Measurement of Residual Stress in Tube Penetration Welds for Ferritic Steel Hemispherical Pressure Vessel Heads

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ABSTRACT

Residual stress distributions were measured at the interface between penetration tubes and J-welds in mock-ups representative of the tube penetrations in hemispherical pressure vessel heads. Two mock-ups were manufactured, one to represent a tube inserted perpendicular to the vessel head and a second with a tube inclined to the vessel head. An appraisal of available measurement methods was carried out and two mechanical strain relaxation methods, incremental centre hole drilling (ICHD) and deep hole drilling (DHD) were selected. This paper describes the application of the DHD method. Hoop and radial residual stresses were measured along the interface to depths up to about 65mm from the welded surface of the mock-ups. The influence of introducing a clad surface was also explored. Peak residual stresses of 430MPa were measured in the hoop direction. The position of the peak hoop stress was located approximately 55mm below the surface close to the root of the J-weld at the "long hillside" of the inclined tube . In practical components there is the potential for lack of fusion defects along the interface between the weld and the tube. Consequently, the radial residual stress is of interest. The peak radial residual stress was found to be 280 MPa and occurred at a similar location to the peak hoop residual stress.

INTRODUCTION

The aim of this work was to gain an understanding of the residual stress levels in tube penetration J-groove welds in a hemispherical head of a large stainless steel clad ferritic pressure vessel. Two configurations of penetration were examined; centre (perpendicular) and off-centre (inclined) penetrations. For these types of weld there is the potential for lack of fusion defects to form along the interface between the J-groove weld and the nozzle tube. This orientation of defect falls under the influence of the radial stresses where radial in this context is defined with respect to the tube axis. The potential for this type of defect is increased at the outer penetration positions, where welding wire access to the root and tube sidewall of the J-groove is particularly restrictive. The principal reason for carrying out the work that is described here was to gain an insight into the value of the radial component of the welding residual stresses. This was required in support of a structural integrity assessment of the welds by using the residual stresses as inputs into defect tolerance calculations.

To obtain experimental measurements of the residual stresses two mock-ups were manufactured. These mock-ups were designed to mimic the main features of the manufacture of tube penetrations in hemispherical heads. Figure 1 shows a schematic of a typical J-groove weld for the tube penetration. Further details of the manufacture of the hemispherical head and welding procedure are given by Watson et al [1].

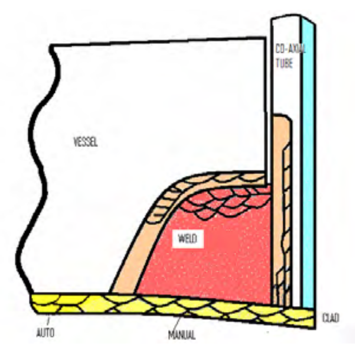

Figure 1. Schematic of J-groove weld

Exact replicas of the real components were not created due to time and material procurement constraints. Nevertheless, the outcomes of the work provided considerable insight to the main features expected in practical components. This paper describes brief details of the manufacture of the mock-ups and appraises critically the methods available for practical residual stress measurement in the mock-ups. As a result of this appraisal two mechanical strain relaxation methods, incremental centre hole drilling (ICHD) and deep hole drilling (DHD) methods, were selected. A short description of the DHD method is given together with the results obtained from its application to the welded mock-ups.

MOCK-UP WELD MANUFACTURE

The mock-ups were fabricated to be as close as possible to the practical components. However, simplifications to the complex manufacturing processes used for the mock-ups were required. Two mock-ups were fabricated from steel blocks and tubes. Mock-up 1 had a perpendicular tube and was therefore representative of a central nozzle penetration on the vessel head, whilst mock-up 2 contained an inclined tube, which was representative of an outer, off-centre location. Both mock-ups were manufactured in a similar way and both had similar basic dimensions. Neither of the mock-ups had buttering applied to either the nozzle tube or the vessel head and they were not subjected to the heat treatment processes used for the practical components. To investigate the influence of a MMA cladding process mock-up 1 was clad after a first set of residual stress measurements were made. The J-groove welds in the mock-ups were made with the same procedure used for the practical components and using similar weld consumables.

A schematic of the block and tube arrangements for mock-ups 1 and 2 are shown in Figures 2 and 3. The welded side of the block was machined with a spherical curvature to more closely resemble the actual shape of the vessel head.

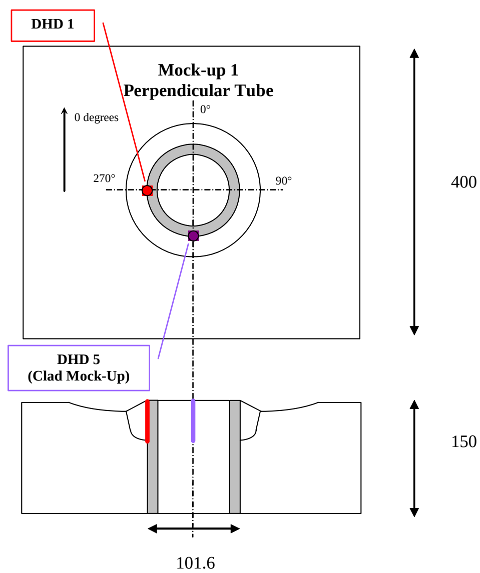

Figure 2. Mock-up 1: central nozzle general arrangement, DHD locations and dimensions (mm)

The overall dimensions of the steel blocks are shown in Figure 2. The thickness of the blocks was 150mm. The outer diameter and thickness of the tubes were 101.6mm and 11mm respectively. The mock-up tube dimensions were smaller than the practical penetration tube where the tube thickness was 13.96mm.

The block, representative of the vessel, was manufactured from mild steel to specification BSEN10025 1993 S275JR. The minimum 0.2% proof stress and ultimate tensile strength for this specification is 215MPa and 380-540MPa respectively. Material tests confirmed the 0.2% proof stress to be above the minimum required at 231MPa. Likewise the ultimate tensile strength was within the required range at 425MPa.

The tube was manufactured from high strength steel. Material tests indicated a 0.2% proof stress value of 572MPa with an ultimate tensile strength of 732MPa.

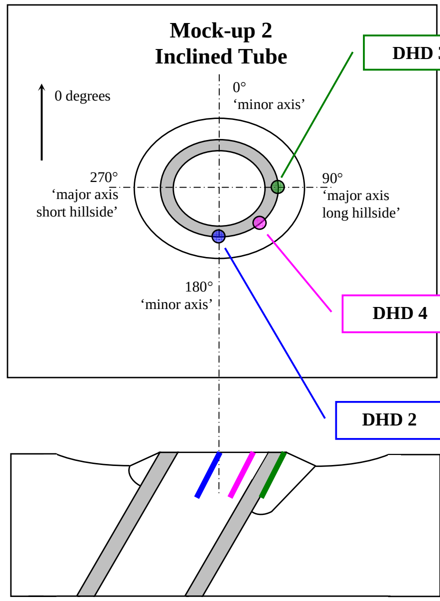

Figure 3. Mock-up 2: off-centre nozzle general arrangement and DHD locations

RESIDUAL STRESS MEASUREMENT METHODS

It was required to obtain the distribution of residual stresses along the interface between the tube insert and the weld retaining the tube in the steel block as shown in Figures 2 and 3. A range of residual stress measurements methods were available and these are summarized in Figure 4.

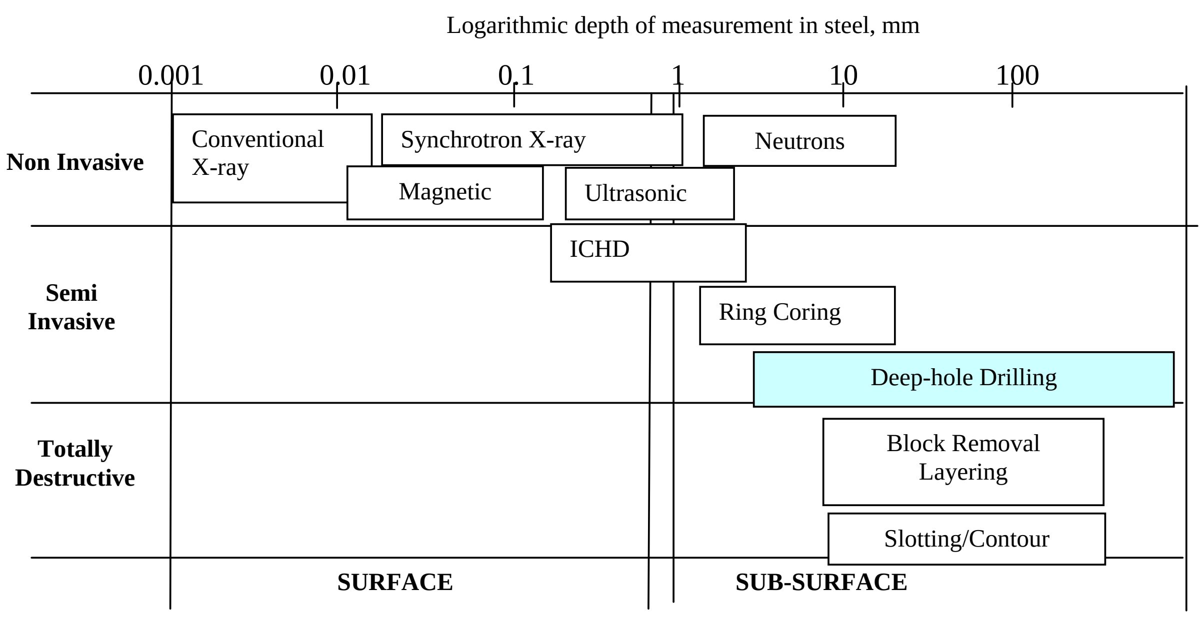

Figure 4. Residual stress measurement methods in steel.

Residual stress measurement techniques are generally classed as non-invasive, semi-invasive and totally destructive. The various methods are able to measure residual stresses to different depths. The different methods are ranked as being capable of measuring residual stresses at the surface or significantly below the surface. The tube penetration mock-ups contained residual stresses that were expected to be extremely difficult to measure, particularly along the interfaces shown in Figure 2 and 3. A summary of the suitability of the methods is given in Tables 1 and 2 together with recommendations for application to the mock-ups.

Non-invasive methods

The methods summarized in Table 1 include diffraction methods such as neutron, X-ray (conventional and synchrotron). There are also magnetic and ultrasonic methods.

Table 1. Summary of non-invasive methods

Method	Path length/Depth of measurement,	Comments about suitability of method for application to mock-ups
Conventional X-ray (XRD)	Several microns	XRD method would measure radial and hoop stresses but needs surface preparation. Potentially can go to much greater depths by removing material locally and then re-measuring at new surface, but usually applied to depths of 1 to 2mm. Small gauge area <1×1mm.
X-ray synchrotron radiation (or high energy X-ray diffraction, HEXRD)	Several millimetres	The method needs to use specialized HEXRD facilities and mock-ups transported to the facility. Similar to ND, the method would only measure axial strains if left intact. Requires samples cut out for strain free diffraction parameters. Gauge volume similar to neutron diffraction.
Magnetic (MM)	Potentially 10mm	MM would obtain radial and hoop stress, however known to be sensitive to microstructural features like welds. Not particularly suited to complex shapes. Requires calibration techniques for material specific parameters. Sampling volume uncertain, particularly at depth.
Neutron diffraction (ND)	≈ 60mm/35mm,	The ND method needs to use reactor facilities and requires mock-ups to be transported to the facility. Maximum measurement depth is about ½ path length. Method could only measure axial (along tube axis) strains if mock-up remained in one piece. However, method requires extracted samples to measure strain free diffraction parameters. Gauge volumes for such depths limited to 3×3×3mm for sensible ND count times.
Ultrasonic (UM)	Can be used to large depths	UM method has poor spatial resolution and requires detailed calibration techniques for material specific parameters. The sampling volume is uncertain.

Overall, the number of non-invasive methods for measuring residual stresses in the mock-ups is limited. The ND and HEXRD methods are capable of measuring to depths relevant to the mock-ups. However, the complex geometry and lack of access to the tube-weld interface precludes direct non-invasive measurement. To obtain hoop and radial strains using these methods would require sectioning the components into smaller and less complex shapes. Both methods also rely on cutting out reference samples to obtain strain free diffraction parameters.

Semi-invasive and totally destructive methods

These methods, summarised in Table 2, are usually classed as mechanical strain relaxation methods and include ICHD, DHD, slotting or crack compliance (CC), contour, ring-core (RC), and block removal and surface layering (BRSL). In all cases, some material is removed that in turn releases residual strain. The strains are measured and used to reconstruct the relaxed stresses. Notably, if it was required to obtain strain free samples for the diffraction methods identified in Table 1, the measurement programme could seek to use a combination of diffraction and mechanical strain relaxation methods.

Based on the comments provided in Tables 1 and 2 it was decided that the simplest, most reliable and lower cost options were the ICHD method for near surface measurements and the DHD technique to obtain through-thickness stresses along the weld tube interfaces. The choice of these techniques did not preclude the potential for utilizing X-ray for near surface measurements. However, adopting other methods would have introduced elements of risk that could not be quantified without recourse to further developments. In the following further details of the DHD method are described. The application of the ICHD method and the measurements obtained are described in [1] and [2].

Table 2. Summary of semi-invasive and totally destructive methods

Method	Path length/Depth of measurement,	Comments about suitability of method for application to mock-ups
Incremental centre hole drilling (ICHD)	≈ 1mm	Strain gauges are attached to the surface and will provide radial and hoop stress profiles. Only provides relatively near surface measurements and requires some surface preparation to attach strain gauges. Sampling area dictated by hole size and strain gauge locations, usually about 1 to 2mm diameter. Macro elastic properties used.
Ring-core (RC)	About 20mm	RC method uses a core that is usually 20mm diameter. RC done step by step similar to ICHD. The diameter of sample volume is about 20mm. RC would provide hoop and radial stress averaged over core diameter.
Slotting/crack compliance (CC)	Potentially applied to full depth of block	Slotting could be done using a fully circumferential slot in mock-up 1. Slot would be concentric to the tube and would provide radial stress. Would require strain gauges attached to the top surface and down the inside of tube. Method would need axisymmetric FE analysis to create compliance function to convert measured strains to stresses. Measurement sampling area based on width of trepan slot <2mm.
Deep hole drilling (DHD)	Applied to full depth of block	DHD conventionally used 3mm reference hole and 10mm core, with recent work using 1.5mm hole and 5mm core, obtains radial and hoop stresses along a line. Sample area within 5mm diameter core. Capable of measuring through thickness stresses to depth up to about 500mm. Macro elastic properties used.
Contour method (CM)	Full depth of block	CM applicable to simple geometric plates and pipes. CM could be applied but would provide only hoop stress by cutting across the tube. CM method requires use of a coordinate measuring machine.
Block removal and surface layering (BRSL)	Full depth of block	BRSL usually applied to simple shapes (e.g. plates) and involves total destruction of sample. BRSL assumes uniform stress across extracted blocks and gauge volume depends on block size.

APPLICATION OF THE DHD TECHNIQUE

The DHD residual stress measurement technique is now a well known [3, 4] semi-invasive, mechanical strain relief technique (i.e. the strain of the component is measured during stress relief from the removal of a small amount of material). The technique has been applied to a range of small and large components [5] and has been used to characterize residual stress distributions in weld repairs for nuclear power plant [6].

The procedure used for the DHD technique can be divided into 5 stages, as shown in Figure 5, for a simple welded component. The stages in the DHD measurement method are:

1. Reference bushes are attached to the front and rear surfaces of the component at the measurement location.

2. A 1.5mm diameter reference hole is gun-drilled through the component and reference bushes.

3. The diameter of the reference hole is measured through the entire thickness of the component and reference bushes. Diameter measurements are taken at 0.2mm increments in depth and at 20º increments in angle about the axis of the reference hole.

4. A cylinder (i.e. core) of material (approximately 5mm OD), containing the reference hole along its axis is cut from the component using electro-discharge machining (EDM).

5. The diameter of the reference hole is re-measured through the entire thickness of the cylinder and reference bushes. Diameter measurements are taken at the same locations as those measured in Stage 3.

The diameter of the reference hole measured in Stage 3 is the diameter when stresses are present. During Stage 4 the stresses are relieved, hence the diameter of the reference hole measured in Stage 5 is the diameter when stresses are not present. The differences between the measured diameters in Stages 3 and 5 enable the original residual stresses to be calculated.

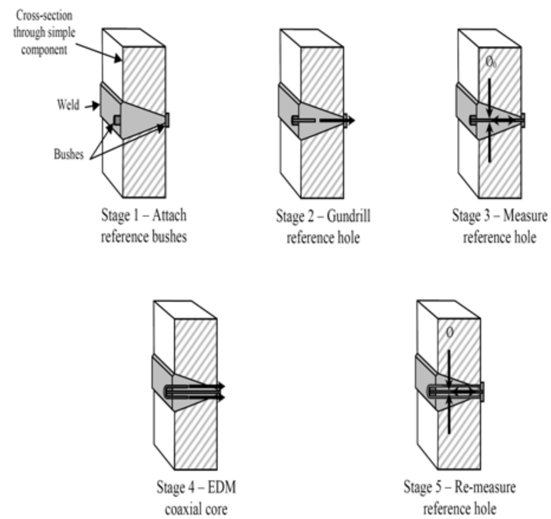

Figure 5. Stages in the deep hole drilling residual stress measurement method

Five sets of DHD measurements were carried out in mock-ups 1 and 2. The locations of the measurements are shown in Figures 2 and 3. All measurements were taken along the interface between the tube and the weld. Unlike the simplified procedure shown in Figure 5, only a front bush was attached at each measurement location prior to the application of the DHD method.

For mock-up 1 (perpendicular tube) the locations were:

- DHD 1 - measurement at 270°.
- DHD 5 - measurement at 180, following cladding of the weld.

For mock-up 2 (inclined tube) measurements were carried out in the following order and positions:

- DHD 3 - measurement at the long hillside, major axis position, 90°.
- DHD 2 - measurement at the "short hillside" minor axis position, 180°.
- DHD 4 - measurement at the mid-point (135°) between the long hillside major axis and short hillside minor axis positions.

At each measurement location a 5mm core was extracted from the mock-up. The cores were then sectioned, polished and etched along their axes to reveal the depth of the weld and the axis of the reference hole with respect to the tube-block interface. This process also confirmed that no significant weld defects were present along the interface. Sectioning, polishing and etching of the core revealed that the full depth of weld at location DHD 1 prior to cladding was approximately 42mm. Sectioning, polishing and etching of the core at location DHD 5 (i.e. after cladding) revealed that the thickness of the stainless steel cladding was approximately 9.2mm.

RESULTS

The measured reference hole distortions (i.e. the difference between results measured in stages 3 and 5) were used to calculate the residual stresses using an analysis method described in detail by Smith et al [4]. Since the hole distortions were measured perpendicular to the axis of the reference hole created in stage 2 (Figure 5) the calculated residual stresses were the in-plane residual stresses corresponding to hoop and radial stresses relative to the axis of the tube penetration. The accuracy of the method has been shown to be ±30MPa, [1,2].

The measured residual stresses are shown in Figures 6 and 7 and illustrate the hoop and radial residual stresses as a function of the distance from the outside surface of the J-weld. In the case of mock-up 1, measurement DHD 5 was made after the block had been cladded and therefore the negative distance in Figure 6 represents the additional cladded material.

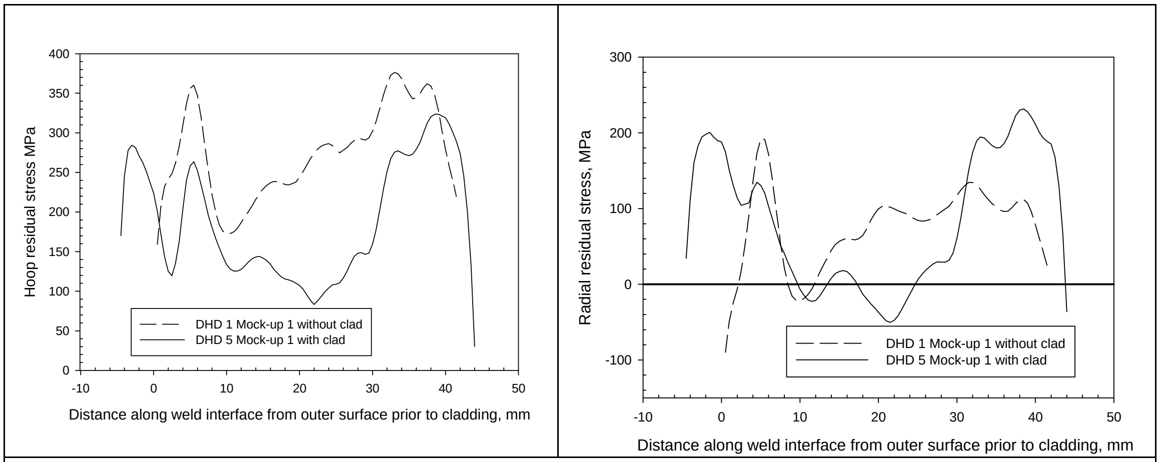

Figure 6. Measured residual stresses in mock-up 1 prior to and after cladding

In general the peak hoop and radial residual stresses occurred well below the surface. For example, in mock-up 1 prior to cladding (Figure 6) a peak residual stress of 380 MPa was measured in the hoop direction at a depth of about 35mm from the J-weld surface. The corresponding peak radial stress was 230MPa. It was also notable that in the uncladded mock-up 1 a peak in the hoop and radial stresses occurred at a depth of about 5mm, just below the surface of the weld. After cladding there were high hoop and radial residual stresses in clad. This is similar to other measurements in stainless steel cladded blocks [7]. The cladding reduced the magnitude of the initial peak hoop residual stress measured in the uncladded tube weld. This reduction was about 100MPa for the hoop stress and 60MPa for the radial stress. Overall the distributions of the residual stresses before and after cladding were similar although the magnitudes differed. This maybe a consequence of the variation in residual stress around the circumference of the J-weld.

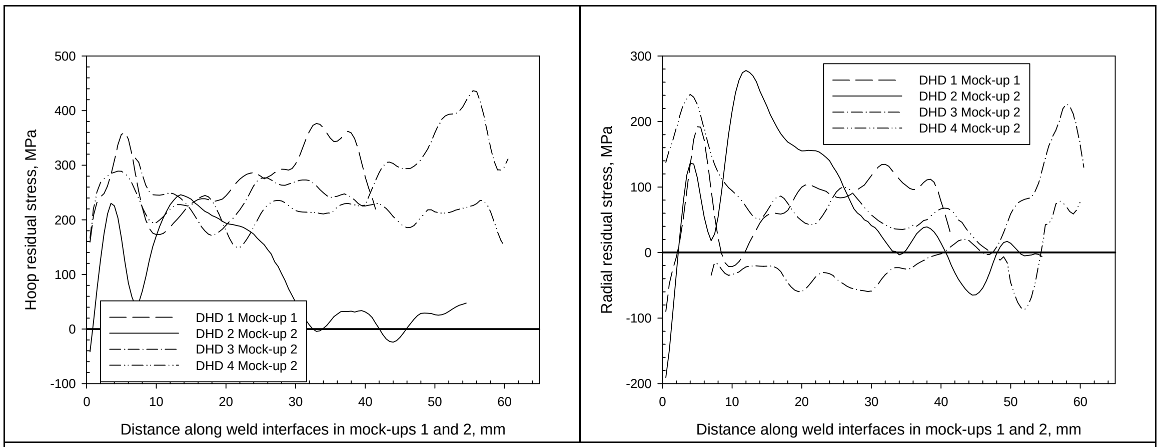

Figure 7. Measured residual stresses in mock-ups 1 and 2

In Figure 7 the measured residual stresses in mock-ups 1 and 2, both in the uncladded condition, are shown. The purpose of the comparisons in Figure 7 is to understand the differences between the residual stresses in perpendicular and inclined tube penetrations. In the case of the inclined tube measurements were made at three locations around the circumference of the J-weld and tube. The maximum hoop residual stress was measured to be 430MPa at a depth of 55mm below the surface (close to the root of the J-weld) at the "long hillside" of the inclined tube (i.e. at 90° as shown in Figure 3 and labeled DHD3). Closer to the weld surface and at depths up to about 30mm, the "long hillside" hoop residual stresses agree remarkably well with those obtained from the perpendicular tube (measurement DHD1). Furthermore, the hoop stresses at the 135° position (DHD 4) were very similar to the measurements obtained from DHD 1 and 3. The overall magnitude of the hoop stresses at the 180° were lower and decreased to zero for depths greater than about 32mm.

The largest residual stress in the radial direction was 280MPa and was at a depth of 12mm from the weld surface. This coincided with a similar peak hoop stress at the 180° position. Overall, and in contrast to the hoop stresses, the radial residual stresses at the "long hillside" (90°) were close to zero. It was also found that at the major axis the tube had distorted radially [2] as a consequence of welding. The tube had not distorted radially at the minor axis. The observed local distortion at the 90° location may have relieved the radial stress while retaining relatively high radial residual stresses at the minor axis. Finally, at the 135° location the radial stress was similar to those found in mock-up 1.

CONCLUDING REMARKS

An appraisal of available measurement methods has been conducted to assess their ability to obtain through thickness residual stress distributions in two welded mock-ups consisting of thick steel blocks containing perpendicular and included tube penetrations. It was found that the simplest, reliable and lower cost options were two mechanical strain relaxation methods; incremental centre hole drilling (ICHD) and deep hole drilling (DHD) methods. Other methods may also have been used but their adoption would have required further developments to assess their ability to measure local residual stresses at depth in complex geometry components.

The DHD method was applied to the two mock-ups to measure the through-thickness hoop and radial stresses along the interfaces between the welds and tubes. Five residual stress profiles were obtained, two in the mock-up containing a perpendicular tube and the remaining three in the inclined tube mock-up. The radial stress is of importance for assessing the significance of the lack of fusion defects along the tube-weld interface. The peak radial residual stress was found to be similar (about 250 to 270MPa) in both mock-ups. However, in the inclined tube mock-up the peak radial stress occurred at the position of the minor axis whereas at the position of the major axis the radial stress was found to be close to zero.

ACKNOWELDGMENTS

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