THROUGH THICKNESS RESIDUAL STRESS MEASUREMENT INA FULL STRUCTURAL WELD OVERLAY ON PWR PRESSURISER NOZZLE

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ABSTRACT

British Energy funded a large programme to pre-emptively investigate the use of structural weld overlays (SWOLs) to mitigate against crack initiation and growth within the dissimilar metal welds (DMW) found in the pressuriser safety/relief valve nozzle components in their Sizewell B nuclear power plant (NPP). Deep-hole drilling (DHD) measurements were carried out to provide confidence in and hence validate the residual stresses predicted along the DMW centreline of the "virgin" and "overlaid" nozzle using finite element analysis (FEA). The predicted residual stresses were then used for subsequent fatigue crack growth rate analysis. The residual stresses measured at all three locations within the "virgin" nozzle were in very good agreement, while for the "overlaid" nozzle good agreement was seen at depths greater than 25% from the inner surface of the nozzle. It was found that the SWOL reduces the magnitude of the tensile stresses in the underlying DMW and causes a much deeper compressive stress zone. Relatively good agreement was observed between the FEA results and the measurement results.

INTRODUCTION

Primary water stress corrosion cracking (PWSCC) can occur in dissimilar metal welds made from Inconel alloy 82/182 filler metal in the primary circuits of pressurised water reactors. It is a major concern to reactor operators and regulatory bodies worldwide, and has triggered extensive research and mitigation programmes [1]. British Energy have funded a large work programme to assess the possible impact of primary water stress corrosion cracking on dissimilar metal welds in the Sizewell 'B' primary circuit. The primary purpose of this programme was to provide support to approve the use of structural weld overlays that have been used extensively as a repair/mitigation technique for PWSCC in pressuriser nozzle dissimilar metal welds (DMW). A multi-disciplinary team from British Energy, Westinghouse Electric Company LLC and VEQTER Ltd were involved in the study.

Currently a number of different residual stress measurement techniques are available, however most of them are not suitable to apply in thick and complex shaped components. The Deep-Hole Drilling (DHD) technique was found to be the most suitable for this application and was employed to measure the through-thickness residual stress distributions through a number of different components. The DHD technique [2][3][4] is a 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).

This paper provides details of (a) fabrication of a mock-up representing the pressuriser safety/relief valve nozzle welds both with and without a structural weld overlay, (b) multiple residual stress measurements that were carried out on both mock-ups using the DHD and incremental DHD (iDHD) [3], and (c) comparison of measured stresses with the finite element predicted weld residual stresses.

COMPONENT FABRICATION

Two pressuriser safety/relief nozzle mock-ups were fabricated based on British Energy's PWR nozzle design roughly 203mm outer diameter and 32mm thick. In the "virgin" state, the two mock-ups were identical to each other and were manufactured to be as similar as possible to those found in the Sizewell B NPP. Both mock-ups included the nozzle to safe-end DMW and the safe-end to stainless steel piping weld. One of the mock-ups then had a SWOL applied to its outer diameter using Westinghouse Electric Company LLC's (WEC) proprietary technique.

Fig. 1 shows the diagram and photograph of Mock-up A (the "virgin" mock-up) and Mock-up B. The "virgin" mock-up consisted of a ferritic steel nozzle welded to a stainless steel safe-end, which in turn was then welded to a section of stainless steel extension pipe. Prior to welding the safe-end to the nozzle a layer of nickel alloy 82/182 buttering was deposited onto the end of the nozzle and machined to a thickness of 7.3mm. Also, for ease of manufacture, the ferritic steel nozzle was not clad on its ID using stainless steel; instead the buttering was extended back towards the pressuriser wall. The nozzle and buttering were heat treated and then fixed onto a dummy pressuriser head at roughly 40° to simulate the actual installed position. Finally the DMW joining the nozzle to the safe-end was manually deposited using nickel alloy 82/182 in an asymmetric, single-V configuration using TIG welding. The DMW capping passes were then ground smooth to roughly the same outer diameter as the nozzle and safe-end.

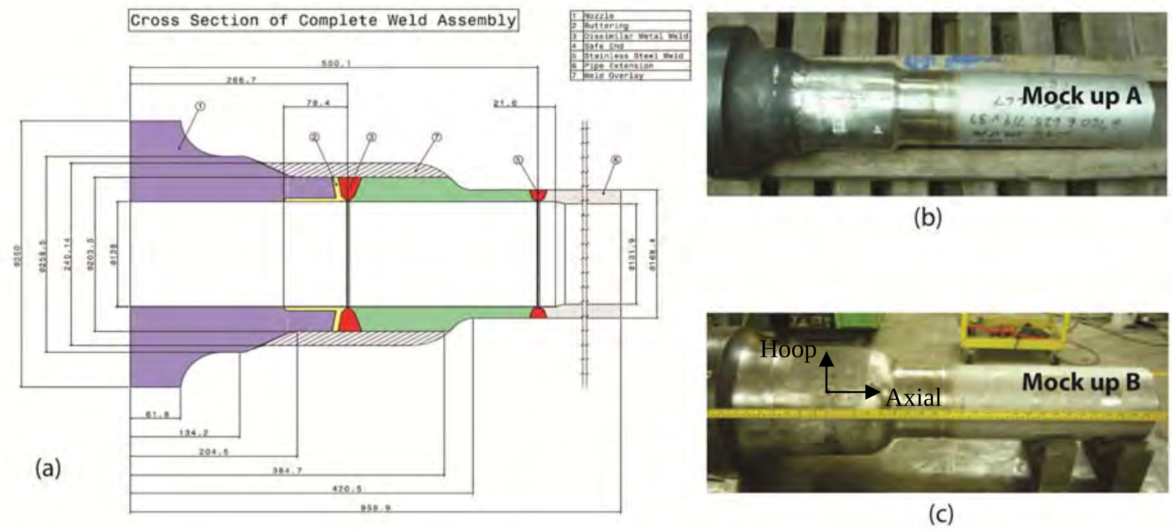

Fig. 1: Schematic diagram and the photograph of the "virgin" and "overlaid" mock up.

As previously stated, Mock-up B was manufactured to be identical to Mock-up A but with the addition of a SWOL covering the OD of the DMW, see Fig. 1a and 1c. A sacrificial layer was first applied in two sections. The first section was applied using ER309L filler material and the second section of the sacrificial layer was applied using ERNiCrFe-7A filler material. The complete sacrificial layer was deposited onto the OD of the nozzle over the area to be covered by the SWOL. The SWOL was then completed by depositing a further 9 layers of ERNiCrFe-7A. Finally, the outer surface of the SWOL was ground smooth. Detailed welding records were maintained during fabrication to aid in Finite Element Simulations.

MEASUREMENT TECHNIQUE

DHD Technique

The DHD residual stress measurement technique is a 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 procedure used for the standard DHD technique can be divided into 4 stages, as shown in Fig. 2 and are as follows, Stage 1: Reference bushes are attached to the front and rear surfaces of the component at the measurement location, and a reference hole is gun drilled through the component and bushes, Stage 2: The diameter, $Ø_o$, of the reference hole is measured through the entire thickness of the component and reference bushes using an air probe. Stage 3: A cylinder (i.e. core) of material containing the reference hole along its axis is extracted from the component using electro-discharge machining (EDM), and Stage 4: The diameter, Ø, of the reference hole is re-measured through the entire thickness of the core and reference bushes. Diameter measurements are taken at the same locations as those measured in Stage 3.

The diameter, $Ø_o$, of the reference hole measured in Stage 2 is the diameter when stresses are present. During Stage 4 the stresses are relieved, hence the diameter, Ø, of the reference hole measured in Stage 4 is the diameter when stresses are not present. The differences between the measured diameters in Stages 2 and 4 enable the original residual stresses to be calculated.

iDHD Technique

If a component contains, high magnitude, tri-axial residual stresses then during the trepanning process the material will undergo plastic relaxation. If this occurs then the deformed shape of the reference hole will not be representative of the original residual stress field and inaccurate results will be calculated. Therefore if it is expected that plasticity will occur during the DHD process then the modified technique, called iDHD, will be used.

During the iDHD technique the core is extracted in incremental machining steps using EDM and the diameter of the reference hole is measured between each increment. The diameters of the reference hole measured at each stage are then compared against each other and the original residual stresses present are calculated. Each increment in EDM depth yields a single set of measured biaxial residual stresses. Further details of the iDHD technique were presented by Mahmoudi et al. [3].

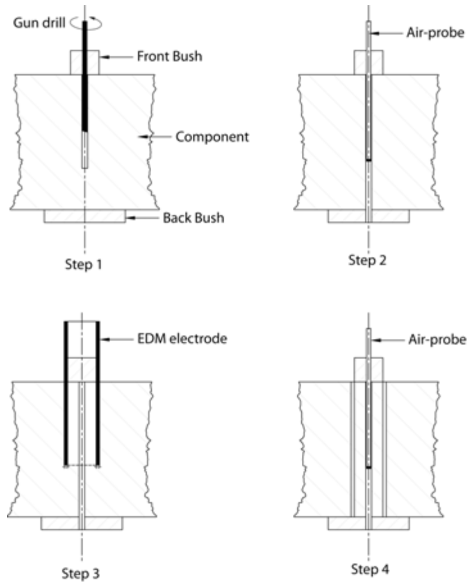

Fig. 2: Schematic diagram of the DHD process.

FINITE ELEMENT MODELLING

Finite element analysis (FEA) of the weld residual stresses before and after SWOL was performed by the Westinghouse Major Reactor Component Design and Analysis group. A detailed description of the FE analysis was provided by Smith et al [1]. The FE analysis was completed prior to the experimental measurements and the measurement results were directly compared to the previously performed FE analysis simulations [5].

An elastic-plastic two-dimensional axisymmetric model was utilised to calculate the through-wall residual stresses at the centerline of the DM weld. The model was simplified by using kinematic strain hardening and the temperature constraint method instead of detailed heat source modeling methods. The temperature constraint method holds the weld beads at near-melt temperature for a range of heat input [5]. Specifically, five different hold times, i.e., 0.1, 0.5, 1.0, 5.0 and 10.0 seconds, were utilized in the thermal solution to capture the effect of heat input on the simulation.

MEASUREMENT LOCATIONS

A total of seven DHD residual stress measurements were carried out on the two mock-ups. Three measurements were carried out on Mock-up A (i.e. 210°, 150° and then 0°) and four measurements were carried out on Mock-up B (i.e. 0°, 210°, 150° and then 90°). The locations of the measurements were chosen to be identical for both mock-ups, and to avoid any weld start/stops and flaws detected within the DMW, except for 0° which purposely represents a concentration of weld start/stop features. The 210° and 150° locations were symmetrically opposite each other from the 180° location and represent a repeatable “steady-state” residual stress field for direct validation against the FEA. As shown later in the Results section, the lack of repeatability between the initial three measurements within Mock-up B (i.e. 0°, 210°, 150°) was unexpected and so a fourth location (i.e. 90°) was measured to gain further results.

All measurements were carried out through the centreline of the DMW with the measurement axes in the nozzle-radial direction. The centreline of the DMW was estimated from the proud weld root bead on the ID of the nozzle. However due to inaccessibility and experimental error, the final locations, measured after carrying out the DHD technique, were within ±2.8mm and ±2.5° of those specified. At all seven locations the DHD technique was carried out with the extraction of a Ø5mm core (roughly) containing a Ø1.5mm reference hole.

Due to concerns about possible plastic relaxation during the DHD process the first two locations measured (i.e. Mock-up A - 210° and Mock-up B - 0°) were carried out using iDHD technique, in order to account for this. Having carried out the iDHD technique at the initial locations, it was discovered that plastic relaxation had occurred near the outer and inner diameters of the nozzle and so all further measurements were carried out using the iDHD technique near the inner and outer surfaces and the standard DHD technique in the mid-thickness region. All measurements were carried out starting from the outer surface and progressing through the wall thickness to completion at the inner surface.

The measurement axis (i.e. nozzle-radial direction) for all locations was such that the residual stresses acting in the hoop, axial and associated in-plane shear directions were measured (see Fig. 1c for axes notation). Measurements were not made of the radial residual stresses.

RESULTS

The measured deformations of the reference holes were converted into residual stresses using a Young's modulus, E, of 213.7GPa [1]. The analysis used to convert the deformations into residual stresses assumes isotropic, plane stress conditions and as such the Poisson's ratio was not required. The residual stresses presented in this paper are a combination of the standard DHD and iDHD measurement results. The combined residual stresses from the seven measurement locations are shown in Fig. 3 and Fig. 4. Each of the measured stress components is given as a function of radial distance from the machined ID surface of the nozzle. In Fig. 4 depths greater than 1 represents the overlay material, i.e. 1 represents the outer surface of Mock up B in its "virgin" state before the SWOL was applied. Any measured data within 1.0mm of a surface is omitted from the residual stress calculations due to surface edge effects.

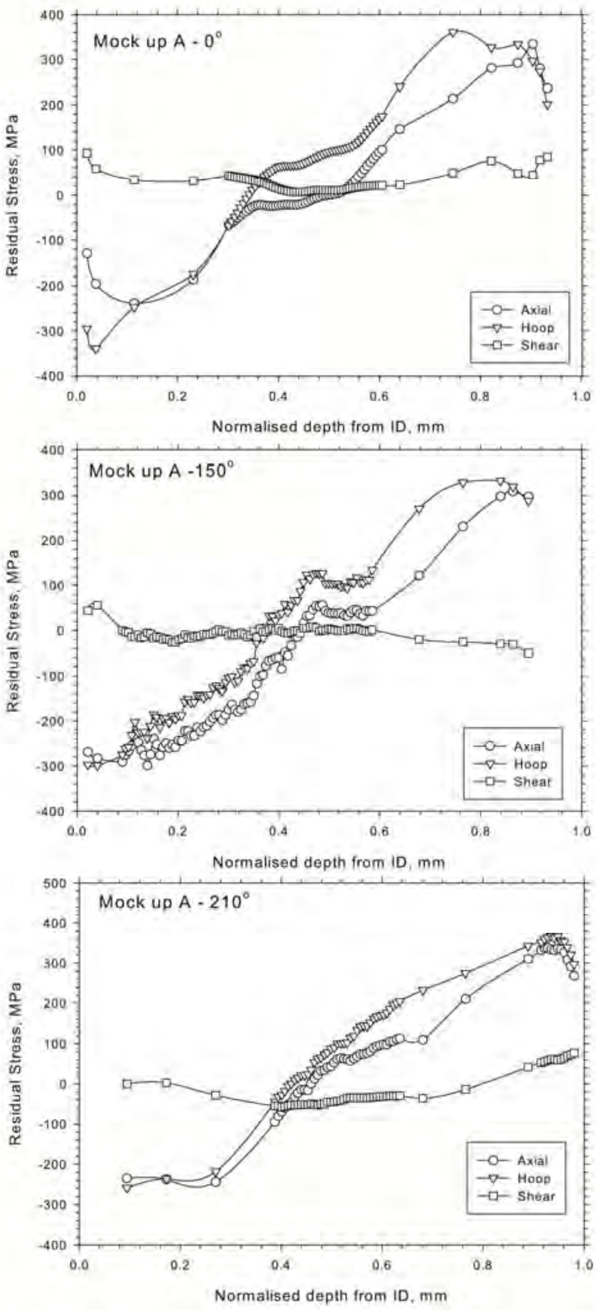

Fig. 3: Measured residual stresses within Mock-up A using a combination of the DHD and iDHD techniques at locations (a) 0°, (b) 150° and (c) 210°.

Mock-up A

The residual stresses measured within Mock-up A at 0°, 150° and 210° using a combination of the DHD and iDHD techniques are shown Fig. 3. Similar trends were observed for all three measurement locations i.e. peak compressive residual stresses near to the inner surface gradually increasing to reach peak tensile residual stresses just below the outer surface. Transition from compression to tension occurs at roughly 40% of "virgin" mock-up wall thickness. The hoop residual stresses were found predominantly the most tensile over the axial residual stresses by an average of 57MPa. Peak compressive residual stresses of -339MPa (hoop) were found at the inner surface and peak tensile residual stresses of 368MPa (hoop) were found at the outer surface

Mock-up B

The residual stresses measured within Mock-up B at 0°, 150°, 210° and 90° using a combination of the DHD and iDHD techniques are shown Fig. 4. Similar to Mock-up A the residual stresses in the axial and hoop directions follow similar trends i.e. compression at the inner surface turning to tension at the outer surface. The transition from compression to tension occurs at roughly 73% of "virgin" mock-up wall thickness. The axial residual stresses were predominantly the most tensile up to mid-thickness and then the hoop residual stresses became most tensile. Peak compressive residual stresses of -347MPa (axial) were found at the inner surface (dubious peak of -572MPa found at the 0° location) and peak tensile residual stresses of 443MPa (hoop) were found at the outer surface.

The measured residual stresses were compared with the Finite Element results and are shown in Fig. 5 and Fig. 6 for mock ups A and B respectively.

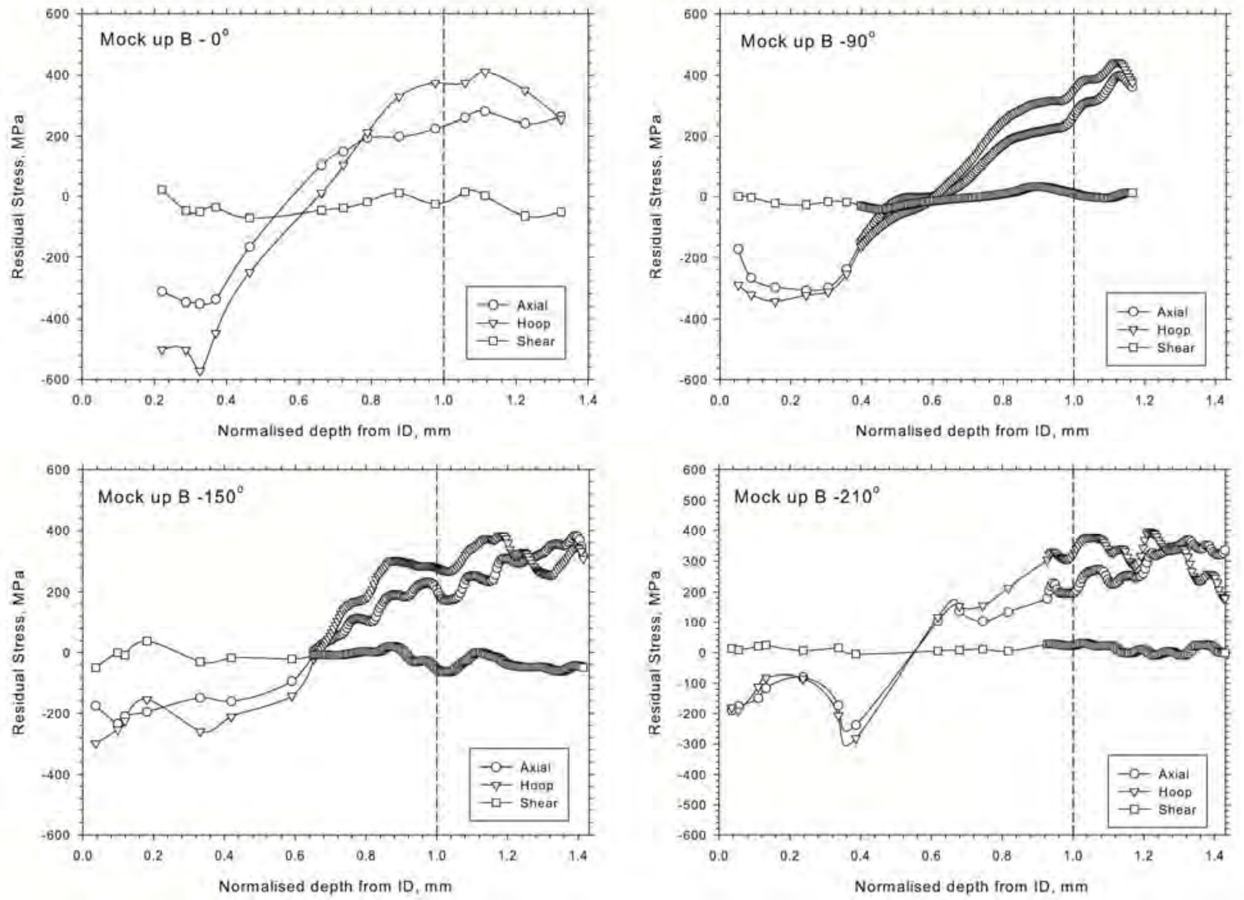

Fig. 4: Measured residual stresses in Mock up B using a combination of DHD and iDHD techniques at locations 0°, 90°, 150°, 210°.

DISCUSSION

Having carried out a total of seven DHD measurements on Mock-ups A and B it is instructive to provide a direct comparison of the residual stresses measured. Hence, Fig. 7a and Fig. 7b respectively show the axial and hoop residual stresses measured at all seven locations for comparison. It can be seen that there is very good agreement between all three measurements within Mock-up A both in the axial and hoop directions, despite the concentration of numerous weld stops at the 0° location. It can also be seen that there is very good agreement between all four measurements within Mock-up B both in the axial and hoop directions at normalised depths greater than 0.4 from the inner surface of the nozzle. At normalised depths within 0.4 of the inner surface of Mock-up B the measurements diverge with a bandwidth of roughly 270MPa for both the axial and hoop directions (neglecting the hoop results at the 0° location). The hoop stresses within Mock-up B at the 0° location seem to be an outlier (by about 300MPa more compressive) at normalised depths within 0.4 of the inner surface of the nozzle. Having reviewed the Mock-up B 0° procedure records and raw data there seem to be no anomalies in the measurement that would explain such a difference and so our current view is that there is no reason to doubt this result. However, having compared the standard DHD and iDHD results, it is important to note that the plasticity experienced at this location does seem to have been more severe than at the other locations and so the interpretation of the raw data may still break down in such extreme cases.

It can be seen that with the addition of the SWOL the general trend of the residual stresses at the inner surface did not become more compressive (although individual peak values near the inner surface were slightly more compressive), merely the zone of compression expanded deeper from the inner surface towards the outer surface. For the axial residual stresses the zone of compression expanded from 45% to 71% of the "virgin" wall thickness and for the hoop residual stresses the zone of compression expanded from 36% to 75% of the "virgin" wall thickness.

Fig. 5 and Fig. 6 provide the comparison of the measured and predicted residual stresses in mock ups A and mock up B respectively. Good agreement between the measured and predicted stresses can be seen near to the ID and OD in the axial direction and at majority of central region and the OD in the hoop direction in mock up A. For mock up B very good comparison can be seen in the hoop direction except at 0^{o} location. In both mock ups the axial measured stresses were slightly more tensile than the predicted stresses which are thought to be due to through-wall bending which was not accounted for in the FE analysis.

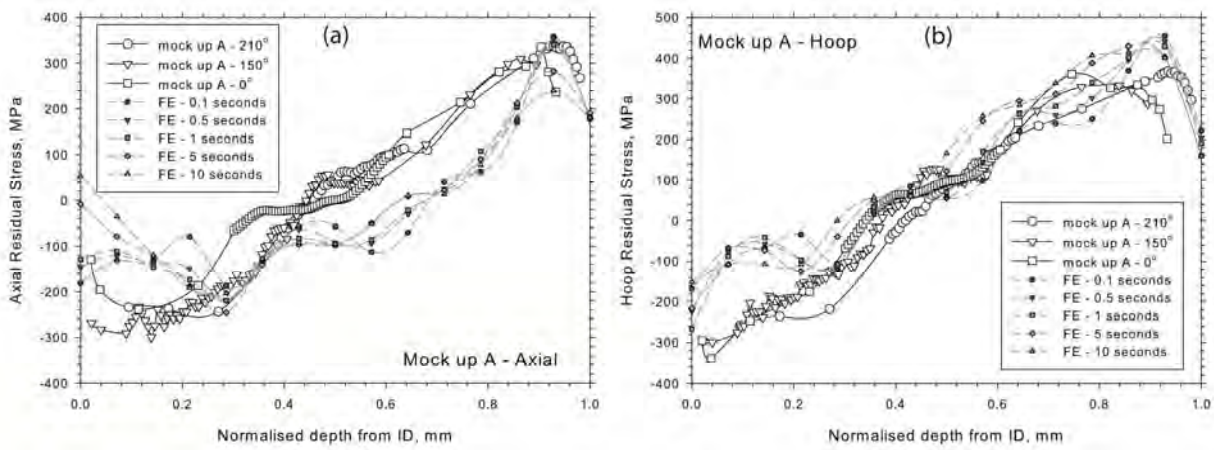

Fig. 5: Comparison of DHD/iDHD measured and finite element predicted residual stresses in Mock up A.

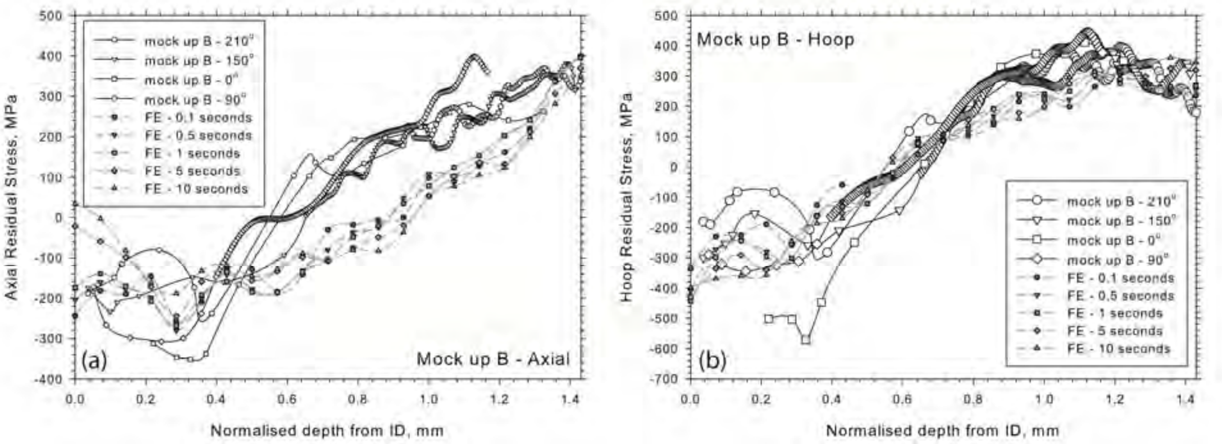

Fig. 6: Comparison of DHD/iDHD measured and finite element predicted residual stresses in Mock up B.

CONCLUSION

Seven residual stress measurements were carried out through the thickness of the DMW of two pressuriser safety/relief nozzle mock-ups. Mock-up A represented the pressuriser safety/relief nozzle in the "virgin" state (i.e. pre-service state) and Mock-up B represented the nozzle after a full structural weld overlay had been attached.

Very good agreement was shown for the axial and hoop residual stresses measured at all three locations within Mock-up A, despite the concentration of numerous weld stops at the 0° location. For both the axial and hoop directions, peak compressive residual stresses of roughly -275MPa were measured at the inner surface of the nozzle increasing to peak tensile residual stresses of roughly 350MPa at the outer surface.

Very good agreement was also shown for the axial and hoop residual stresses measured at all four locations within Mock-up B at normalised depths greater than 0.4 from the inner surface of the nozzle. At normalised depths within 0.4 of the inner surface the measurements diverged with a bandwidth of roughly 270MPa for both the axial and hoop directions (neglecting the hoop results at the 0° location). Again for both the axial and hoop directions, peak compressive residual stresses averaging at roughly -200MPa were measured at the inner surface of the nozzle increasing to peak tensile residual stresses of roughly 325MPa at the outer surface.

For both Mock up A and B, generally a good agreement was seen between the measured and predicted axial results near to the ID and OD surfaces, with the measured being more compressive. In the hoop direction the comparison was much better in majority of central region and near to the OD.

The average level of uncertainty for the axial and hoop residual stresses measured using the standard DHD technique was ±26MPa [6].

It can be seen that with the addition of the SWOL the general trend of the residual stresses at the inner surface did not become more compressive (although individual peak values near the inner surface were slightly more compressive), merely the zone of compression expanded deeper from the inner surface towards the outer surface. For the axial residual stresses the zone of compression expanded from 45% to 71% of the “virgin” wall thickness and for the hoop residual stresses the zone of compression expanded from 36% to 75% of the “virgin” wall thickness. Therefore it can be concluded that the introduction of further compressive stresses by the SWOL lead to increased resistance towards crack propagation in the DMW prolonging the safe operation of the nozzle.

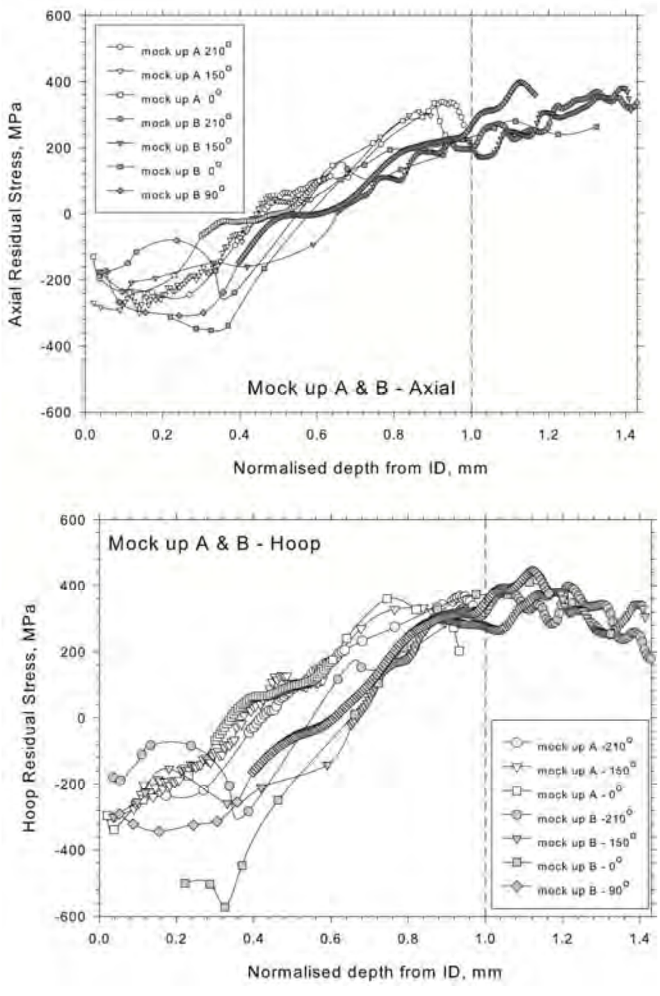

Fig. 7: Comparison of measured residual stresses at all locations in mock up A and mock up B.

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