in Figure 19. The last measurement that was made on each of the welded
joints was made after release of the restraint. It can be seen that a significant increment in distortion was not observed when the restraint was released.

![Graph showing distance between pock marks on the top surface of the GTAW and SAW test pieces as a function of the thickness of the weld metal ligament (mm). The final measurements were made after the release of the restraint upon completion of welding.]

**Figure 19:** Distance between pock marks on the top surface of the GTAW and SAW test pieces as a function of the thickness of the weld metal ligament (mm). The final measurements were made after the release of the restraint upon completion of welding.

### 9 Cutting Sequence

After welding and all distortion measurements were complete, the plates were prepared for residual stress measurements and the assessment of microstructures. One objective of this work was to measure residual stresses in both the as-welded condition and after PWHT, as is described in Part 2. Slices of material in each condition also needed to be retained for hardness mapping and microscopy, while mechanical properties needed to be determined after PWHT. Careful planning of the cutting and measurement sequence was necessary in order to meet all requirements. Further details of the work sequence are given in Part 2, but a simple overview is represented schematically in Figure 20. In the first instance, incremental deep-hole drilling (iDHD) was carried out on all specimens in the as-welded condition, followed by a contour method measurement. After the contour cut was made, only half of each welded test piece was subjected to PWHT and the subsequent measurement of residual stresses (by conventional deep-hole drilling) and mechanical properties. Figure 20 provides an accurate summary for the EB and NG-SAW joints. However, at a later stage, the remnant of the NG-GTAW joint in the as-welded condition was also subjected to PWHT in order to obtain a further measurement of the stresses after PWHT. The additional measurement was made by conventional deep hole drilling, with the drilling axis coinciding with the weld centreline.
Figure 20: Schematic overview of the sequence in which residual stress measurements, cutting and PWHT took place. Only half of each weld test piece underwent PWHT.

10 Post Weld Heat Treatment

The PWHT procedure for the relevant half of each weld test piece was broadly in accordance with the guidelines in ASME Section III [18], with the principal exception being that a slower heating and cooling rate was employed. The PWHT procedure was as follows:

- Maximum heating rate of 20°C/hr between 300 and 607°C;
- Hold at 607°C ± 13°C for 6 hours;
- Maximum cooling rate of 20°C/hr between 607 and 300°C.

There were no ramp rate requirements at temperatures below 300°C during either the heating or cooling stages. The heat treatments were carried out in air.

11 Weld Qualification

Nondestructive evaluation was carried out in accordance with the guidance that is provided in ASME Sec-V [19]. The acceptance criteria for such welds are listed in ASME Sec-IX [20]. All welds were subjected to 100% radiographic inspection, and all of the acceptance criteria were met in each case. Two cap-bend and two root-bend tests were also carried out on each of the welds, with the results of all tests being acceptable. Cross-weld tensile testing
was carried out on specimens that were extracted from the top, middle and bottom region of the welded joints, in accordance with ASTM E8M [21] using standard sheet-type specimens. Three coupons were extracted from each position in each of the welds, and testing was carried out on an INSTRON 5569 test machine using a strain rate of 0.0005 per second.

The tensile coupons that were extracted from the arc welded specimens fractured in the weld metal, while those for the EB weld fractured in the parent metal. The properties that were measured in this work are summarized in Table 4, which includes estimates for the 95% confidence interval for the mean value of the ultimate tensile strength (UTS). Due to the inhomogeneity associated with the test pieces, values for the yield stress and elongation are not provided. It can be seen that the strength of the SAW joint is somewhat lower than those of the GTAW and EB joints. Furthermore, for reasons that are not immediately apparent, the EB weld achieved a higher UTS towards the top of the weld than it did in the middle and at the bottom. According to ASTM A508M [22], the minimum value of the UTS for the parent material should be at least 550 MPa. It is clear that the GTAW and EB joints meet this requirement, whereas the SAW joint falls short of the requirements for the parent material. This may be related to the chemical composition of the filler wire that was used (Table 1), which had a slightly lower carbon content and a lower nickel content than the wire that was used for the GTAW joint.

Table 4: Summary of mechanical properties as determined from cross-weld tensile tests.

| Welding Process | Number of Tests | Ultimate Tensile Strength (MPa) |
|-----------------|----------------|---------------------------------|
|                 |                | Top | Middle | Bottom |
| GTAW            | 3              | 559 ± 2 | 564 ± 20 | 572 ± 12 |
| SAW             | 3              | 526 ± 29 | 516 ± 14 | 543 ± 9 |
| Electron Beam   | 3              | 593 ± 20 | 547 ± 42 | 556 ± 5 |
12 Metallography and Hardness Testing

Macrographs were prepared for each of the welded joints, and these are shown in Figure 21. The specimens were polished with diamond paste to a finish of 0.25 μm and then etched with 2% Nital. Macrograph photos were then acquired and digital imaging was carried out for the purpose of correlating subsequent hardness measurements with metallurgical zones. Prior to undertaking hardness measurements, the specimens were again polished with diamond paste to a 1 μm finish.

Hardness maps were prepared using a Struers DuraScan hardness tester, employing a Vickers indenter and a load of 1 kg, for each of the welded joints in both the as-welded condition and after PWHT (Figure 22). In general, the density of measurements was highest in the vicinity of the FZ and HAZ. The measurement locations are denoted by crosses in Figure 22. In the vicinity of the arc welds, indentations were made at intervals of 1.5 mm in both the through-thickness direction and transverse to the welding direction, while the indentations were at intervals of 3 mm × 3 mm further from the FZ and HAZ. For the EB welds, measurements in the vicinity of the FZ and HAZ were made at intervals of 0.6 mm transverse to the welding direction, and at intervals of 2.0 mm in the through thickness direction, whereas in the far field intervals of 3 mm were employed in both directions.

In Figure 21, some porosity can be seen in the GTAW test piece, while no porosity is evident in the SAW test piece. This indicates that the layer of welding flux was more effective in shielding the molten pool from the atmosphere than the shroud of argon that was employed in GTAW. Indeed, it can be very difficult to achieve effective shielding in deep and narrow weld grooves. However, the levels of porosity that were seen in the GTAW test piece were still within allowable limits [20], since the ASME codes are quite forgiving in the case of volumetric defects (rounded pores), where the maximum permissible diameter for a rounded pore is 3 mm for thick section welds. In contrast, no level of lack-of-fusion is acceptable.
Figure 21: Macrographs for 130 mm thick welded joints made using (left) NG-SAW, (middle) NG-GTAW and (right) RPEB welding. It is possible to distinguish the individual weld passes in both the SAW and GTAW macrographs. There are clearly two weld passes per layer of weld metal in the joint manufactured using SAW. Porosity is evident in the NG-GTAW macrograph.
Figure 22: Hardness maps for 130 mm thick welded joints made using (left) NG-SAW, (middle) NG-GTAW and (right) RPEB welding. Maps are shown in the as-welded condition (top) and after PWHT (bottom). It is possible to discern that two passes were used in each layer of weld metal when examining the map for the SAW joint in the as-welded condition.

Interestingly, Figure 21 reveals that the HAZ is much wider in the EB weld than it is in each of the arc welds. The cumulative heat input (i.e. the total heat delivered to the joint over all weld passes) was much lower when employing the EB process, since only one weld pass was required to complete the joint. However, EB welding in keyhole mode can be considered as a line-source of heat moving through a plate, so that heat propagation into the plate is essentially two-dimensional in nature (i.e. within the plane of the plate). In contrast, the nature of heat propagation in the case of the arc welds is closer to that of a point source of heat moving through a thick plate: a problem which is associated with three-dimensional heat transfer. The three-dimensional nature of the heat sink in the case of the arc welds, and the utilization of a lower heat input in individual weld passes (when compared to EB welding), will have played a role in reducing the extent of the HAZ. The absence of convective cooling in the vacuum chamber may also have played a role in contributing to the larger HAZ in the EB weld.
13 Concluding Remarks

Welded joints at a thickness of 130 mm have been made with three different welding processes: narrow-gap gas-tungsten arc (NG-GTAW), narrow-gap submerged arc (NG-SAW), and reduced pressure electron beam (EB) welding. Manufacture has been documented in detail, to allow the weldments to act as benchmarks for the subsequent modelling of these welding processes and their impact on long-term structural performance. Access to the data that has been generated will be available through the authors upon request, and the information that has been generated should enable finite element thermal analyses of all three processes to be validated, providing a solid foundation for subsequent metallurgical and mechanical simulations. Some information is also available on the distortion and restraining forces that were involved, enabling an informed choice of the structural boundary conditions for finite element models, and offering scope for the validation of predicted structural distortions. Some preliminary observations arising from the work are as follows:

EB welding resulted in the largest HAZ by some margin, since welding in keyhole mode leads to heat being delivered simultaneously and relatively uniformly to the entire thickness of the joint during a single thermal cycle. EB welding was also associated with the slowest cooling rate after welding, which will have been partly related to the fact that this joint cooled in a vacuum chamber.

The level of butterfly distortion was highest for the GTAW joint (3.65°), followed by the SAW joint (1.87°), while butterfly distortion was almost non-existent for the EB weld (0.08°). Single-sided multipass welds are known to result in a much greater level of butterfly distortion than single-pass welds made in keyhole mode. However, there is also a considerable difference between the levels of distortion that resulted in each of the arc welds. It is noted that a much higher weld heat input was employed during the filling passes for GTAW, when compared to SAW. Further work on the modelling of these test pieces will be required to establish whether the level of distortion can be correlated with the weld heat input in this way.

The most significant challenges associated with maintaining weld quality were associated with the avoidance of porosity in the case of NG-GTAW. There are clearly engineering challenges associated with the establishment of an electric arc at the base of a narrow weld groove, when concurrently delivering an independently-fed filler metal to the weld pool,
while maintaining a blanket of inert gas. In spite of these difficulties, NG-GTAW produced a welded joint that clearly met the minimum property requirements that are specified for the parent material by the American Society for Testing and Materials.

The authors had few difficulties in achieving sound welds with the NG-SAW and EB processes. NG-SAW was the only process that did not meet the minimum requirement for the ultimate tensile strength in cross-weld tests. However, the margin was narrow, and the outcome is likely to be related to the choice of filler wire for NG-SAW, which had slightly lower levels of both carbon and nickel. As such, the authors believe that there is every reason to be confident that NG-SAW can also produce compliant welds of high quality.

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15 References

[1] B. Jeyaganesh, M. D. Callaghan, J. A. Francis, P. D. English, A. Vasileiou, M. J. Roy, W. Guo, N. M. Irvine, M. C. Smith, L. Li and A. H. Sherry: “Overview of Welding Research under the New Nuclear Manufacturing (NNUMAN) Programme”, Proceedings of the ASME 2014 Pressure Vessels and Piping Conference (PVP2014-29015), Anaheim, California, Vol. 6B, 2014, DOI: 10.1115/PVP2014-29015.

[2] A. S. Sanderson, C. S. Punshon and J. D. Russell: “Advanced welding processes for fusion reactor fabrication”, Fusion Engineering and Design, 49-50, pp. 77-87, 2000.

[3] S. Shono, S. Kawaguchi, M. Sugino and N. Nakajima: “Application Of New Welding Technology For The Manufacturing Of Nuclear Pressure Vessels”, Proceedings of the Sixth
International Conference on Pressure Vessel Technology, Beijing, People's Republic of China, 11–15 September 1988, Volume 2, Pages 1279-1286, 1989.

[4] K. R. Ayres, P. R. Hurrell, C. M. Gill, K. Bridger, L. D. Burling, C. S. Punshon, Liwu Wei and N. Bagshaw: “Development of Reduced Pressure Electron Beam Welding Process for Thick Section Pressure Vessel Welds”, Paper PVP2010-25957, Proceedings of the ASME 2010 Pressure Vessels and Piping Division Conference, Bellevue, Washington, USA, July 18–22, 2010.

[5] P. J. Withers: “Residual Stress and it Role in Failure”, Reports on Progress in Physics, 70, 2211-2264, 2007.

[6] D.P.G. LIDBURY: “The Significance of Residual Stresses in Relation to the Integrity of LWR Pressure Vessels”, International Journal of Pressure Vessels and Piping, 17 (4), 197-328, 1984.

[7] R6: Assessment of the integrity of structures containing defects, Revision 4, EDF Energy, Barnwood, Gloucester, U.K., 2009.

[8] D.T. READ: “Measurement of Applied J-Integral Produced by Residual-Stress”, Engineering Fracture Mechanics, 32 (1), 147-153, 1989.

[9] D.J HORNBACK and P.S. PREVEY: “The Effect of Prior Cold Work on Tensile Residual Stress Development in Nuclear Weldments”, Journal of Pressure Vessel Technology - Transactions of the ASME, 124 (3), 359-365, 2002.

[10] M. Kerr, M.B. Prime, H. Swenson, M.A. Buechler, M. Steinzig, B. Clausen and T. Sisneros: “Residual Stress Characterization in a Dissimilar Metal Weld Nuclear Reactor Piping System Mock Up”, Journal of Pressure Vessel Technology - Transactions of the ASME, 135 (4), 041205, 2013.

[11] O. Muránsky, M.C. Smith, P.J. Bendeich and L. Edwards: “Validated numerical analysis of residual stresses in Safety Relief Valve (SRV) nozzle mock-ups”, Computational Materials Science, 50 (7), 2203-2215, 2011.

[12] D. J. Smith, G. Zheng, P. R. Hurrell, C. M. Gill, B. M. E. Pellereau, K. Ayres, D. Goudar and E. Kingston: “Measured and predicted residual stresses in thick section electron beam welded steels”, International Journal of Pressure Vessels and Piping, 120-121, 66-79, 2014.
[13] J. Balakrishnan, A.N. Vasileiou, J.A. Francis, M.C. Smith, M.J. Roy, M.D. Callaghan, N.M. Irvine: “Residual stress distributions in arc, laser and electron-beam welds in 30 mm thick SA508 steel: A cross-process comparison”, *International Journal of Pressure Vessels and Piping*, **162**, 59-70, 2018.

[14] G. R. Odette: “On the Dominant Mechanism of Irradiation Embrittlement of Reactor Pressure Vessels Steels”, *Scripta Metallurgica*, **17**, 1183-1188, 1983.

[15] A.A. Shirzadi, H.K.D.H. Bhadeshia, L. Karlsson and P. J. Withers: “Stainless steel weld metal designed to mitigate residual stresses”, *Science and Technology of Welding and Joining*, **14** (6), 559-565, 2009.

[16] D.W. Rathod, J.A. Francis, M. J. Roy, G. Obasi and N.M. Irvine: “Thermal cycle-dependent metallurgical variations and their effects on the through-thickness mechanical properties in thick section narrow-gap welds”, *Materials Science & Engineering A*, **707**, 399-411, 2017.

[17] A.N. Vasileiou, M.C. Smith, D. Gandy, A. Ferhati, R. Romac and S. Paddea, “Residual Stresses In Thick-Section Electron Beam Welds In RPV Steels”, *Proceedings of the ASME 2016 Pressure Vessels and Piping Conference (PVP2016)*, Vancouver, British Columbia, 6(B), 2016. doi:10.1115/PVP2016-63940

[18] ASME Boiler and Pressure Vessel Code Section III, Division 1, Subsection NB – Class 1 Components, 2017.

[19] ASME Boiler and Pressure Vessel Code, Section V, 2017.

[20] ASME Boiler and Pressure Vessel Code, Section IX, 2017.

[21] ASTM E8M: “Standard Test Methods for Tension Testing of Metallic Materials”, *ASTM International*, 2016.

[22] ASTM A508/A508M: “Standard Specification for Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels”, *ASTM International*, 2018.

**APPENDIX 1 – SUMMARY OF WELDING PARAMETERS FOR GTAW**

| Pass No. | Pass Type | V (A) | I (A) | v (mm/min) | WFS (m/min) | Hotwire Current (A) | Oscillation Half-Width, W_o (mm) | Dwell Time, t_d (L:R) (s) | Heat Input (kJ/mm) |
|----------|-----------|-------|-------|------------|-------------|---------------------|-------------------------------|----------------------|-------------------|
| 1        | root      | 10.2  | 175   | 75         | 0.5         | 50                  | 0.5                           | 0.1, 0.1             | 1.4               |
| 2 | hot | 10.2 | 190 | 75  | 0.5 | 50  | 5   | 0.3, 0.3 | 1.6 |
|---|-----|------|-----|-----|-----|-----|-----|----------|-----|
| 3 | hot | 10.2 | 220 | 75  | 0.6 | 50  | 6   | 0.3, 0.3 | 1.8 |
| 4 | fill| 10.2 | 325 | 75  | 0.8 | 50  | 8   | 0.3, 0.3 | 2.7 |
| 5 | fill| 10.2 | 325 | 75  | 0.8 | 60  | 10  | 0.3, 0.3 | 2.7 |
| 6 | fill| 10.2 | 375 | 65  | 1   | 60  | 10  | 0.4, 0.4 | 3.5 |
| 7 | fill| 10.2 | 375 | 55  | 1.2 | 70  | 10  | 0.5, 0.5 | 4.2 |
| 8 | fill| 10.2 | 375 | 55  | 1.2 | 70  | 10.5| 0.5, 0.5 | 4.2 |
| 9 | fill| 10.2 | 450 | 55  | 1.5 | 70  | 10.5| 0.5, 0.5 | 5.0 |
| 10| fill| 10.2 | 450 | 55  | 1.5 | 70  | 10.5| 0.5, 0.5 | 5.0 |
| 11| fill| 10.2 | 450 | 55  | 1.8 | 70  | 10.5| 0.5, 0.5 | 5.0 |
| 12| fill| 10.2 | 450 | 55  | 1.8 | 70  | 10.5| 0.5, 0.5 | 5.0 |
| 13| fill| 10.2 | 450 | 55  | 1.8 | 70  | 10.5| 0.5, 0.5 | 5.0 |
| 14| fill| 10.2 | 450 | 55  | 1.8 | 70  | 10.5| 0.5, 0.5 | 5.0 |
| 15| fill| 10.2 | 450 | 55  | 2.1 | 70  | 10.5| 0.5, 0.5 | 5.0 |
| 16| fill| 10.2 | 450 | 55  | 2.1 | 70  | 10.5| 0.5, 0.5 | 5.0 |
| 17| fill| 10.2 | 450 | 55  | 1.8 | 75  | 10.5| 0.5, 0.5 | 5.0 |
| 18| fill| 10.2 | 450 | 55  | 1.8 | 75  | 10.5| 0.5, 0.5 | 5.0 |
| 19| fill| 10.2 | 450 | 55  | 1.8 | 75  | 10.5| 0.5, 0.5 | 5.0 |
| 20| fill| 10.2 | 450 | 55  | 1.8 | 75  | 10.5| 0.5, 0.5 | 5.0 |
| 21| fill| 10.2 | 450 | 55  | 1.8 | 75  | 10.5| 0.5, 0.5 | 5.0 |
| 22| fill| 10.2 | 450 | 55  | 1.8 | 75  | 10.5| 0.5, 0.5 | 5.0 |
| 23| fill| 10.2 | 450 | 55  | 1.8 | 75  | 11   | 0.6, 0.6 | 5.0 |
| 24| fill| 10.2 | 450 | 55  | 1.8 | 75  | 11   | 0.6, 0.6 | 5.0 |
| 25| fill| 10.2 | 450 | 55  | 1.8 | 75  | 11   | 0.6, 0.6 | 4.7 |
| 26| fill| 10.2 | 425 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 4.7 |
| 27| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 5.3 |
| 28| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 5.3 |
| 29| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 5.3 |
| 30| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 5.3 |
| 31| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 5.3 |
| 32| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 5.3 |
| 33| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 34| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 35| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 36| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 37| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 38| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 39| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 40| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 41| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 42| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 43| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 44| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.5, 0.7 | 5.3 |
| 45| fill| 11.5 | 425 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 5.3 |
| 46| fill| 11.5 | 415 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 5.2 |
| 47| fill| 11.5 | 415 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 5.2 |
| 48| fill| 11.5 | 415 | 55  | 1.8 | 75  | 11.5 | 0.6, 0.6 | 5.2 |
APPENDIX 2 – SUMMARY OF WELDING PARAMETERS FOR SAW*

| Pass No. | Pass Type | V  | I (A) | v  (mm/min) | Heat Input (kJ/mm) |
|----------|-----------|----|-------|-------------|--------------------|
| 1        | root      | 27 | 300   | 344         | 1.4                |
| 2        | hot       | 27 | 300   | 373         | 1.3                |
| 3        | hot       | 27 | 300   | 373         | 1.3                |
| 4 - 58   | fill      | 27 | 350   | 373         | 1.5                |
| 59 - 61  | fill      | 29 | 350   | 373         | 1.6                |
| 62 - 77  | fill      | 29 | 360   | 373         | 1.7                |
| 78 - 100 | fill      | 29 | 370   | 373         | 1.7                |
| 101 - 104| cap       | 29 | 370   | 344         | 1.9                |

*V = voltage, I = current, v = welding traverse speed.
Highlights

130 mm thick welds were manufactured in a nuclear pedigree steel using three processes, namely gas-tungsten arc welding (GTAW), submerged-arc welding (SAW) and electron beam (EB) welding. The first two welding processes are currently applied in the manufacture of nuclear reactors, while the EB process is a candidate technology for future application.

Residual stresses are measured using both the contour method and incremental deep-hole drilling, and results are presented in both the as-welded and post-weld heat treated conditions.

Part 1 of this article documents the full history of the weld test pieces, including a detailed account of the provenance of the base material, the manufacture of the welded joints, details of instrumentation and restraint, and it provides sufficient information to enable detailed weld models to be developed by readers.

Part 2 deals with the residual stress measurements, and presents the major conclusions that arise from the work.

The results obtained in this work reveal that the effectiveness of post-weld heat treatment operations is best assessed by carrying out experiments on weld mock-ups that are larger than those typically employed in university laboratories. Final levels of stress after post-weld heat treatment were found to be high than comparable studies on smaller test pieces, and this is likely to be significant for safety assessments on nuclear components.