Effect of ultrasonic peening and accelerated corrosion exposure on the residual stress distribution in welded marine steel

Ahmad, B. and Fitzpatrick, M.E.

Effect of Ultrasonic Peening and Accelerated Corrosion Exposure on the Residual Stress Distribution in Welded Marine Steel

Bilal Ahmad[1, a], Michael E. Fitzpatrick[2, b*]

[1]Department of Engineering and Innovation, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK

[2]Faculty of Engineering and Computing, Coventry University, Priory Street, Coventry CV1 5FB, UK

[a]bilal.ahmad@open.ac.uk, Tel: +44 1908655019, Fax: +44 1908 653858

[b]michael.fitzpatrick@coventry.ac.uk, Tel: +44 2477 685673

Abstract

Specimens of DH36 marine steel were prepared with welded attachments. Residual stress measurements were made on the samples as-welded, following an ultrasonic peening treatment, and following accelerated corrosion exposure after ultrasonic peening. Neutron diffraction and the contour method were used for determining the residual stress profiles. The welding introduces tensile near-surface residual stress, approaching the material yield strength, and the ultrasonic peening overlays this with a compressive residual stress. Material removal by corrosion decreases the peak surface compressive stress slightly, by removal of a layer of stressed material, but does not cause significant redistribution of the residual stress profile.

Keywords: Marine steels; welding; ultrasonic peening; residual stress; neutron diffraction; contour method

1. Introduction

Residual stress can cause premature failure even if the applied service stresses are reasonably low. Residual stresses combine with the applied stresses in-service. Residual stresses can be generated as a result of mechanical, thermal and chemical manufacturing operations. Residual stresses must be considered in design assessments where safety of a structure is critical and/or the magnitude of residual stress is expected to be high. In addition, measurement of residual stress is required for modern surface treatment techniques which often need to be refined to obtain optimal compressive residual stresses for various materials.

Statnikov *et al.* [1] invented the ultrasonic peening (UP) method in the 1970s. The method uses continuous ultrasonic vibrations transferred through a hardened material tip that is placed in contact with the surface being treated. The tools required for UP treatment are portable and relatively easy to use. The near-surface region of the material experiences high-rate plastic straining during the impact and Kudryavtsev *et al.* [2] described that UP produces a 0.2 to 0.5 mm deep and 2 to 7 mm wide groove at the weld toe with a uniformly smooth surface finish. Statnikov [3] noted that UP is used by a number of industries, including those dealing with the manufacture and maintenance of welded structures and machinery components. UP alters the weld profile by introducing a smooth radius and therefore reduces the stress concentration, and introduces a compressive residual stress into the weld toe which Cheng *et al*. [4] found to extend to 1.5 mm below the surface.

Martinez *et al.* [5] found that samples with attachments welded on both sides of a base plate showed an improvement in fatigue life of 2.25 times for a stress range of 80 MPa. Weich *et al.* [6] tried to correlate the depth of the UP groove to the surface residual stresses produced. Maddox *et al.* [7] carried out fatigue tests on UP treated fillet welded samples and also found increased life.

A number of residual stress measurement techniques are now available. Each technique has its own inherent advantages and limitations. The selection of a technique for a particular measurement depends upon various factors such as sample material, geometry and dimensions of the component, desired measurement locations, stress components of interest, availability of technique, measurement accuracy, cost, and time involved. For the ultrasonically-peened fillet welded samples in this study, the contour method and neutron diffraction are considered the most valuable techniques to characterize the residual stress. Destructive techniques such as the contour method are based on elastic relaxation after sectioning or material removal; and non-destructive diffraction techniques such as neutron diffraction measure strain by using the atomic lattice as a strain gauge.

The contour method gives a uniaxial residual stress map over the whole cross-section and is applicable to thick samples. It consists of cutting a sample in two using wire electric discharge machining (WEDM), followed by measurement of the relaxed surface profile using a co-ordinate measuring machine (CMM), and finally recalculation of the pre-existing residual stress field by means of a straightforward elastic finite element (FE) analysis. Pagliaro *et al.* [8] demonstrated that it is possible to obtain multiple stress components in a sample if multiple cuts are made.

Neutron diffraction can provide the complete triaxial residual stress profile in a sample. It has good penetration (up to 20 mm depth in steel) and measurement accuracy. Neutron diffraction instruments are now available that are specialized and optimized for residual stress measurements. Neutron diffraction typically has a long lead time and access is limited, whilst application of the contour method is relatively time-efficient if the appropriate tools are available.

Both techniques have limitations for near-surface measurements of residual stress. Neutron diffraction exhibits "pseudo-strain" effects if the measurement gauge volume straddles the surface [9]. The contour method often suffers from near-surface cutting artefacts [10], and difficulties in both data acquisition and in the analysis techniques.

Finally, when applying the contour method, uncertainties may be introduced during cutting because of cutting artefacts including wire breakage, transients at the cut start and cut stop positions, and the effects of surface roughness.

2. Sample details

Fillet welded samples were supplied by Lloyd's Register Group UK in conditions as-welded, ultrasonically-peened, and accelerated corrosion tested after ultrasonic peening. The material is marine grade carbon-manganese DH36 steel, commonly used in commercial ship construction. The 25-mm-thick base plate was prepared by rolling. Longitudinal attachments of 15 mm thickness were welded on both sides of plate. Figure 1 shows the samples and the detail of the longitudinal attachment.

Ultrasonic peening was performed at the weld toe locations at the attachment corners, as these areas are more susceptible to fatigue cracks (Figure 1b). The ultrasonically peened groove is 3 mm wide and 0.5 mm deep.

The accelerated corrosion tested sample was similar to the other two samples in dimensions before corrosion. The sample post-corrosion is shown in Figure 1c. The sample was exposed to laboratory simulated corrosion exposure with artificial sea water for an equivalent of 7.5 years. Before residual stress measurements the surface of the sample was cleaned with a rust removal gel. The feasibility of using hydro-blasting for surface preparation of corrosion tested sample was examined in terms of the residual stresses induced by this process, and the results showed that hydro-blasting induces compressive stress, thus it was decided not to use this process for surface preparation of the corrosion tested sample [11].

The contour method and neutron diffraction were used to characterise the residual stress in all the samples. X-ray diffraction and incremental center hole drilling techniques were not suitable for all the samples owing to the irregular geometry of the peened area and the rough surface after corrosion exposure.

3. Experimental setup and procedure

For all three types of sample, the contour method measurements were carried out at The Open University, and neutron diffraction experiments using the ENGIN-X instrument [12] at the UK's ISIS neutron source. For the as-welded sample, measurements were also carried out on the surface using laboratory X-ray diffraction. The detail and procedure of these measurements is as follows.

3.1. X-Ray diffraction measurement setup

The surface residual stress distribution at the weld toe of the as-welded sample was characterized using laboratory X-ray diffraction. Residual stresses and the surface profile at the weld toe strongly influence the onset of fatigue damage. Maddox *et al.* [7] found that in case of fillet welds with longitudinal attachments the weld toe at the attachment corner is a location where fatigue cracks initiate owing to a combination of the weld tensile residual stress and the stress concentration from the change in geometry. The sample has four weld toe locations where cracking may initiate, as shown in Figure 2.

A Stresstech XSTRESS 3000 laboratory X-ray diffractometer was used for the $\sin^2\psi$ method of stress determination. Measurements were taken at all four weld toe locations with measurements made as close as possible to the attachment. Because of the obstruction of the welded attachment, movement of the X-ray goniometer head was possible in one direction only, and this may lead to an error in stress calculation by ignoring the effect of shear stress: the stress is conventionally determined from the slope of both negative and positive ψ tilts as described by Fitzpatrick *et al*. [13], however in this case only one set of ψ tilts was available. The measurements were recorded with a 3-mm-diameter collimator and in the longitudinal (X) direction of the sample at each weld toe location with measurement points as shown in Figure 3. The transverse stress component of stress was not measureable owing to obstruction of the goniometer head by the attachment.

The calibration of the equipment was made with a stress-free powder of ferrite with the same 3-mm-diameter collimator tip.

3.2. Neutron diffraction measurement setup

The neutron diffraction experiment was conducted using the ENGIN-X instrument on the ISIS time-of-flight (TOF) pulsed neutron source [14]. 2 mm collimators were used to define the scattered sampling dimension. A brief procedure for residual stress measurement on ENGIN-X is as follows.

Before measurements the positioning table was aligned and the detectors calibrated. The sample, with fiducial markers attached, was scanned using a Metris laser scanner, and the result was used to simulate the experiment using the SScanSS software developed by James *et al*. [15-16]. After clamping the sample on the positioning table the fiducial points on sample were again scanned by touch-probe CMM. For automated positioning of samples a script file was generated by SScanSS and fed to the instrument control PC. To estimate the measurement time for suitable strain accuracy, test measurement was carried out for two points in the weld and heat affected zone (HAZ). The experimental runs were analysed using Open Genie software to calculate lattice parameters.

Stress-free reference values were obtained from 10 d_0 cubes of size 3 × 3 × 3 mm^3 which were extracted using wire electro-discharge machining (WEDM) from the as-welded sample in the weld, HAZ, and at a distance of 7 mm below the weld toe. For measurement of the stress-free cubes, a gauge volume of 2 × 2 × 2 mm^3 was used. The centers of measurement locations for the samples are shown in Figure 4 and were scanned through the plate thickness from the weld toe at the attachment corner of two ultrasonically peened samples and one as-welded sample.

For sample normal and transverse strain components a gauge volume of 2 × 2 × 2 mm^3 was used, whereas for the longitudinal strain component a gauge volume of 5 × 2 × 2 mm^3 was used. The measured locations were at the center width of the plate at the attachment edge. In the case of the ultrasonically peened samples the measurement locations are at the center of the peened groove.

3.3. Contour method measurement setup

The contour method of residual stress measurement uses wire electro-discharge machining (WEDM) to cut the component into two halves, and from the contour of the cut surfaces the pre-existing stress state is determined. WEDM is designed for manufacturing of mechanical parts/components and for this purpose multiple cuts are often made at the same location: a first “rough” cut followed by successive cuts for good dimensional accuracy and surface finish. However, the contour method must use only a single cut to relax the stresses.

The depth of compressive stress associated with peening techniques is relatively small and to measure stresses accurately in this region using the contour method a high-quality WEDM cut is desired. A good cut for the contour method means one that gives a flat surface and the best surface finish with little scatter on a stress free material coupon. Kundu *et al.* [17] used small thickness sacrificial layers composed of similar material at the EDM wire entry and exit points, and the start and end of the cut, in order to reduce the cutting artefacts that are often seen in these regions.

WEDM machine cutting parameters must be optimized in respect of surface profile, surface roughness, and induced residual stress. For this purpose a series of cutting tests were undertaken on stress-free blocks of DH36 steel. Cutting tests looked at the selection of available machines, wire diameters, and machine settings. Tests were conducted without and with sacrificial layers made of DH36 steel or a low melting point alloy. Out of these cutting tests, a condition was selected based on a reduced pulse duration setting using sacrificial layers, as it gave best surface roughness as well as a flat cut and no notable cutting artefacts along the wire travel and cut paths. Significant improvement in surface roughness was seen from default machine settings giving R_a of 2.6 µm to the selected conditions that gave 1.6 µm for the DH36 steel. The best possible surface finish of the cut surface tends to minimize errors in the contour method measurement.

The contour method provided a map of the longitudinal residual stress component in the samples over the whole cross-section. The weld toe is a particular location of interest, therefore the contour cut was made at one end of the attachment: note that the cut sampled two weld toes as it passed through the welds for the attachments on both sides of the plate. It was seen from neutron diffraction measurements that the sample longitudinal stress component is of highest magnitude and hence most influential on failure. The cut location on the as-welded sample is illustrated in Figure 5.

The cutting of the samples was carried out on a GF Agie Charmilles wire electro-discharge machine (WEDM). The sample was aligned and clamped near the cutting location to restrain all degrees of freedom during cutting: Prime *et al*. [18] indicate that proper alignment and clamping tends to reduce the cutting errors. Brass cutting wire of 0.25 mm diameter was used for all three samples. After successful cutting, the cut surfaces were cleaned in an ultrasonic bath to remove any debris. In the case of the ultrasonically peened sample, the WEDM cut passed through different regions of the peened grooves on the upper and lower sides of the plate because of asymmetry: on one side the cut passed through the center of the groove and on the other side through the edge of the groove near the weld toe. It is important to note the location through which the contour cut passed when interpreting the results.

The surface contours of both cut halves were measured using a Mitotuyo CrystaPlus 574 co-ordinate measuring machine (CMM) with 3-mm-diameter ruby-tipped Renishaw PH10M touch trigger probe. Displacement data from both cut faces were measured with a point spacing of 0.5 × 0.5 mm. The distance from the edges was also kept as 0.5 mm. Ferritic steels tend to rust rapidly and for such steels the time in the WEDM chamber should not be too long: the rust forms a very thin layer on the cut faces which may not be uniformly distributed and consequently imparts error during CMM measurement. For the ultrasonically-peened samples, the displacement data were also acquired using a CMM 4-mm-diameter scanning probe with 0.1 mm point spacing in both directions and minimum 0.1 mm distance from the edges.

Isometric views of the averaged surface contour of all three types of samples are shown in Figure 6. The measured contours show symmetry reflecting the welding on upper and lower surfaces of the plate. Owing to the presence and relief of shear stress, the relaxed contour is different for both cut surfaces. By averaging the displacements of both cut faces, the effect of shear stresses and some other sources of error can be eliminated [19]. Both surface contours were processed using Matlab analysis routines for data aligning, averaging, cleaning, smoothing, and then finally fitted with cubic splines according to Johnson (2008). FE analysis was performed using Abaqus with 8-node brick elements. To avoid rigid body motion, constraints were applied at the edges of the FE model. Linear elastic finite element (FE) analysis was performed with modulus of elasticity E = 210 GPa and Poisson's ratio υ = 0.3.

Figure 7 gives the averaged surface profile through the thickness of the corrosion-exposed ultrasonically-peened sample measured using CMM touch and scanning probes. Depending upon the condition of the cut surface, the CMM scanning probe can acquire data quickly with higher measurement density. No significant difference between the measured surface profiles can be seen.

For two-dimensional smoothing and fitting of the contour displacement data, spline functions are used. Different orders of spline fit can alter the results to some extent. In this study we selected a cubic spline and focussed on optimization of the knot spacing. Figure 8 shows the effect of selection of different knot spacings on the fitting to the measured data. In Figure 8a, for data through the sample thickness (i.e. along the Z-axis), a smaller knot spacing gives a better fit, whilst in Figure 8b, for data across the sample width (i.e. along the Y-axis), the fit is relatively insensitive to knot spacing. The CMM touch probe data with 0.5 mm measurement density is shown in Figure 8c. For this case only a 2-mm spline knot spacing was seen to follow the trend in data whereas higher knot spacings missed more of the detail. This indicates that the CMM measurement density should be high enough to allow the fitting routines to follow the trend in data as smoothly as possible.

Prime *et al.* [18] proposed another method of selecting the appropriate spline knot spacing, which calculates the uncertainty in stress at a given FE node by comparing the standard deviation of stress values from a fit with a finer spacing to that obtained from a previous coarser knot spacing as per equation 1:

$$\partial\sigma(i,j) = \frac{1}{\sqrt{2}}|\sigma(i,j) - \sigma(i,j-1)| \tag{1}$$

Where $\sigma(i,j)$ is the stress at node i for spline knot spacing j and j–1 refers to the previous, coarser spline knot spacing.

Then the average stress map over the whole cut surface is calculated by taking the root mean square (RMS) of all nodal uncertainties according to equation 2:

$$\partial\sigma(j) = \frac{1}{\sqrt{n}}\sqrt{\sum_i^n[\partial\sigma(i,j)]^2} \tag{2}$$

Where n = number of nodes.

This technique was employed for the selection of the spline knot spacing in addition to fitting of the average displacement data.

After selecting the best WEDM cutting parameters and displacement data fitting routine, to obtain reliable results from the contour method it is also important that the cut surface geometry be modelled as near to reality as possible. This helps to improve near-surface residual stress results, in particular. The contour cut surface of the ultrasonically-peened samples was modelled by taking into account the actual cut portion of the groove produced by ultrasonic peening, as well as the actual material removed by corrosion testing. The FE model used a non-uniform mesh through the sample thickness with a refined mesh near the surfaces. The overall dimensions as well as the size of the peened grooves were accurately reproduced. For the corrosion-exposed sample the corrosion rate was less at the peened region compared to the rest of the sample. The material removal by the corrosion process was considered as:

Material removal in non-peened region = 0.5 mm;

Material removal at peened region = 0.1 mm.

4. Results and discussion

4.1. X-Ray diffraction measurement results

The results of on-surface residual stress measurements carried out using X-ray diffraction at all four weld toe locations in the as-welded sample are shown in Figure 9. The results represent the stress profile at the weld toe as a function of position across the width of the sample. The peak weld toe stress is found at the center-line of the attachment.

From the XRD measurements it is evident that the tensile residual stress at the weld toe locations is more than 300 MPa, approaching the minimum yield strength of the DH36 steel of 355 MPa. The tensile stress decreased away from the center-line along the Y-direction owing to the shape of the weld (see figure 5). There is some variation in the magnitude of the profiles between the four attachments, which is attributed to process variation in the welding and final profile of the weld toes. The residual stress distribution as a function of distance from the weld toe along the length of the sample is shown in Figure 10.

4.2. Neutron diffraction results

The neutron diffraction measurements of stress-free d_0 cubes revealed that in the welds there is higher directional-dependence of the lattice parameters as compared to the heat-affected zone and the parent metal at a location of 7 mm below the weld toe. The directional dependence in the weld is about 0.0009 Å, equivalent to a strain error of several hundred micro-strain. The individual measurement of cubes for all three regions showed better consistency, and therefore average directional-dependent lattice parameter values were used for residual stress calculation along with bulk material elastic modulus E = 210 GPa and Poisson's ratio υ = 0.3. The lattice parameter values in the weld are higher than the other regions, reflecting changes in the alloy solution content as a consequence of the heating effects.

The stress profiles in the longitudinal, transverse and normal directions at the weld toe region are shown in Figure 11. For the as-welded sample measurements were possible at one weld toe only.

From the residual stress profile in the as-welded sample it can be seen that the longitudinal stress component is of highest magnitude. For the ultrasonically-peened sample, although it was ensured that measurement setup and location remain the same for both weld toes, there is a difference in the magnitude of the residual stress at the two toes. This difference is attributed to variation in the quality of the peening. Ultrasonic peening has reduced the near-surface tensile residual stresses at both weld toe locations.

The sample subjected to accelerated corrosion exposure following ultrasonic peening showed that there is retained compressive residual stress following corrosion exposure. After accelerated corrosion testing the compressive stresses have apparently increased in the case of the longitudinal stress component, although this may simply be a consequence of variability in the UP process applied.

4.3. Contour method measurement results

For contour method measurements a single stress component was measured at the weld toe location: the longitudinal σ_X stress. Figure 12 shows the stress maps for the three sample types. For comparison purposes the plotted contour stress maps were processed with a cubic spline knot spacing of 11 mm in both directions. The arrows on the stress maps also show the direction of cut and EDM wire travel direction.

The weld at the attachment edge had a length of about 30 mm in the y-direction. For the as-welded sample the magnitude of tensile stress is highest near the surface of the weld and is close to the material yield strength. Compressive residual stresses are seen on the sample surface away from the weld zone as a result of the rolling process for the plate manufacture. There is a slight variation in distribution and magnitude of residual stress at the two weld locations, which is attributed to variation in the welding conditions.

The contour results of the as-welded sample are compared with neutron diffraction measurements in Figure 13. The neutron diffraction measurements were carried out at one weld toe only, however in Figure 13 they are mirrored and plotted at both weld toe locations to facilitate comparison with the contour results. XRD on-surface measurements are also shown in Figure 13.

For the as-welded sample no sacrificial layers were used and the wire EDM cutting conditions were not optimal. The influence of WEDM cutting artefacts and a relatively rough surface was seen for this case, and is reflected in the results up to 1.5 mm below the surface: after this depth the contour method stress profile matches well with the neutron diffraction results. Toparli *et al.* [10] suggest that XRD measurements are more reliable for near-surface measurements than the contour method, as a consequence of inherent artefacts in the WEDM cutting and the subsequent data fitting.

The presence of such high tensile residual stress in the as-welded sample suggests the application of a post-weld treatment method would be beneficial for enhancing the fatigue life. A mitigating compressive residual stresses can be induced by plastic deformation methods such as ultrasonic peening.

The depth of the compressive stress layer induced by ultrasonic peening treatments is relatively low, and to measure near surface stresses accurately in this region using the contour method special care must be taken. For the ultrasonically peened samples the WEDM cutting conditions were optimized and sacrificial layers were used around the wire path.

Contour method residual stress results from the ultrasonically peened sample are shown in Figure 14, including comparison with the neutron diffraction data.

In the case of the ultrasonically-peened sample the contour cut passed through different locations for the peened grooves on the top and bottom sides of the base plate. On one side of plate the cut passed through the center of the peened groove and on other side it passed through the edge of the groove towards the welded attachment. This variation in cut location resulted into some misfit of peak tensile stress with the neutron diffraction results at one of the weld toes. The compressive stresses at the two weld toes are different, confirmed by both neutron and contour data, showing a variation in peening quality. The depth of compressive stress is up to 1.5 mm below the surface. The detailed near surface stress profiles for the two weld toes are shown in Figure 15. The variation in magnitude of residual stress at the two weld toes is considered to be a consequence of a variation in peening quality.

The contour method residual stress profile from the peened and corrosion-exposed sample is plotted in Figure 16. The accelerated corrosion test has removed some of the compressive layer induced by ultrasonic peening. The surface of the corrosion-exposed sample after removal of corrosion product was irregular, and the non-uniform surface resulted in a partially-filled gauge volume for the near-surface measurements with neutron diffraction, as well as incorrect calculation of some measurement locations below the surface. We estimate positional errors of up to 0.75 mm occurred because of the surface roughness. Hence we have more confidence in the contour method results for the corrosion-exposed sample. Detailed line plots of the contour method results are shown in Figure 17. The variation in residual stress between the two peened regions in the corrosion-exposed sample is again attributed to variation in peening quality. Compressive stress is seen up to 1 mm below surface even after equivalent corrosion exposure of 7.5 years.

Comparative longitudinal residual stress profiles of the contour method results for the as-welded, ultrasonically peened and corrosion tested samples are shown in Figure 18.

The corrosion exposure removed a small layer of compressively-stressed in the ultrasonically-peened region; below that the stress profile is nearly identical to the as-peened sample. In reference to the as-welded sample, a significant reduction in tensile residual stress is achieved with ultrasonic peening, which sustains even after corrosion exposure equivalent to 7.5 years.

5. Conclusions

1. A combination of neutron diffraction, X-ray diffraction and the contour method has been used to determine the residual stress in welded samples subjected to ultrasonic peening and accelerated corrosion exposure. The samples were made of DH36 marine steel with welded attachments.

2. As-welded, the samples contain significant levels of tensile residual stress, approaching the yield strength of the material. Following ultrasonic peening, the surface stresses are compressive to a depth of over 1 mm, and the peak tensile stresses are reduced.

3. Following accelerated corrosion testing, a small layer (<1 mm) of compressively-stressed material is removed from the peened region (in fact, the material removal rate at the peened region appears to be slightly less than that for the rest of the sample). This reduces the magnitude of the compressive stress at the surface but there is relatively little change in the residual stress in the depth.

4. The use of sacrificial layers in the application of the contour method allows for improved accuracy in the determination of near-surface residual stresses, which is of use in the near-surface region where neutron diffraction becomes difficult to apply.

Acknowledgements

We are grateful to Peter Ledgard for WEDM cutting of the samples at The Open University. Special thanks to Sanjooram Paddea and instrument scientist Dr Shu Zhang for their help in execution of the neutron diffraction experiment at ENGIN-X. The UK Science and Technology Facilities Council is thanked for the provision of beamtime at the ISIS neutron source. The authors are grateful for funding from the Lloyd's Register Foundation, a charitable foundation helping to protect life and property by supporting engineering-related education, public engagement and the application of research.

References

1. E. Statnikov, L. V. Zhuravlev and A. F. Alekseev, 1975, USSR Inventor's Certificate No. 472782.

2. Y. Kudryavtsev, J. Kleiman, G. Prokopenko, V. Knysh and L. Gimbrede, In *SEM X International Congress & Exposition on Experimental & Applied Mechanics*, (2004), http://sem-proceedings.com/04s/sem.org-SEM-X-Int-Cong-s250p08-Effect-Ultrasonic-Peening-Microhardness-Residual-Stress-Materials.pdf.

3. E. Statnikov, *IIW Document XIII-2004-04* (2004). http://superiorshotpeening.com/pdf/WhitePaper-PhysicsOfEsonixUIT.pdf

4. Xiaohua Cheng, John W. Fisher, Henry J. Prask, Thomas Gnäupel-Herold, Ben T. Yen and Sougata Roy, *International Journal of Fatigue* 2003, vol. 25, pp. 1259-1269.

5. L. L. Martinenz and P. J. Haagensen, (2006), http://lets-global.com/doc/Life-Extension-of-class-F-and-Class-F2-details-using-ultrasonic-peening-IIW-2006.pdf.

6. Imke Weich, Thomas Ummenhofer, Thomas Nitschke-Pagel, Klaus Dilger and Hamdollah Eslami Chalandar, *Weld World* 2009, vol. 53, pp. R322-R332.

7. Stephen J. Maddox, M. J. Doré and Simon D. Smith, *Weld World* 2011, vol. 55, pp. 56-67.

8. P. Pagliaro, M. B. Prime, H. Swenson and B. Zuccarello, *Experimental Mechanics* 2010, vol. 50, pp. 187-194.

9. L. Edwards, In *Analysis of Residual Stress using Neutron and Synchrotron Radiation*, ed. M. E. Fitzpatrick and Lodini A. (Taylor & Francis: London, 2003), pp 233-248.

10. M. B. Toparli, M. E. Fitzpatrick and S. Gungor, *Experimental Mechanics* 2013, vol. 53, pp. 1705-1718.

11. B. Ahmad and M. E. Fitzpatrick, *Corrosion Science* 2014, doi:10.1016/j.corsci.2014.11.008.

12. J R Santisteban, M R Daymond, J A James and L Edwards, *J. Appl. Crystallography* 2006, vol. 39, pp. 812-825.

13. M. E. Fitzpatrick, A. T. Fry, P. Holdway, F. A. Kandil and J. Shackleton, Measurement Good Practice Guide no. 52, ISSN 1473-2734, National Physical Laboratory, Teddington, 2002.

14. L. Edwards, M. E. Fitzpatrick, M. R. Daymond, M. W. Johnson, G. A. Webster, N. P. O'Dowd, P. J. Webster and P. J. Withers, In *6th Intl Conf. on Residual Stresses* (Institute of Materials, UK: Oxford, UK, 2000), pp 1116-1123.

15. J A James and L Edwards, *Nuclear Instr. Methods in Physics Res. A* 2007, vol. 571, pp. 709-718.

16. S. Ganguly, J. A. James, M. E. Fitzpatrick and A. Tanguy, *Appl. Phys. A* 2010, vol. 99, pp. 601-606.

17. A. Kundu, P. J. Bouchard, S. Kumar, K. Venkata, J. Francis, A. Paradowska, G. Dey and C. Truman, *Sci. Technol. Welding Joining* 2013, vol. 18, pp. 70-75.

18. M. B. Prime, R. J. Sebring, J. M. Edwards, D. J. Hughes and P. J. Webster, *Experimental Mechanics* 2004, vol. 44, pp. 176-184.

19. M. B. Prime, *Journal of Engineering Materials and Technology* 2000, vol. 123, pp. 162-168.

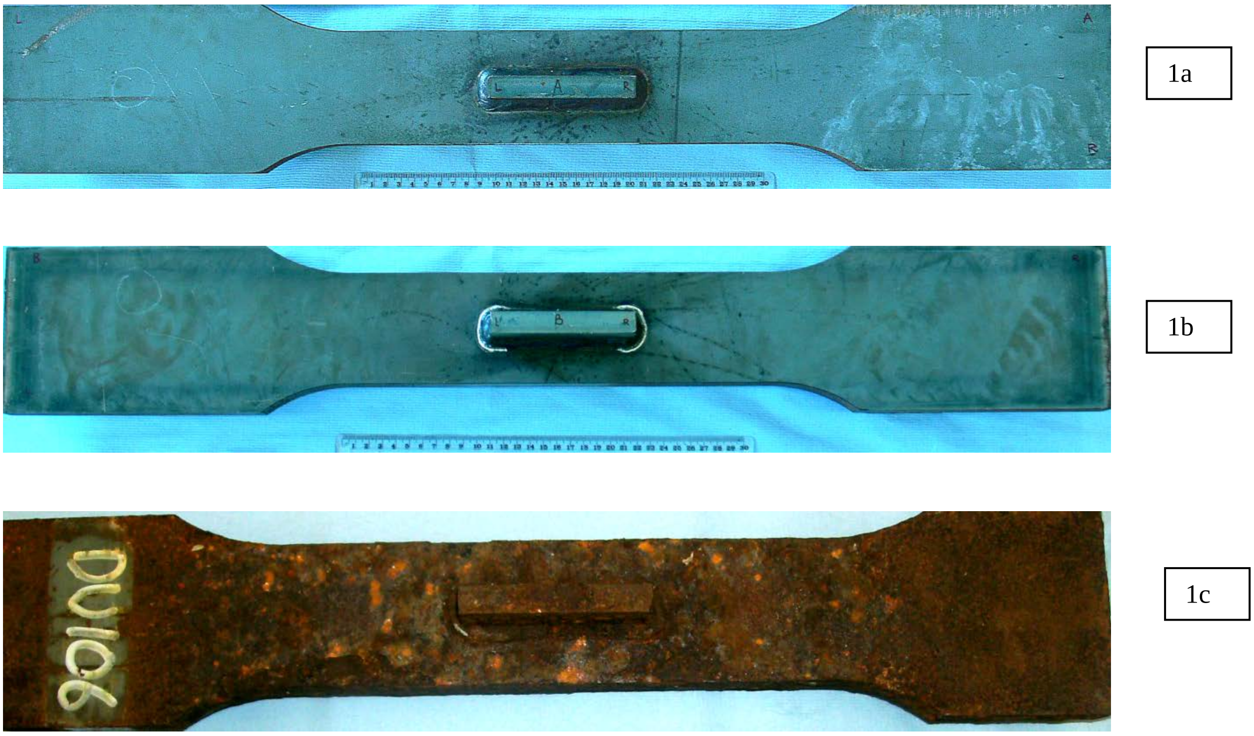


Figure 1. Top view of the welded samples. Note that a second, identical attachment is present below the plate as shown. (a): As-welded. (b): Ultrasonically peened. (c): Accelerated corrosion tested.

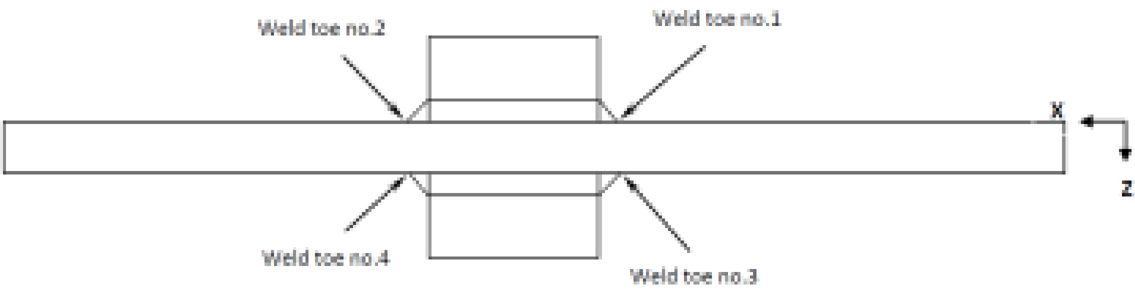


Figure 2. Weld toe locations. Side view of the sample geometry shown in Figure 1(a).

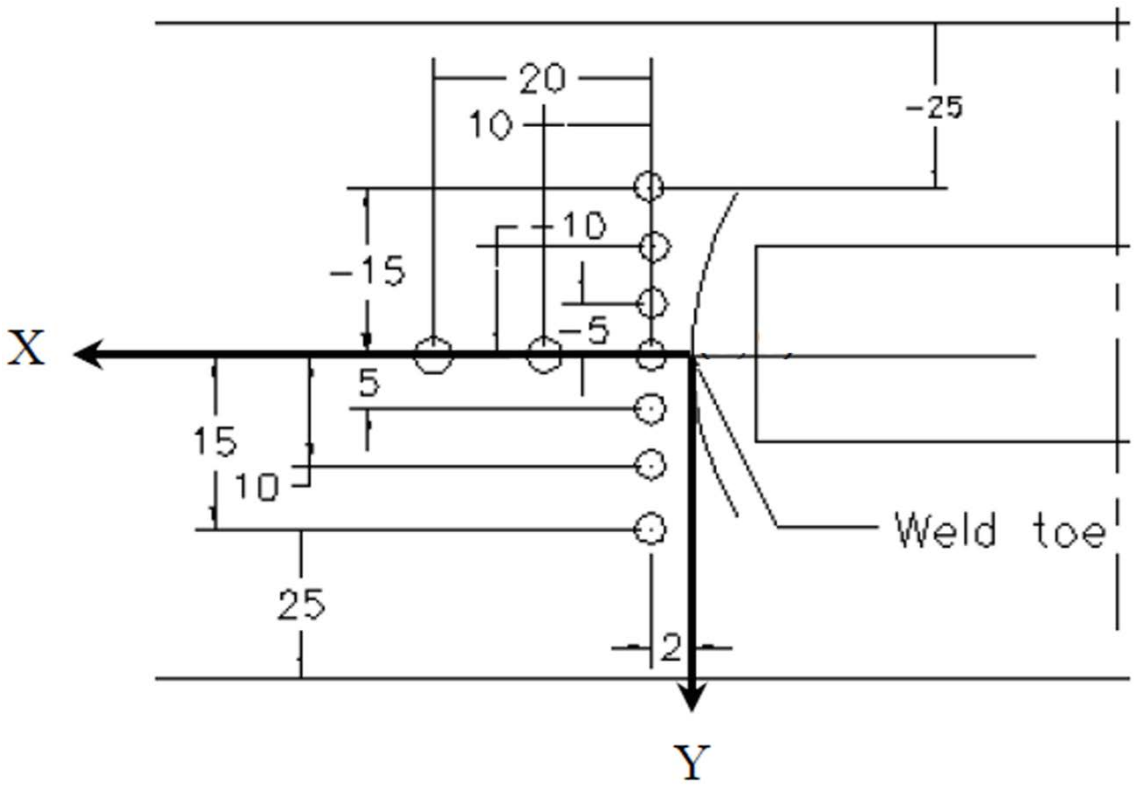


Figure 3. XRD measurement points for one weld toe location of the fillet welded DH36 steel samples. The circles indicate the measurement positions.

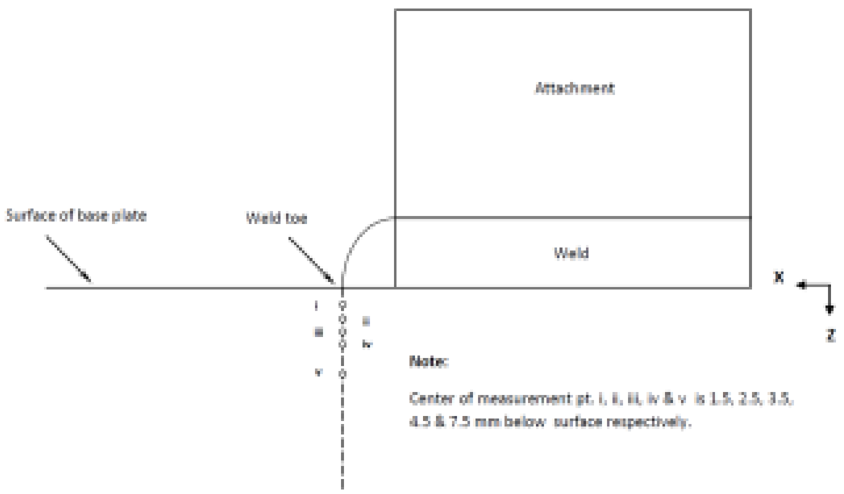
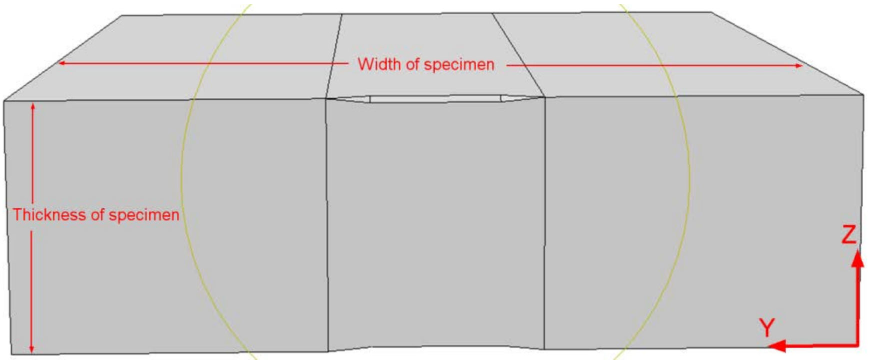
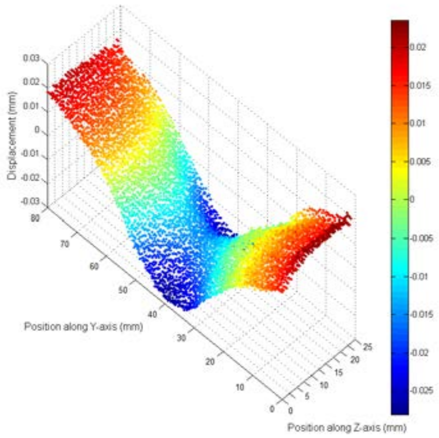


Figure 4. Neutron diffraction measured locations at the weld toe on one side of base plate

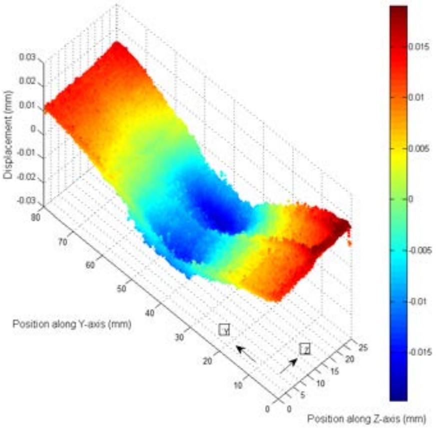
Figure 5. Contour method cut location for as-welded sample. Note that there is a second attachment on the bottom surface of the plate.



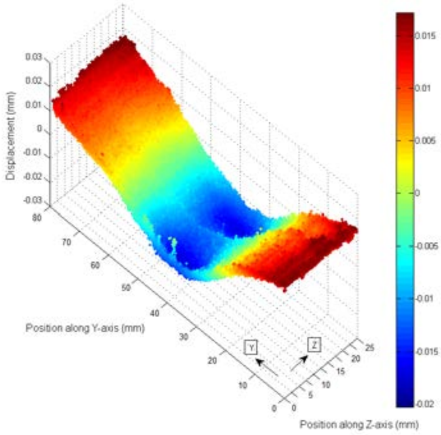
6a



6b

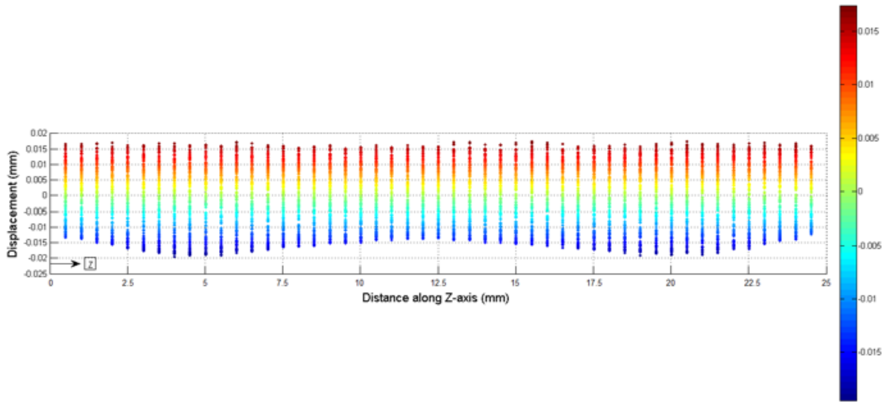


6c

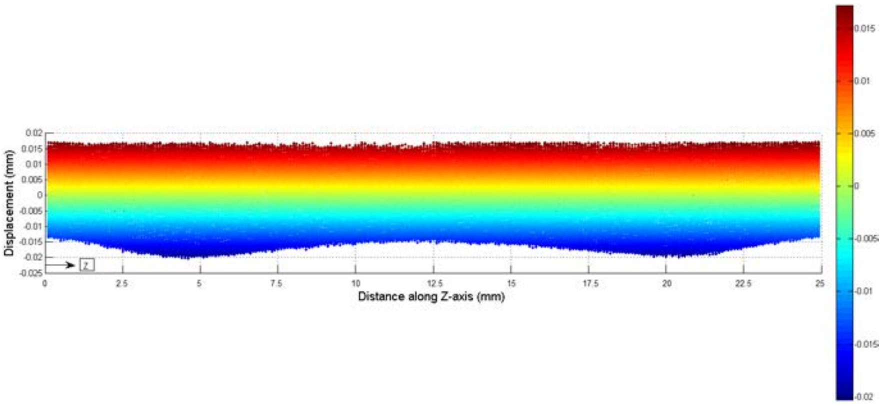


6d

Figure 6. Contour method isometric views of averaged displacement data from both surfaces. (a). Axis definition. (b). As-welded. (c). Ultrasonically peened. (d). Ultrasonically peened and subjected to accelerated corrosion testing.

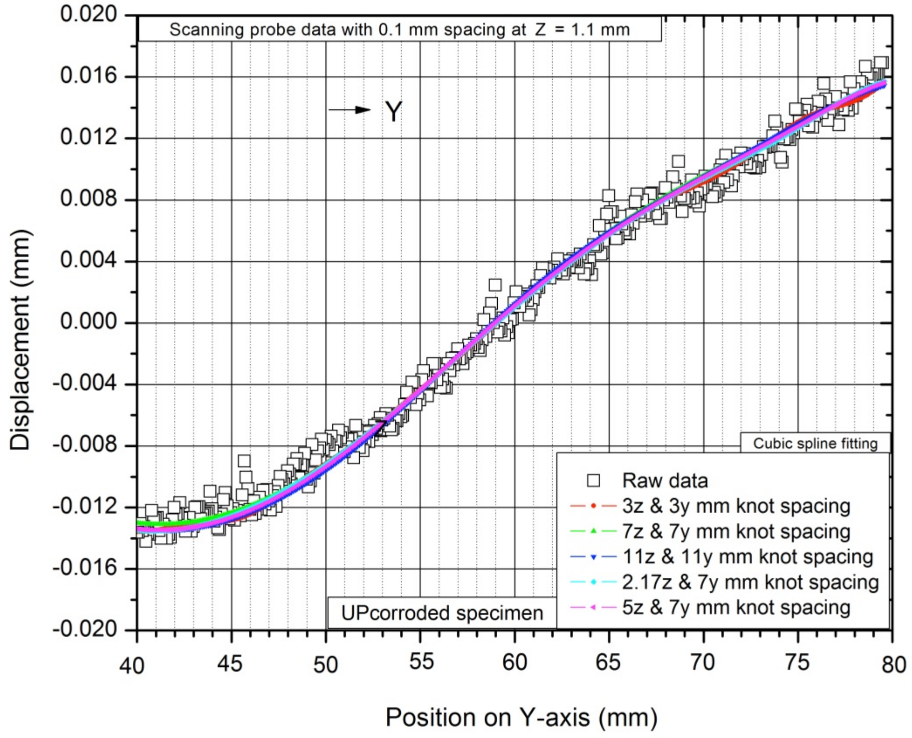


7a

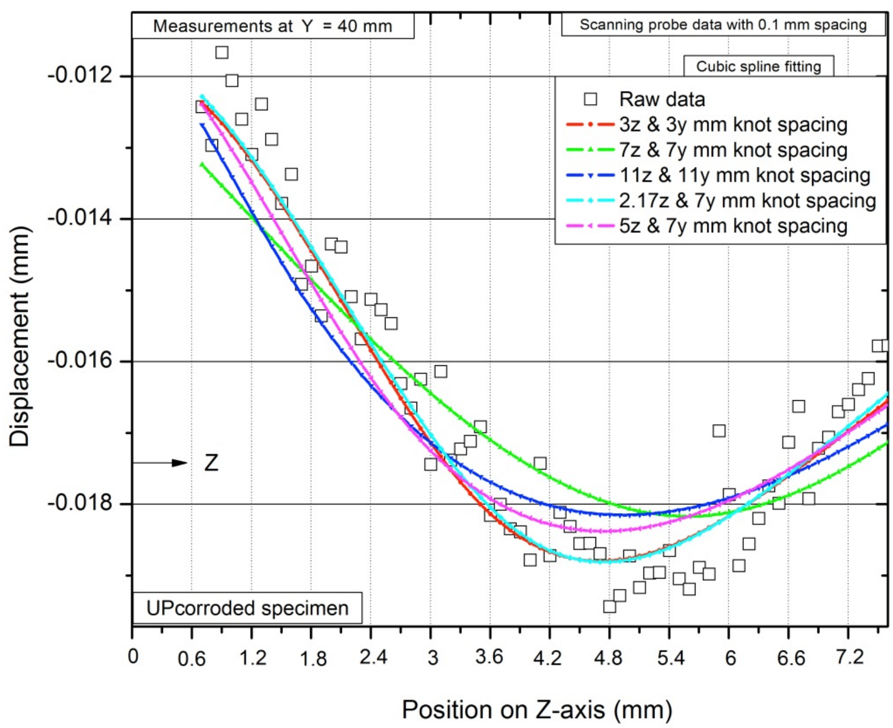


7b

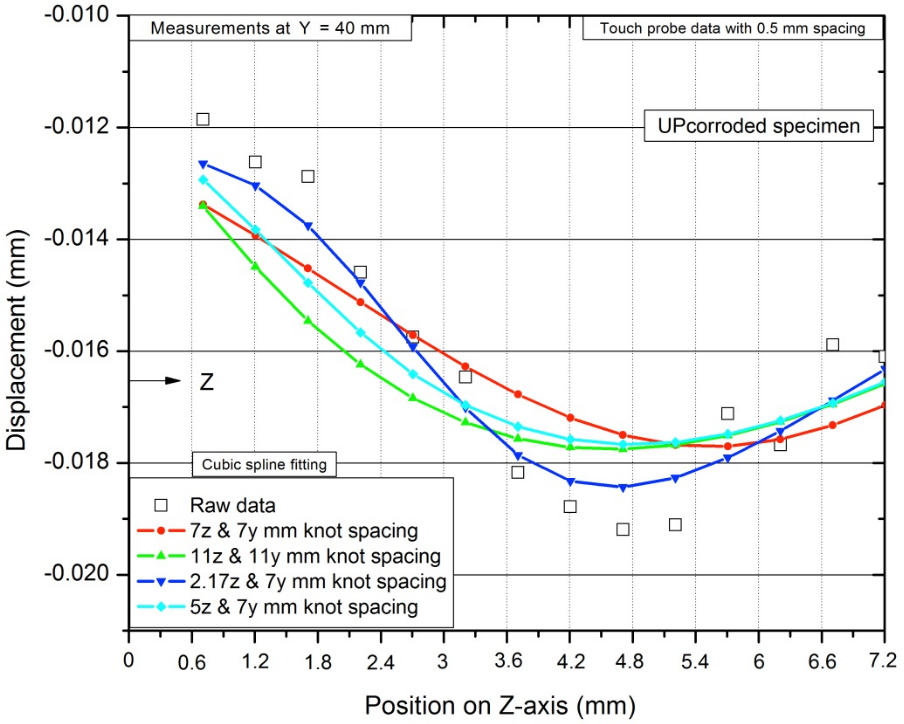
Figure 7. Contour method averaged and flattened displacement data for the cut surface of the ultrasonically-peened sample subjected to corrosion exposure as a function of position through the thickness (i.e. along the Z-axis) (a). CMM touch probe data with 3 mm diameter (b). CMM scanning probe data with 4 mm diameter


Scanning probe data with 0.1 mm spacing at Z = 1.1 mm
Y
Cubic spline fitting
Raw data
3z & 3y mm knot spacing
7z & 7y mm knot spacing
11z & 11y mm knot spacing
2.17z & 7y mm knot spacing
5z & 7y mm knot spacing
UPcorroded specimen
Displacement (mm)
Position on Y-axis (mm)

8a


Measurements at Y = 40 mm
Scanning probe data with 0.1 mm spacing
Cubic spline fitting
Raw data
3z & 3y mm knot spacing
7z & 7y mm knot spacing
11z & 11y mm knot spacing
2.17z & 7y mm knot spacing
5z & 7y mm knot spacing
Z
UPcorroded specimen
Displacement (mm)
Position on Z-axis (mm)

8b



8c

Figure 8. Contour method averaged displacement data fitting (a) through-thickness (Z-axis) and (b) through-width (Y-axis) with 0.1 mm measurement density; (c) through-thickness (Z-axis) with 0.5 mm measurement density.

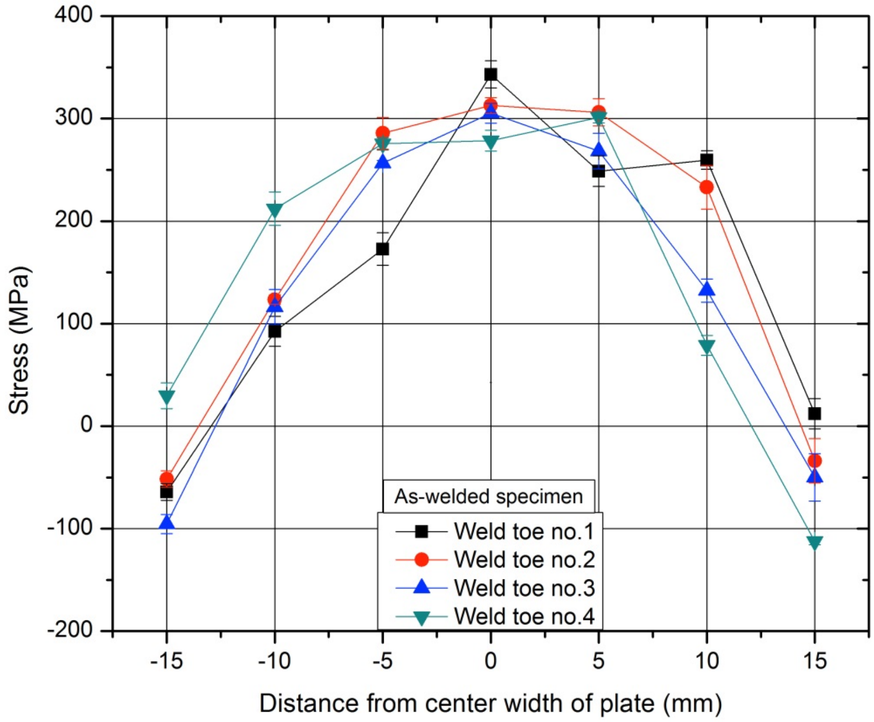


Figure 9. Longitudinal (σ_X) surface residual stress profile at the four weld toe locations, as a function of distance from the center width of the plate, along the Y-axis (i.e. across the specimen width), as measured by XRD

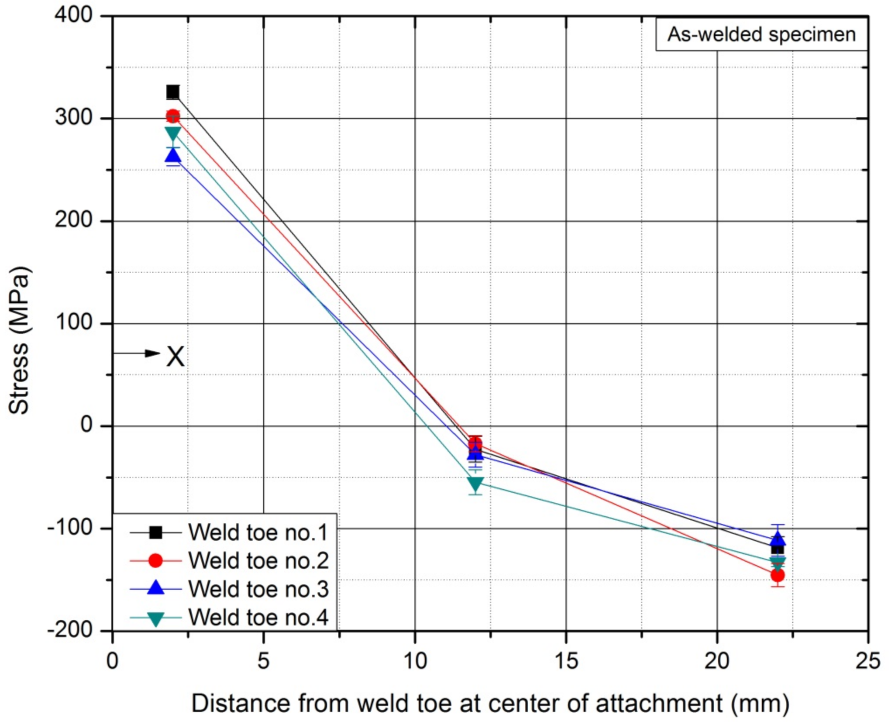
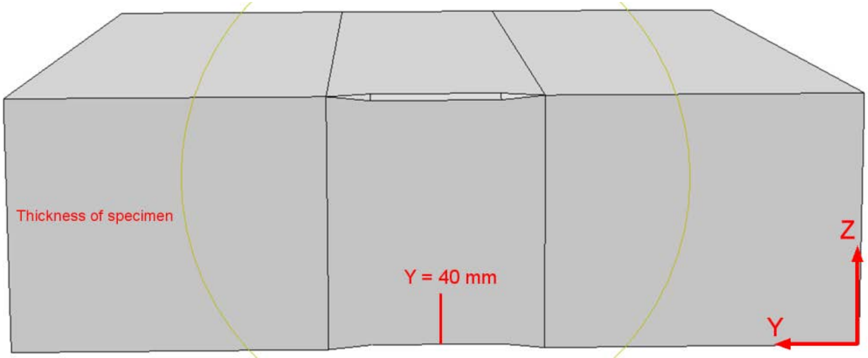
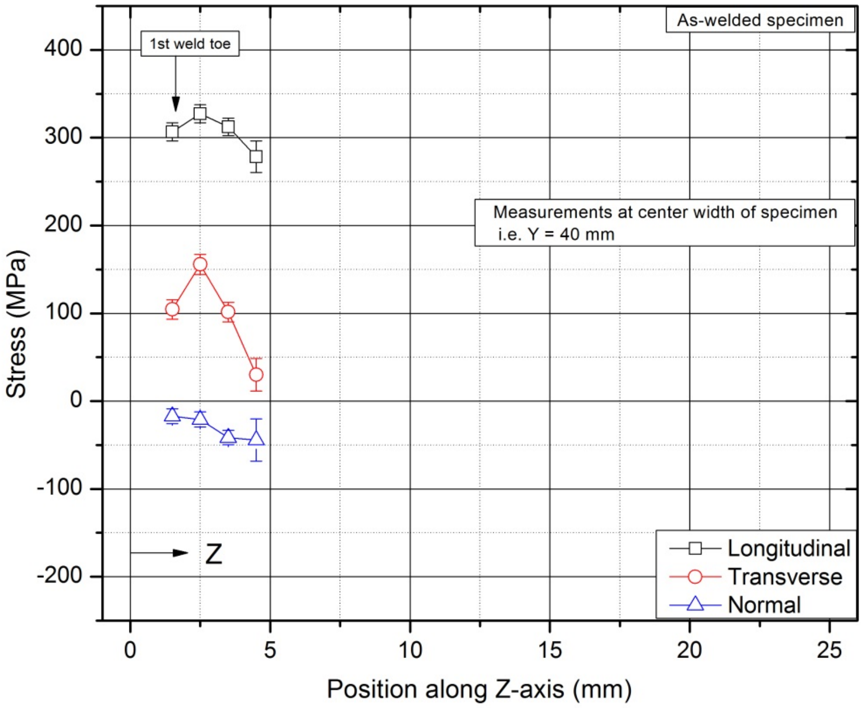


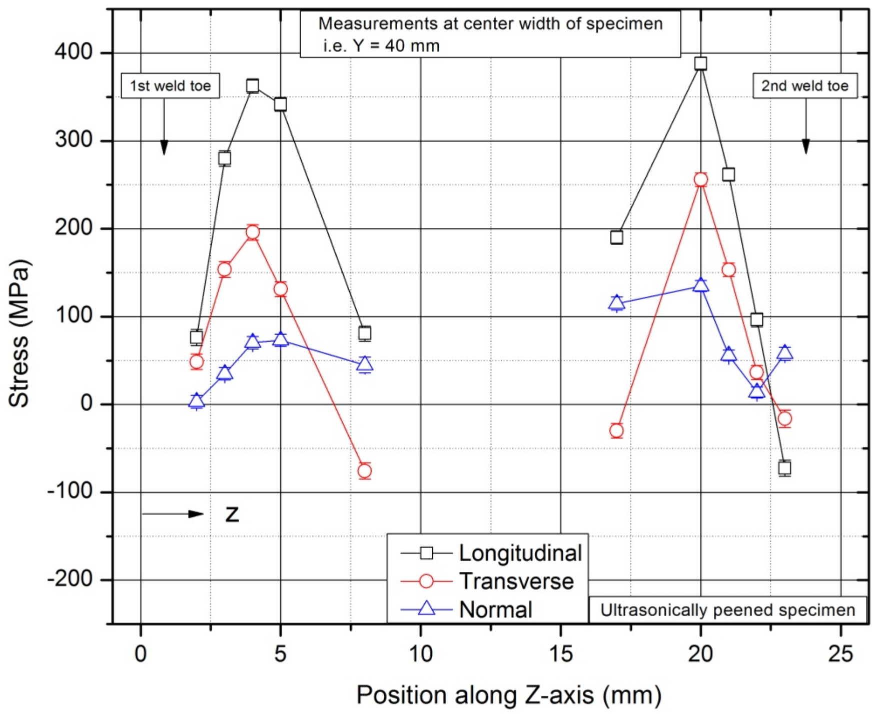
Figure 10. Longitudinal (σ_X) surface residual stress distribution as a function of distance from the weld toe along the length (X-axis) of the as-welded sample, as measured by XRD


Thickness of specimen
Y = 40 mm
Z
Y

11a

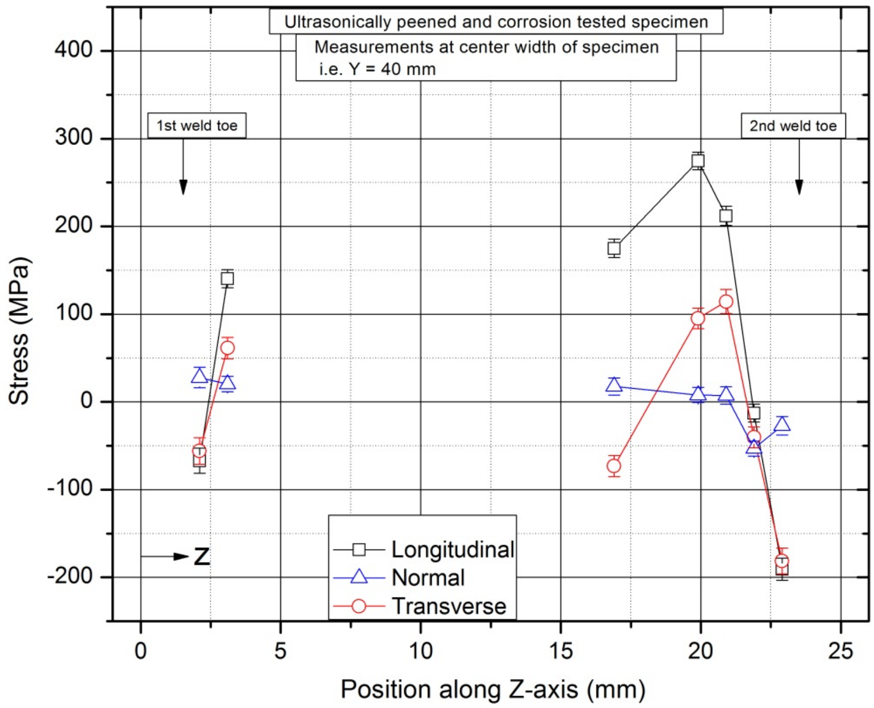

As-welded specimen
1st weld toe
Measurements at center width of specimen
i.e. Y = 40 mm
Stress (MPa)
Position along Z-axis (mm)
Z
Longitudinal
Transverse
Normal

11b



Measurements at center width of specimen
i.e. Y = 40 mm
1st weld toe
2nd weld toe
Z
Longitudinal
Transverse
Normal
Ultrasonically peened specimen
Stress (MPa)
Position along Z-axis (mm)

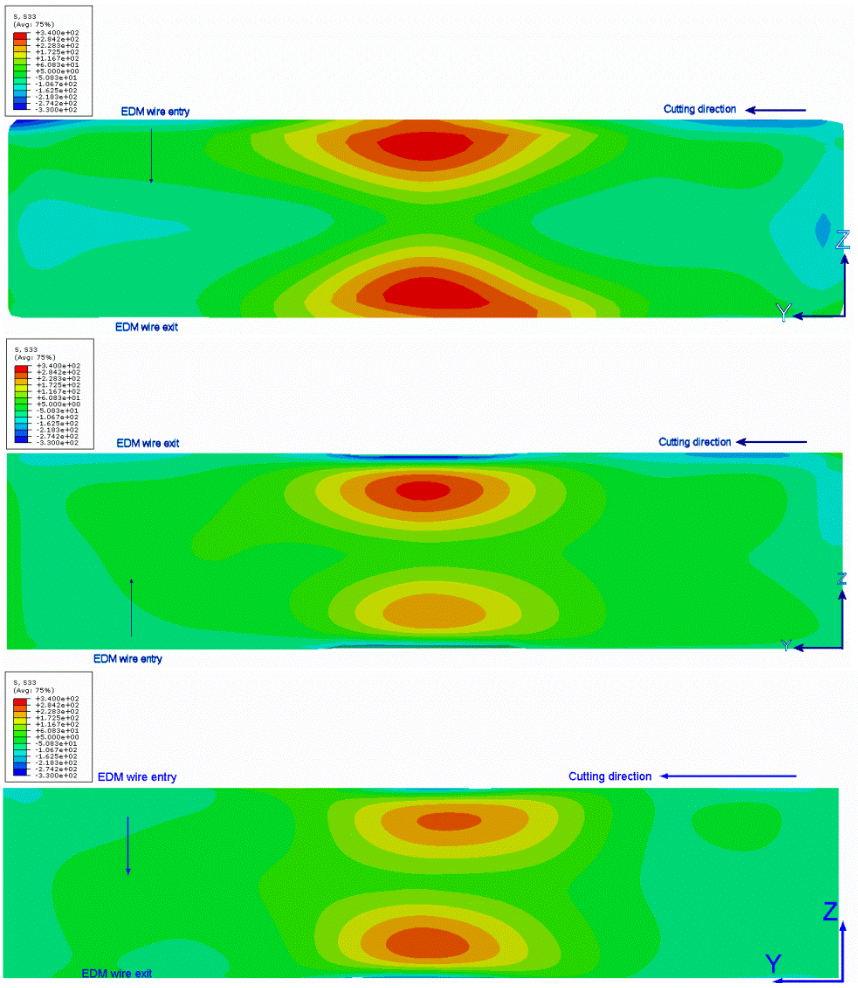
11c



Ultrasonically peened and corrosion tested specimen
Measurements at center width of specimen
i.e. Y = 40 mm
1st weld toe
2nd weld toe
Z
Longitudinal
Normal
Transverse
Stress (MPa)
Position along Z-axis (mm)

11d

Figure 11. Through-thickness residual stress profile measured by neutron diffraction between the weld toes. (a) Axis and origin definition. (b) As-welded. (c) Ultrasonically peened. (d) Ultrasonically peened and accelerated corrosion exposed.

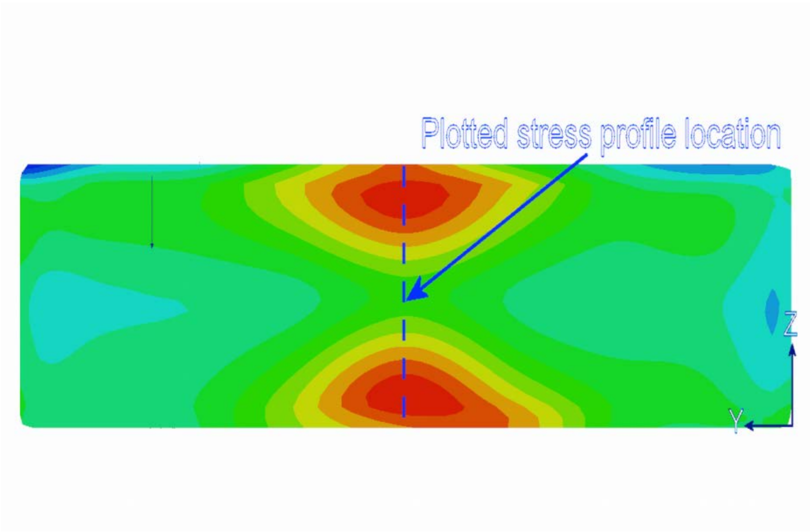


12a

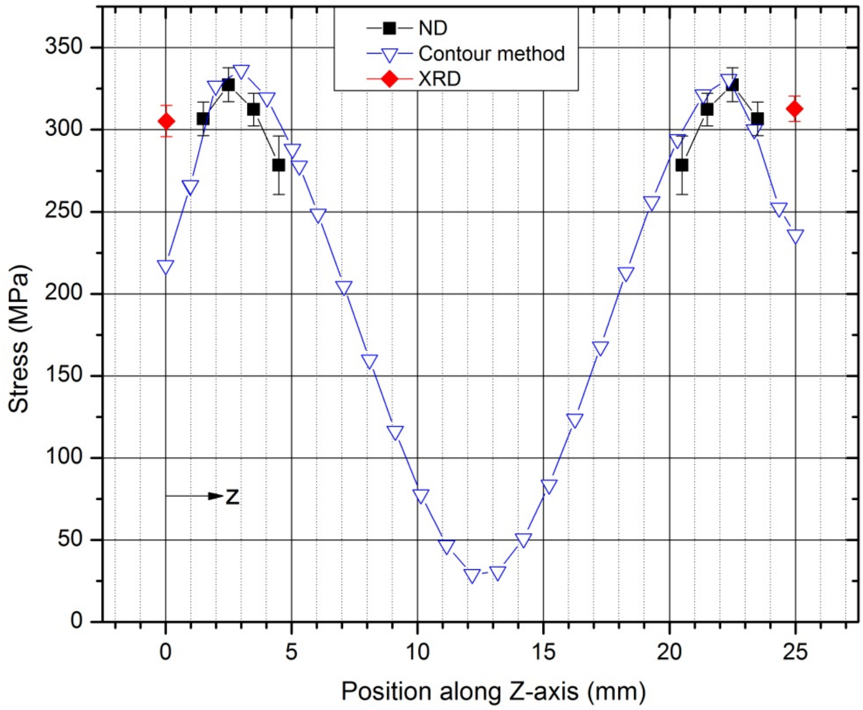
12b

12c

Figure 12. Contour method residual stress maps for the longitudinal σ_X stress component. (a) As-welded. (b) Ultrasonically peened. (c) Ultrasonically peened and accelerated corrosion exposed.



13a



13b

Figure 13. Contour method residual stress profile from the as-welded sample as a function of position through the thickness at the center width from the weld toe, and comparison with neutron diffraction and surface XRD results. (a) Measurement location. (b) Results for the σ_X stress component.

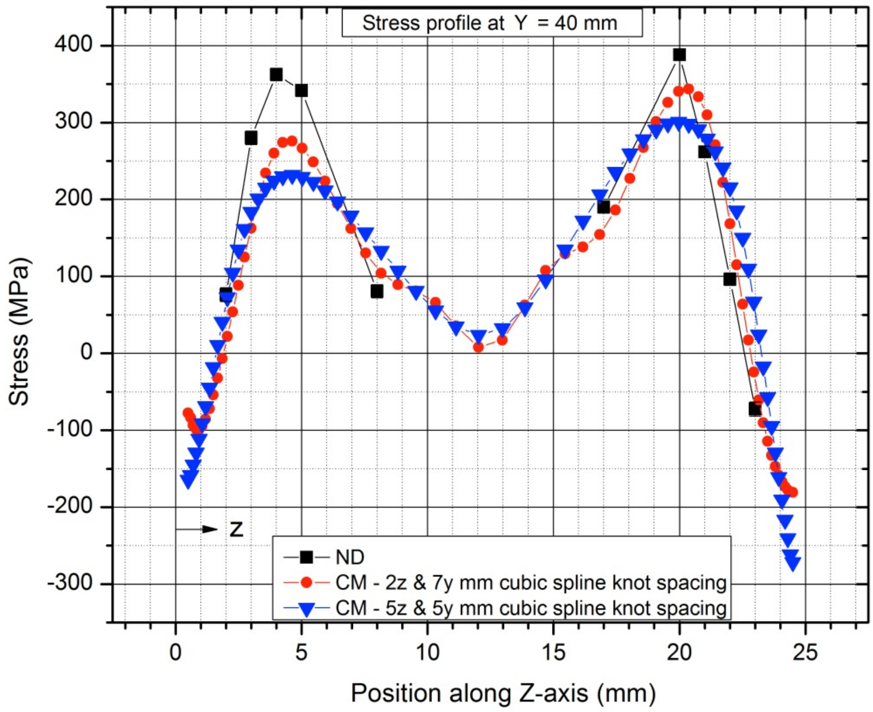
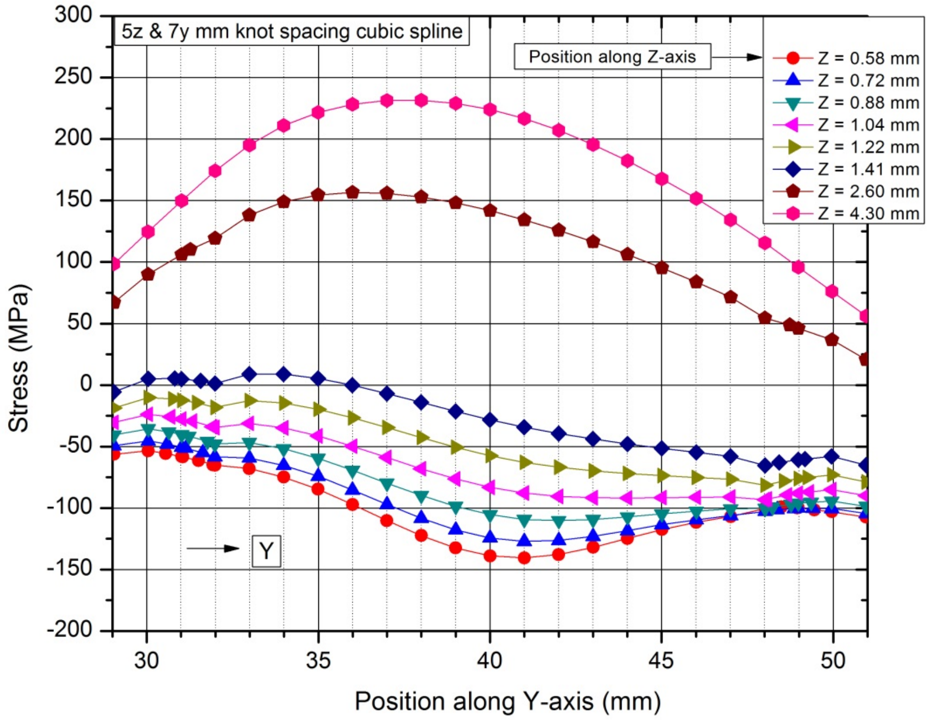
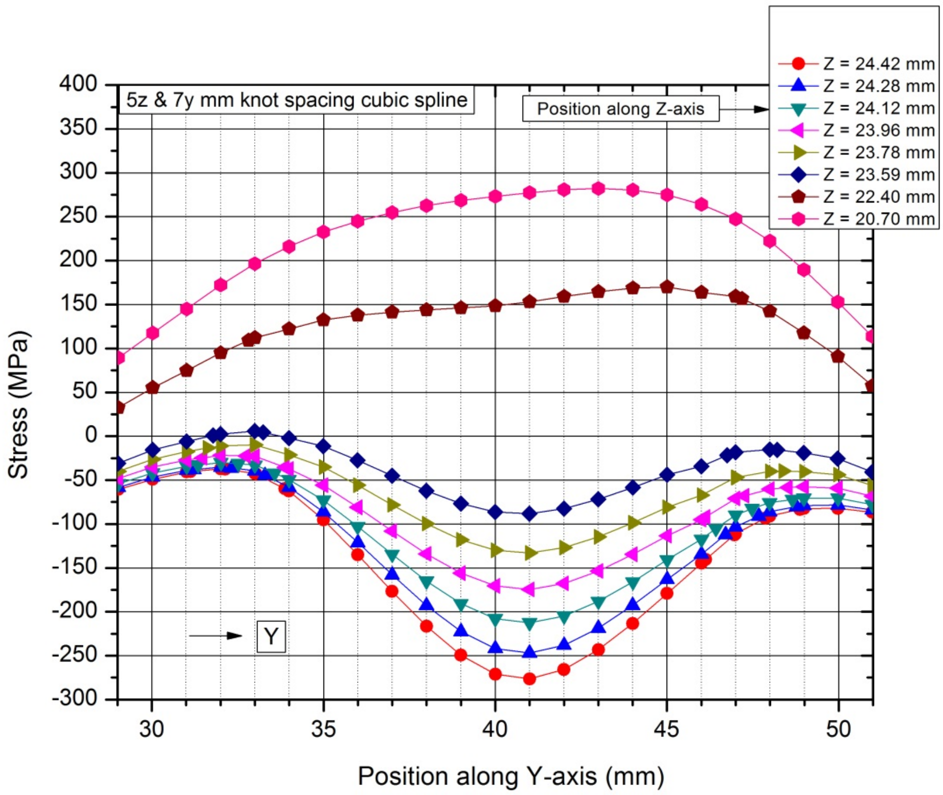


Figure 14. Contour method line profiles of the longitudinal σ_X component of residual stress in the ultrasonically-peened sample as a function of position through the thickness at the center width (as in figure 13a), and comparison with neutron diffraction (ND)


5z & 7y mm knot spacing cubic spline
Position along Z-axis
Z = 0.58 mm
Z = 0.72 mm
Z = 0.88 mm
Z = 1.04 mm
Z = 1.22 mm
Z = 1.41 mm
Z = 2.60 mm
Z = 4.30 mm
Y
Stress (MPa)
Position along Y-axis (mm)

15a


5z & 7y mm knot spacing cubic spline
Position along Z-axis
Z = 24.42 mm
Z = 24.28 mm
Z = 24.12 mm
Z = 23.96 mm
Z = 23.78 mm
Z = 23.59 mm
Z = 22.40 mm
Z = 20.70 mm
Y
Stress (MPa)
Position along Y-axis (mm)

15b

Figure 15. Contour method stress line profiles below the two weld toes in the ultrasonically-peened sample. The results show the longitudinal σ_X residual stress profile across the plate width (along the Y-axis), below the peened groove. The different line plots are at different depths (along the Z-axis) below the specimen surface. The sample surfaces are at z = 0 and z = 25 mm. Axis system as in figure 13a.

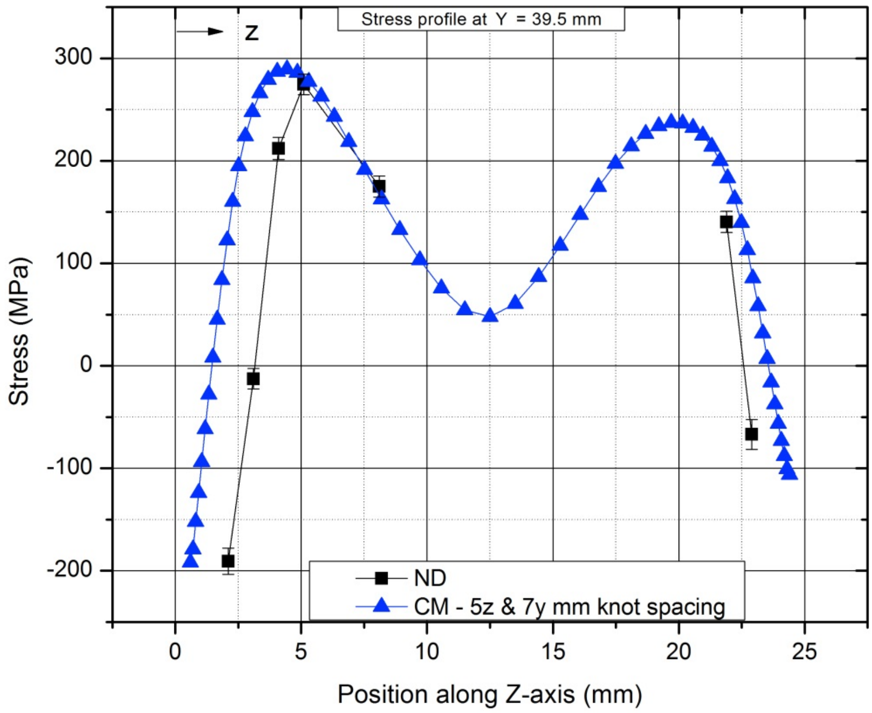
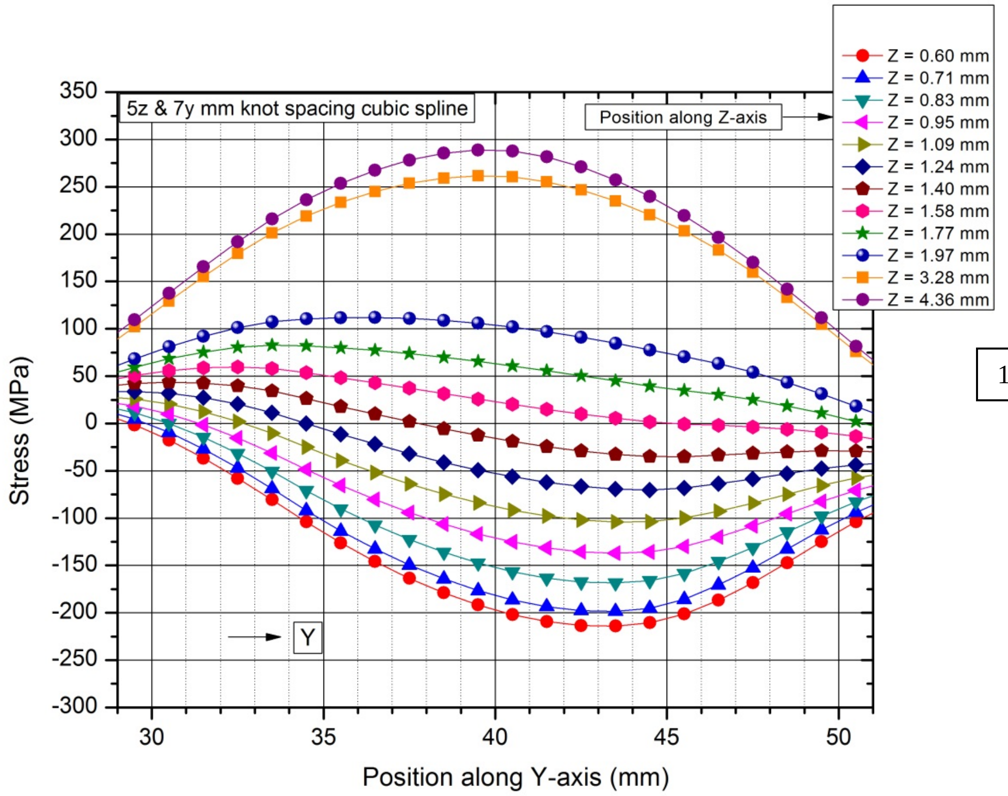
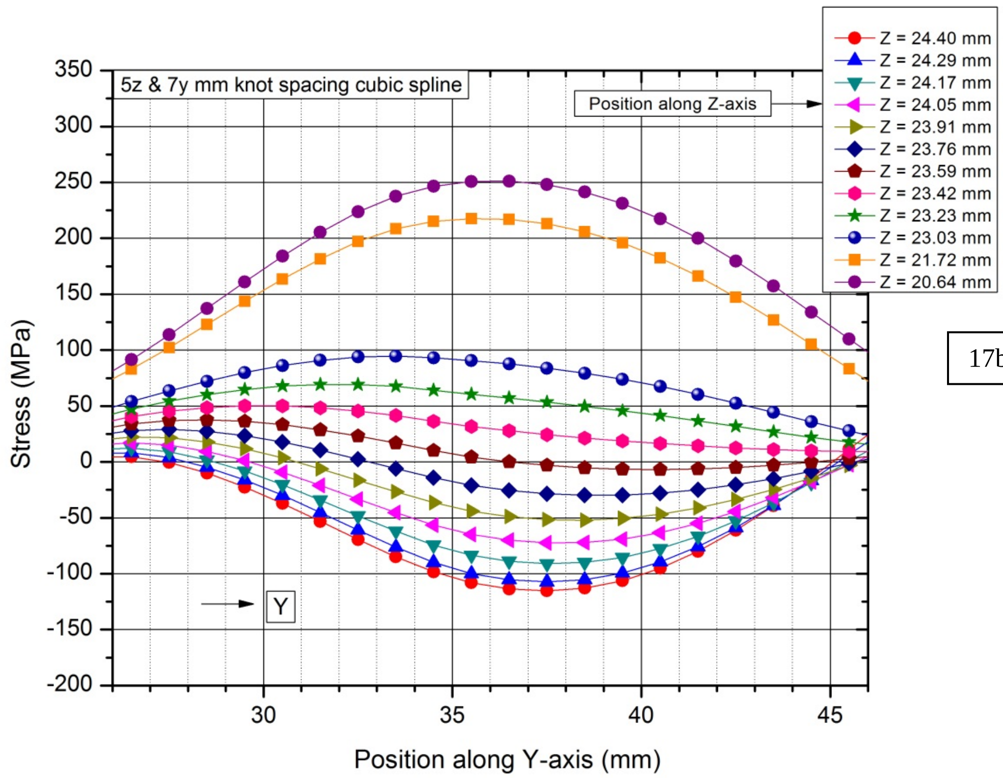


Figure 16. Contour method line profile of the longitudinal σ_X component of residual stress in the peened and corrosion exposed sample as a function of position through the thickness at the center width (as in figure 13a), and comparison with neutron diffraction (ND).



17a



17b

Figure 17. Contour method stress line profiles below the two weld toes in the sample that was corrosion-exposed following ultrasonic peening. The results show the longitudinal σ_X residual

stress profile across the plate width (along the Y-axis), below the peened groove. The different line plots are at different depths (along the Z-axis) below the specimen surface. The sample surfaces are at z = 0.5 and z = 24.5 mm. Axis system as in figure 13a.

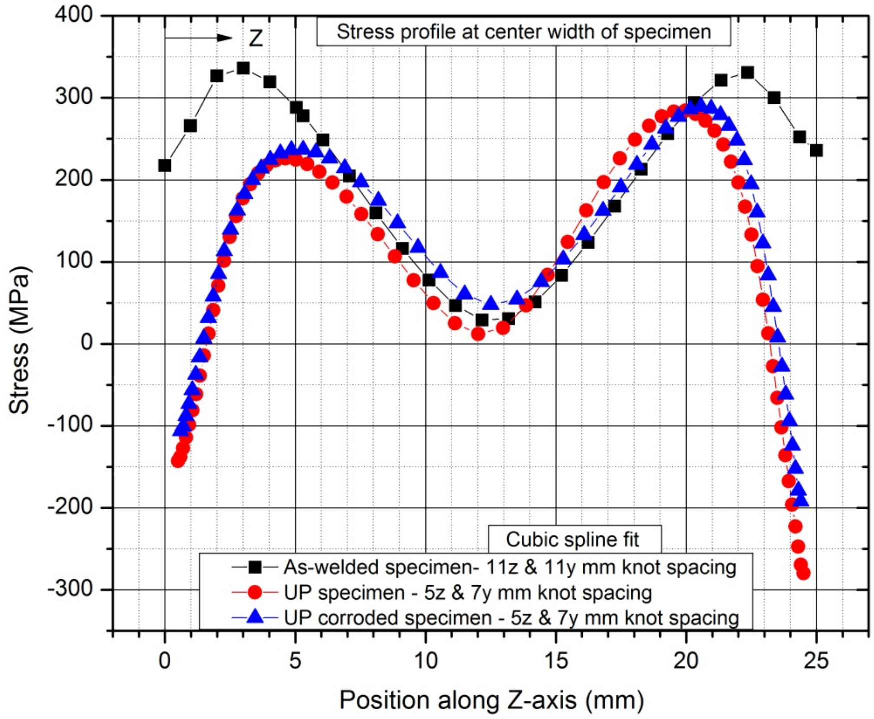


Figure 18. Comparison of contour method residual stress line profiles of the as-welded, ultrasonically peened and corrosion exposed samples. The results show the longitudinal σ_X component of residual stress as a function of position through the thickness at the center width (as in figure 13a).