Analysis of Residual Stresses in Laser-Shock-Peened and Shot-Peened Marine Steel Welds

BILAL AHMAD and MICHAEL E. FITZPATRICK

Laser peening is now the preferred method of surface treatment in many applications. The magnitude and depth of the compressive residual stress induced by laser peening can be influenced strongly by the number of peen layers (the number of laser hits at each point) and by processing conditions including the use of a protective ablative layer. In this study, residual stresses have been characterized in laser and shot-peened marine butt welds with a particular focus at the fatigue crack initiation location at the weld toe. X-ray diffraction, synchrotron X-ray diffraction, incremental center-hole drilling, and the contour method were used for determination of residual stress. Results showed that the use of ablative tape increased the surface compressive stress, and the depth of compressive stress increased with an increase in number of peening layers. A key result is that variation of residual stress profile across laser peen spots was seen, and the residual stress magnitude varies between the center and edges of the spots.

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I. INTRODUCTION

COMPRESSIVE residual stress has a beneficial effect on fatigue life. For surface treatments aimed at inducing a compressive residual stress, key parameters include the magnitude and the depth of the compressive stress. Conventionally shot peening has been used to improve the fatigue life of structural members. Laser shock peening (LSP) is a relatively new technique that is already being deployed widely for aeroengine components, and that is being optimized with regard to process parameters for its application to different materials.

Laser peening uses a high power density laser beam that is pulsed on to a metal surface that is covered by a water layer and which may also be protected by paint or tape with thickness around 100 μm[1] which then acts as an ablative layer, to protect the metal surface from thermal effects.[2] The laser energy vaporizes the surface layer to form a plasma. The pressure of the plasma rises as the laser pulse continues, and it is confined by the water layer to create a shock wave that plastically strains the near-surface material.[3] The elastic relaxation of the surrounding material then forces the surface material into compression. The depth of plastic deformation and the resulting compressive residual stress is significantly greater than most other surface treatment techniques. Laser peening imparts compressive residual stress to a depth of 1 to 4 mm and the near-surface magnitude of the residual stress can approach the material's yield strength. Multiple layers of peening are commonly used to ensure a uniform stress distribution, with subsequent layers offset to the first layer.[2,4] While some early studies on laser peening implied that the absence of an ablative layer would always lead to tensile residual stress at the surface of a sample, more recent work has shown that this is not necessarily the case, and surface compression can be obtained even in the absence of an ablative layer.[5]

Shot peening is the process of bombardment of a surface with small spherical media called shot. The shots are usually made of steel, glass *etc*., and the diameter of shot is typically 0.5 to 1.5 mm. Shot peening involves multiple and repeated impacts. Each shot striking the metal yields the material in tension, and when the elastically strained material below the surface relaxes it pushes the surface material into compression. The magnitude of compressive stress is directly related to the yield strength of the base material, and typically reaches 80 pct of that value. Complete coverage of the shot-peened area is critical for high-quality treatment, as fatigue and stress corrosion cracks can initiate in any non-peened area. The intensity of residual stress can be increased by the use of larger media and by increasing the velocity of the shot stream.[6]

For the butt-welded samples studied in this paper, it was found previously by fatigue testing in the as-welded condition that cracks initiated, in the absence of a welding flaw, at the toe of the weld crown.[7] In this study, the application of laser peening and shot peening have been studied in respect of the mitigation of the tensile residual stresses associated with the weld and local variations in the residual stress from laser peening. For residual stress characterization of these samples the

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BILAL AHMAD, Research Associate, and MICHAEL E. FITZPATRICK, Professor, Lloyd's Register Foundation Chair in Structural Integrity and Systems Performance, formerly with the Department of Engineering and Innovation, The Open University, Walton Hall, Milton Keynes, MK7 6AA, UK, are now with the Centre for Manufacturing and Materials Engineering, Coventry University, Priory Street, Coventry CV1 5FB, UK. Contact e-mail: michael.fitzpatrick@coventry.ac.uk
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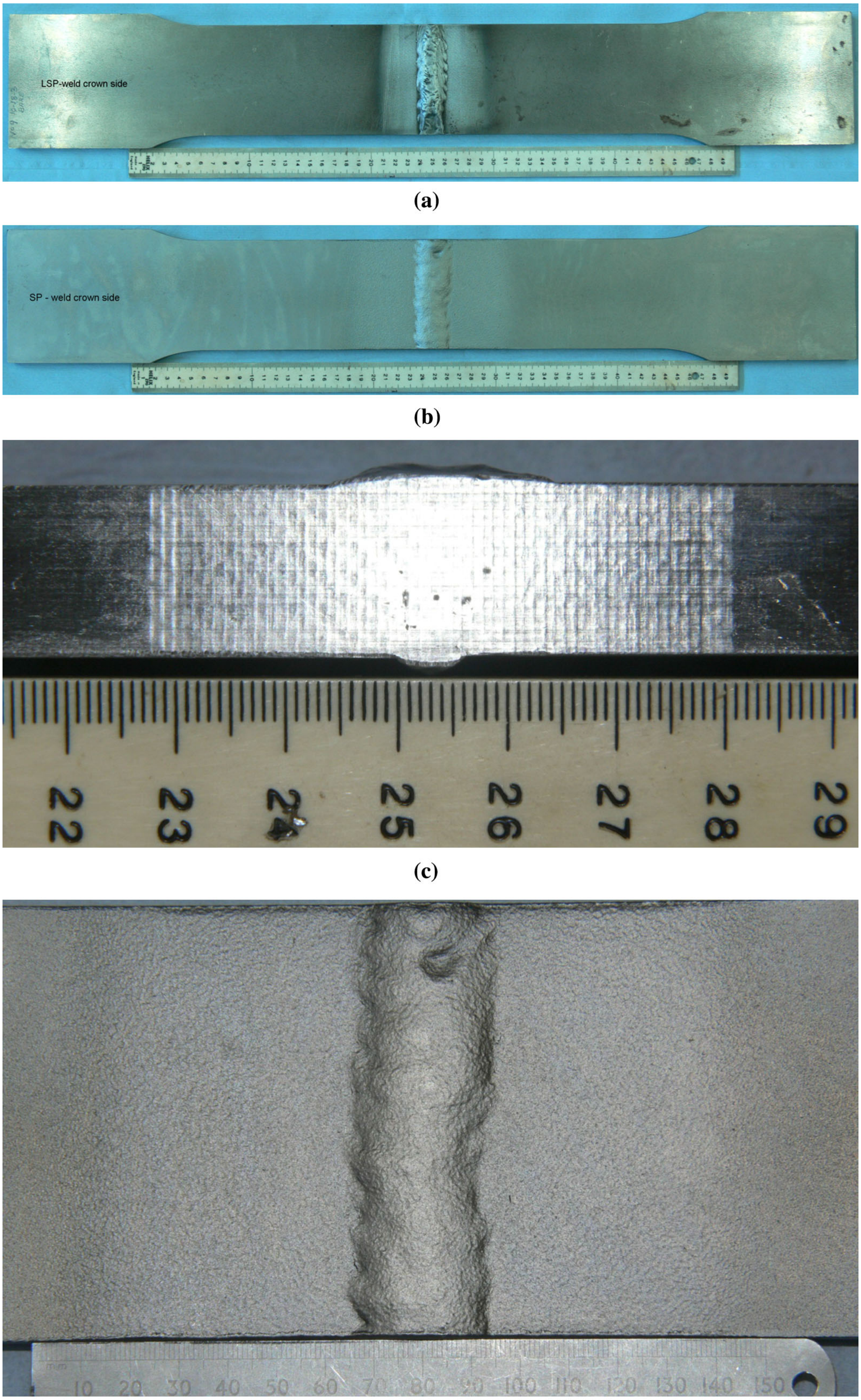

Fig. 1—Butt-welded ship structural steel samples: (*a*) Laser-peened butt-welded sample, showing the weld crown; (*b*) Shot-peened butt-welded sample, showing the weld crown; (*c*) Close-up of the laser-peened surface; (*d*) Close-up of the shot-peened weld crown.

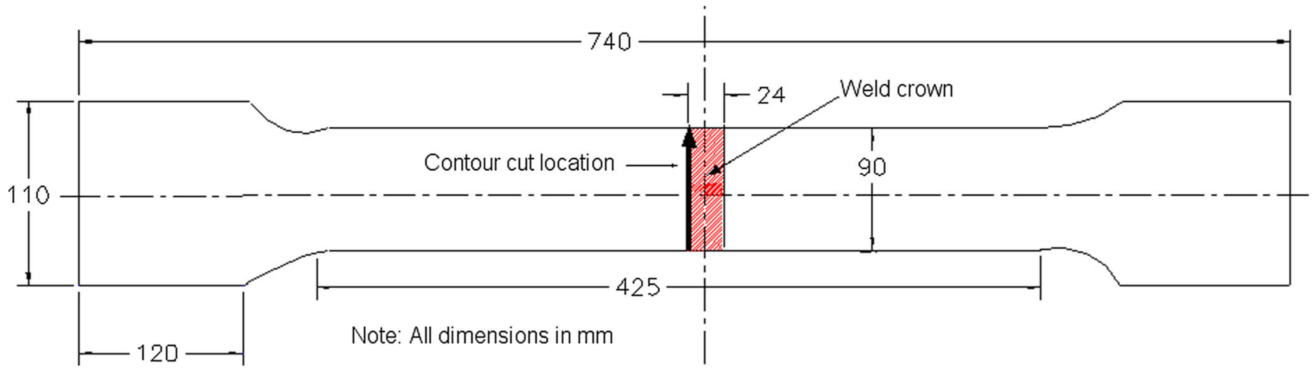

Fig. 2—Contour cut location at the weld crown toe of the butt-welded samples.

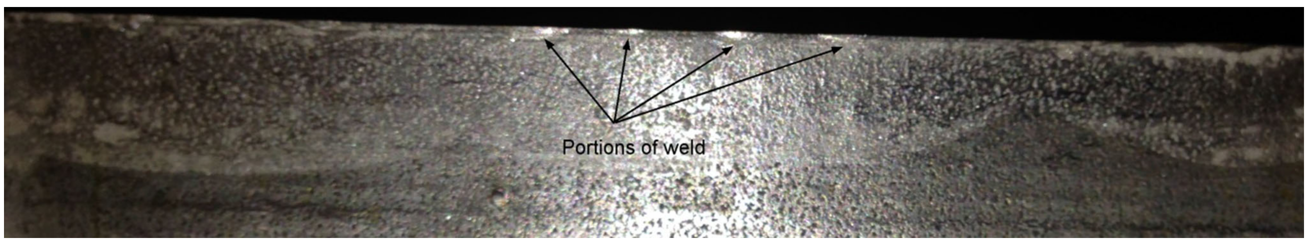

Fig. 3—Contour cut surface showing regions of the weld material.

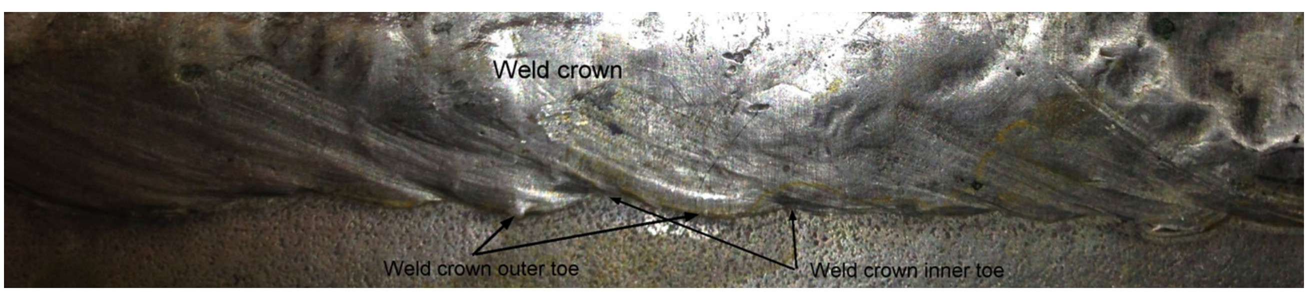

Fig. 4—Weld toe geometry on weld crown side of the sample laser peened with two layers.

near- and on-surface stresses were measured by synchrotron X-ray diffraction (SXRD), conventional X-ray diffraction (XRD), and incremental center-hole drilling (ICHD). The contour method and neutron diffraction were applied to determine the through-thickness residual stress distribution. Synchrotron X-ray diffraction measurements were performed using the EDDI instrument at BESSY II, Berlin.[8]

II. SAMPLE DETAILS

Butt-welded samples with 16-mm-thick base plate were provided by Lloyd's Register Group UK in conditions of laser and shot peened as shown in Figure 1. Laser and shot peening was carried out by Metal Improvement Company (MIC) UK. The material of the samples is carbon-manganese ship structural steel DH275. The yield and tensile strength of non-peened parent material was found to be 436 and 560 MPa, respectively.

Laser peening was performed as per SAE specification AMS2546 with the following details:Peened locations = Weld crown and root sides, and sample edges. Peened area on weld crown and root side = 53×90 mm^2; Peened area at edges = 53×16 mm^2; Laser spot size = 3×3 mm^2; Laser power density = 10 GW/cm^2; Energy = 16.2 J; Pulse width = 18 ns.

Two types of laser peening were used: one sample was peened with three successive layers of peening, without ablative tape covering, and the other was peened with two layers, with an ablative tape.

Shot peening was performed as per MIC process D0311 ISSA with the following details:Peened locations = Weld crown and root sides, and sample edges; Peened area at weld crown and root face sides = 136×90 mm^2; Peened area at edges = 256×16 mm^2.

III. EXPERIMENTAL SETUP AND PROCEDURE

A. *Contour Method Measurement Setup*

The contour method[4,9,10] was applied to determine the sample longitudinal residual stress at the weld crown toe location as shown in Figure 2 (dimensions in mm).

The samples were clamped to restrain movement during the cutting. Steel sacrificial layers were used at the EDM wire entry and exit locations as well as at the start and end of the cut. The WEDM cutting conditions/parameters used for these samples are discussed elsewhere.[11] The weld crown toe geometry is not smooth and straight, as shown in Figure 3, while the contour cut has to proceed in a perfectly straight path. Therefore, the contour cut at some locations along the cut path passed through portions of the weld as shown in Figure 3. Two regions of the weld crown toes were defined as extremes of this feature—*i.e.*, inner and outer weld toes—as shown in Figure 4. The inner toe location was the focus for the contour cutting of the two-laser-peen layer and the shot-peened samples. For the contour cutting of the laser-peened three-layer sample, the focus was on the outer weld toe location, and therefore for that sample, there was no remnant portion of weld on the cut halves. It is important to know the exact location through which the WEDM cut passes in order to correctly interpret the contour method results.

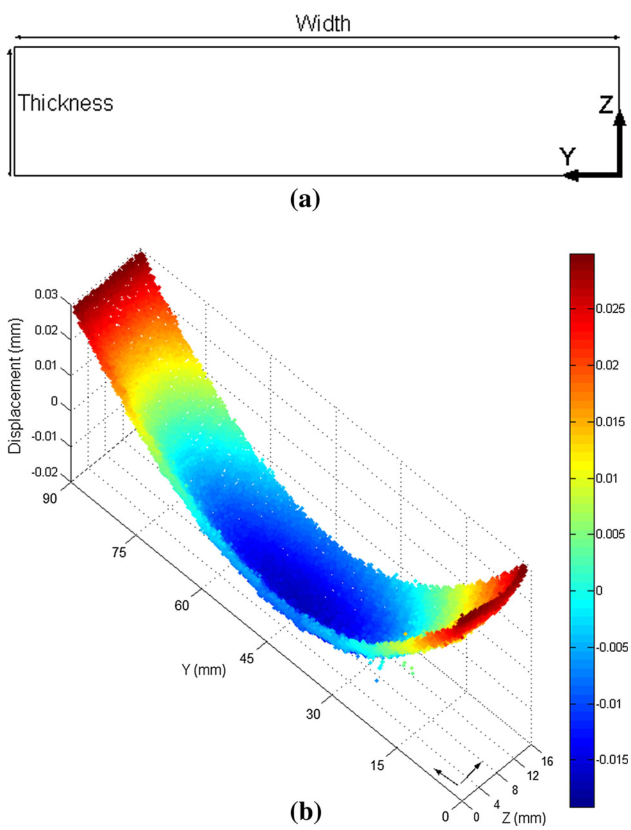

Fig. 5—(*a*) Axis definition and (*b*) Averaged displacement data of the three-layer-peen LSP sample.

The contour cut surfaces were subjected to cleaning in an ultrasonic bath to remove any deposited debris from the WEDM cutting chamber. The surface displacement data of the contour cut surfaces of the two-laser-peen layer and the shot-peened sample were measured with a coordinate measuring machine using a Mitutoyo CrystaPlus 574 coordinate measuring machine (CMM) with a Renishaw PH10M touch trigger probe of 3 mm diameter, whereas for the LSP-3 peen layer sample, a 1-mm-diameter touch probe was used. The measurement point density in both directions as well as the distance from the edges was set as 0.2 mm.

The displacement data of the contour cut surfaces were processed using a standard procedure for data aligning, averaging, cleaning, and flattening.[12] The processed displacement data for the three-laser-peen layer sample in isometric view are shown in Figure 5.

The processed displacement data of all three samples were corrected to take into account a cutting artifact for this material that meant the cut obtained in the stress-free condition was not macroscopically flat. The details of the convex shape WEDM cutting artifact observed through the sample thickness and its correction procedure are presented elsewhere.[11] The corrected displacement data were used to calculate the contour method stress results. Improvement of the displacement data near surface as well as at the mid-thickness of the sample was achieved by applying the correction.

The processed and corrected displacement data were smoothed and fitted by cubic splines with various knot spacings. The optimum cubic spline knot spacing is chosen by fitting the raw displacement data and

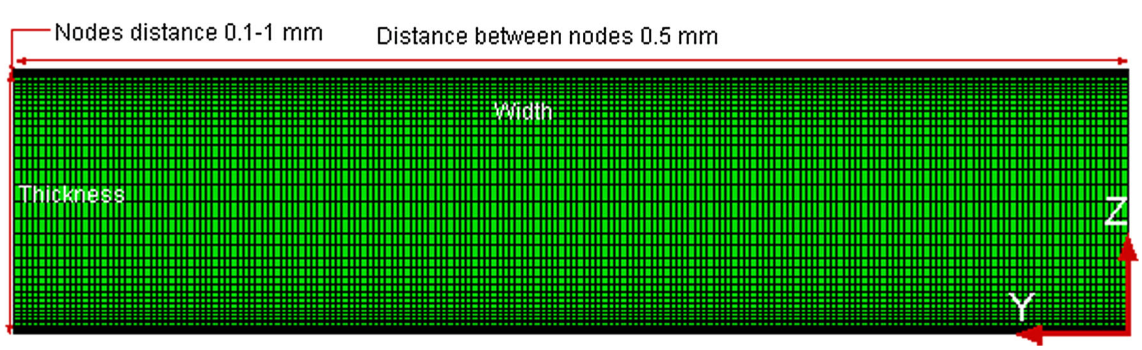

Fig. 6—FE model used for the butt-welded samples.

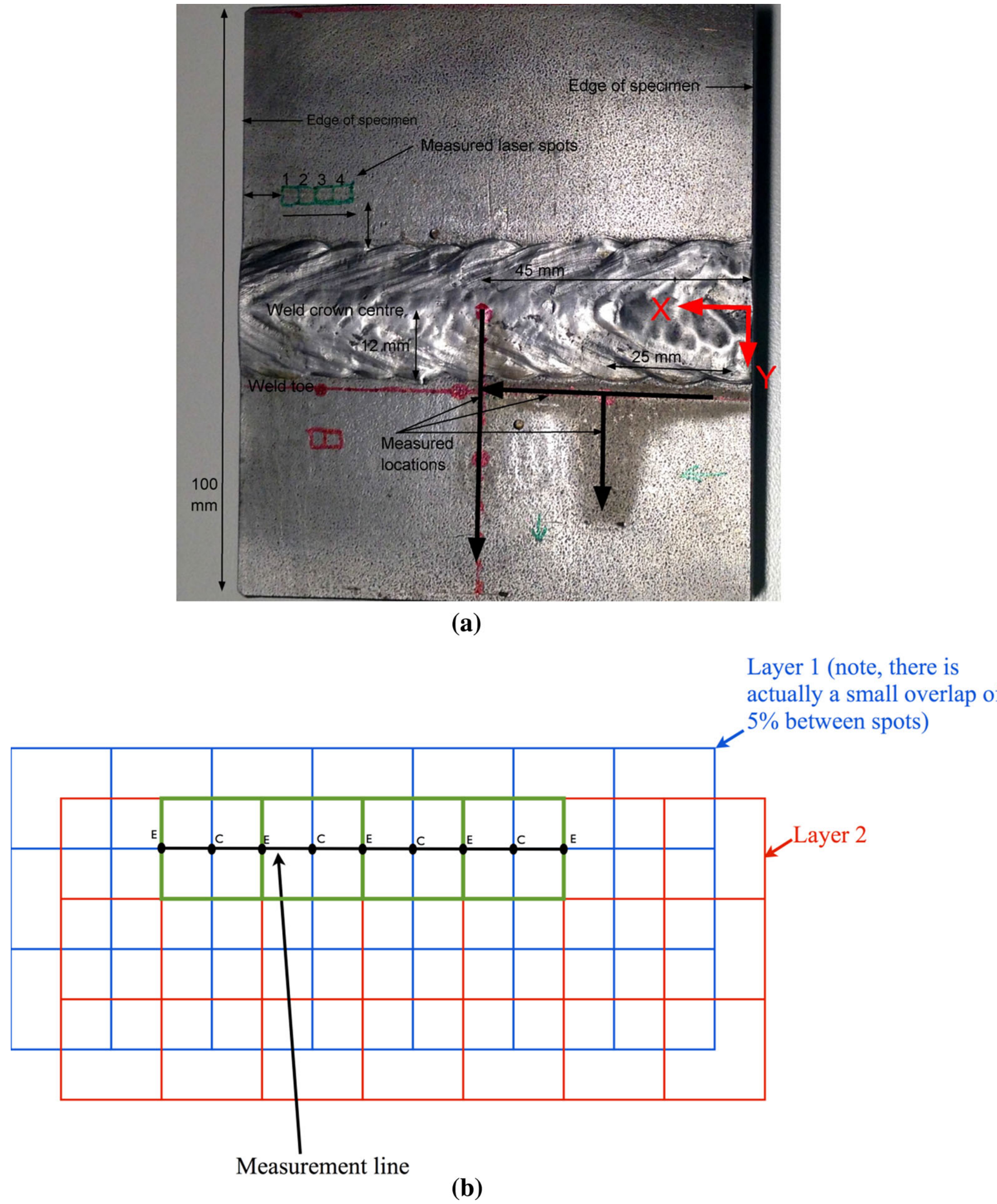

Fig. 7—(*a*) LSP-2 peen layer butt-welded sample and the measured locations; (*b*) Details of the peen pattern around the highlighted spots.

minimizing the stress uncertainty.[13] The processed and corrected displacement data were applied as displacement boundary conditions to a finite element (FE) model, using material elastic properties: modulus of elasticity $E = 210$ GPa and Poisson's ratio $v = 0.3$. Two boundary nodes along the Y and Z directions were constrained to avoid rigid body motion. A linear elastic FE analysis was performed to calculate the residual stress. A uniform FE mesh was used across the width (Y-axis) of the sample with a fixed distance between nodes of 0.5 mm. However, through the sample thickness (Z-axis), a non-uniform mesh was used with a distance between nodes in a range of 0.1 to 1 mm from the surface to the center thickness. A non-uniform mesh with a reduced distance between adjacent FE nodes (*i.e.,* a higher mesh density) was used at the near-surface locations on both sides of plate to improve the accuracy of the results in those regions where the stress was expected to have a high gradient.

The geometry and mesh used for the FE model is shown in Figure 6.

B. *Synchrotron X-ray Diffraction Measurement Setup*

Synchrotron X-ray diffraction measurements were carried out at BESSY II, Berlin, using the EDDI instrument.[8] The instrument is based on energy-dispersive diffraction and works in reflection geometry using the $\sin^2\psi$ technique. It uses a polychromatic (white) beam, and diffraction peaks are acquired from different

Table I. X-ray Energies Relevant to the hkl Planes

hkl	E (keV)
110	21.975
200	31.0772
211	38.062
220	43.950
310	49.138
222	53.828
321	58.140
411	65.925

lattice planes in the photon energy range of 10 to 80 keV. A laser and CCD camera are used for positioning control.

The length of the samples was reduced in order to facilitate the positioning and measurement on the diffractometer. The measurement locations on the two-layer LSP sample are shown in Figure 7.

Only the sample longitudinal (*i.e.*, weld transverse) stress component was measureable. The sample transverse (*i.e.*, weld longitudinal) stress component was not measureable owing to attenuation/absorption of the beam in the weld crown. The diffraction angle 2θ was fixed at 16 deg, and the φ angle was aligned with the θ

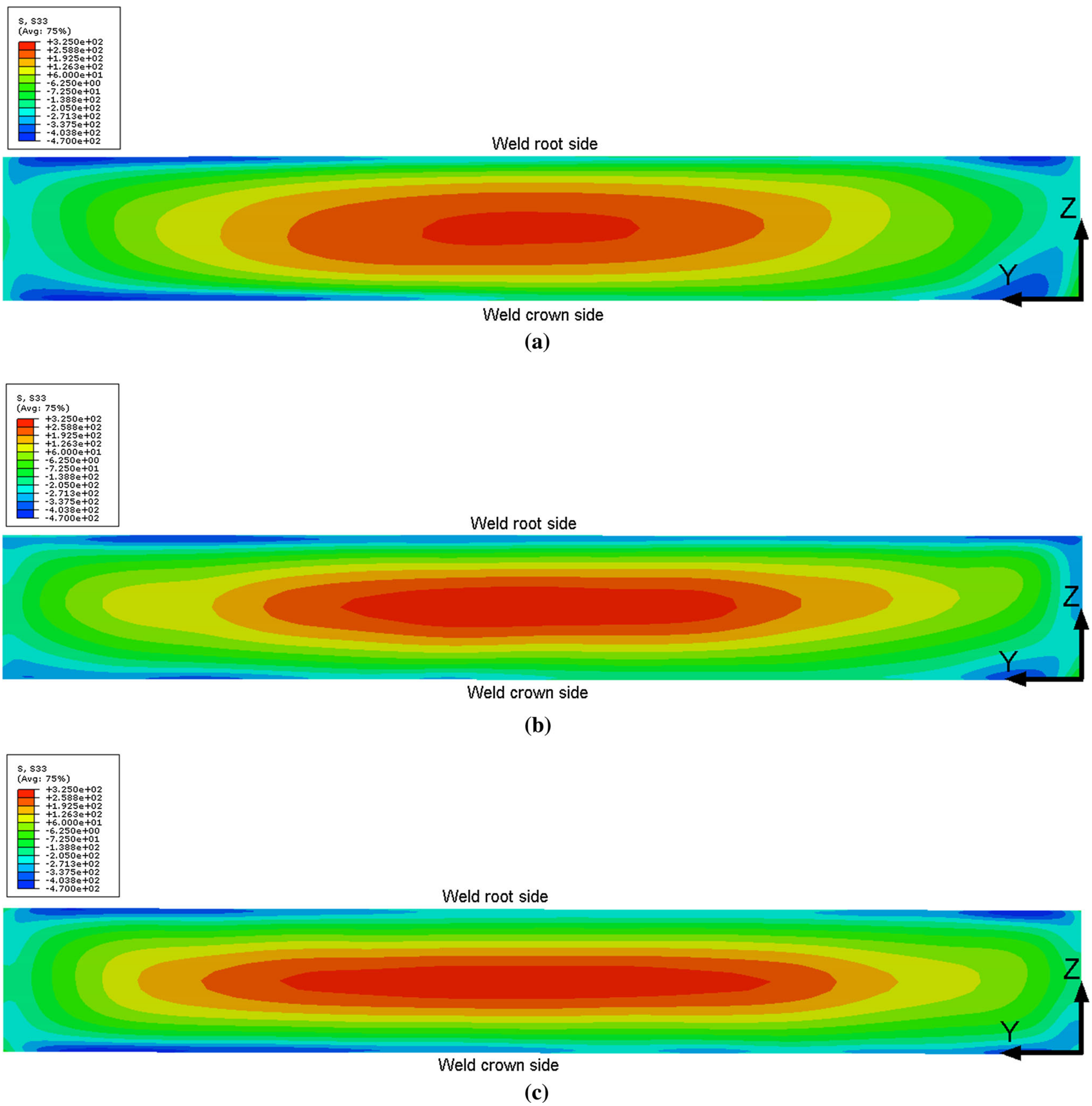

Fig. 8—Contour method stress maps for (*a*) Shot-peened, (*b*) LSP-2 peen layer, and (*c*) LSP-3 peen layer samples.

angle *i.e.*, 8 deg. 10 ψ tilts were used between 0 deg and 90 deg. The measurements were carried out along the weld crown toe (*X*-axis at $Y = 13$ mm from the weld crown center) and across the weld crown (*Y*-axis) from its center. Eight hkl lattice planes were selected for the ferritic steel.

The measured hkl planes and their corresponding energies are given in Table I.

For the incoming beam, a slit size of 0.5×0.5 mm^2 was used, and for the outgoing beam, a slit size of 30 µm was used. The peak fitting was performed with a pseudo-Voigt function. For measurements on the weld crown, owing to its shape, the instrument z-position was adjusted for each measured point. All measurements were performed on the weld crown side, and for the LSP-2 peen layer sample, the stress profile was also determined across the laser peen spots at the locations shown in Figure 7. In addition to obtaining the stress values from each individual hkl plane, with each representing a particular depth in the sample, an average stress value per single measurement point was also obtained by averaging the data of all eight hkl planes.

C. *X-ray Diffraction Measurement Setup*

For laboratory XRD measurements, a Stresstech XSTRESS-3000 X-ray diffractometer was used, which applies the $\sin^2\psi$ method of stress determination. For all three types of sample, the measurements were carried out at the center width of the plate. A 3-mm-diameter collimator was used, and measurements were conducted in accordance with the UK NPL Good Practice Guide.[14]

D. *Incremental Center-Hole Drilling Measurement Setup*

A Stresscraft driller was used for the incremental center-hole drilling (ICHD) measurements, with analysis software based on the integral method.[15,16] To measure near the weld crown toe of the butt-welded samples, a Vishay type B strain gage CEA-06-062UM-120 was selected. The hole diameter is 2 mm. The analyses were performed using Stresscraft analysis software versions RS INT v5.1.3 and v5.1.2. Measurements were conducted in accordance with the UK NPL Good Practice Guide.[16]

E. *Neutron Diffraction Measurement Setup*

The neutron diffraction experiment was conducted using the SALSA instrument at the Institut Laue Langevin, France, which is a monochromatic strain diffractometer.[17] A neutron wavelength of 1.7 Å was used for strain measurement at a scattering angle of 90 deg from the ferrite {211} lattice planes. For stress-free reference, d_0 cubes of size $3 \times 3 \times 3$ mm^3 were used. A gage volume of $0.6 \times 0.6 \times 2$ mm^3 was used for the d_0 cubes. For measurements in the sample, a gage volume of $0.6 \times 0.6 \times 10$ mm^3 was used for sample normal and longitudinal directions, whereas for the sample transverse direction, a gage volume of $0.6 \times 0.6 \times 2$ mm^3 was used. For sample normal and longitudinal stress components, the measurements were averaged over a distance of 10 mm along the width of sample, *i.e.*, along the length of the weld, for fast capture of strain data. For the sample transverse strain component the measurements were averaged over a reduced distance of 2 mm along the length of the sample.

IV. RESULTS AND DISCUSSION

A. *Through-Thickness Residual Stress Profiles*

The contour residual stress maps for the laser- and shot-peened samples are shown in Figure 8. The cutting direction was across the width of the sample (*Y*-axis) with the EDM wire travel direction through the thickness along the *Z*-axis. For comparison purposes, all the

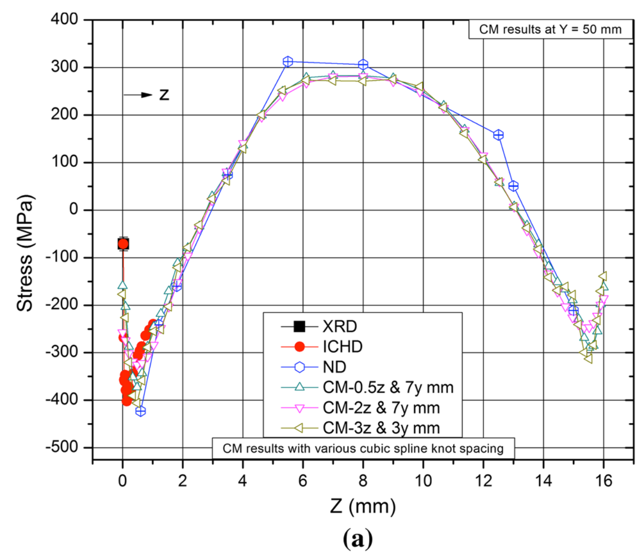

Fig. 9—Comparison of the contour method stress line profiles with XRD, ICHD, and neutron diffraction for the LSP-3 peen layer sample. (*a*) Through-thickness profile. (*b*) Detail of near-surface stresses.

stress maps were obtained with cubic spline knot spacing of 7 mm × 7 mm.

It can be seen that the depth of compressive stress induced by the laser peening process is deeper than the shot peening. The welding has created a tensile residual stress at the center of the samples that reduces toward the edges.

The contour method stress line profiles through the thickness of the LSP-3 peen layer sample were compared with XRD, ICHD, and neutron diffraction results at similar locations. The neutron diffraction measurements were corrected for misalignment which incorporated near-surface pseudo strain. The results shown in Figure 9 are at the location of the center width of the sample (Y = 45 mm). It can be seen that for the near-surface data, good agreement exists between XRD and ICHD results.

The contour method stress line profiles through thickness of the LSP-2 peen layer sample are compared with XRD, ICHD, and neutron diffraction results at the center width location in Figure 10. It can be seen that for the near-surface data good agreement exists with the other measurement techniques.

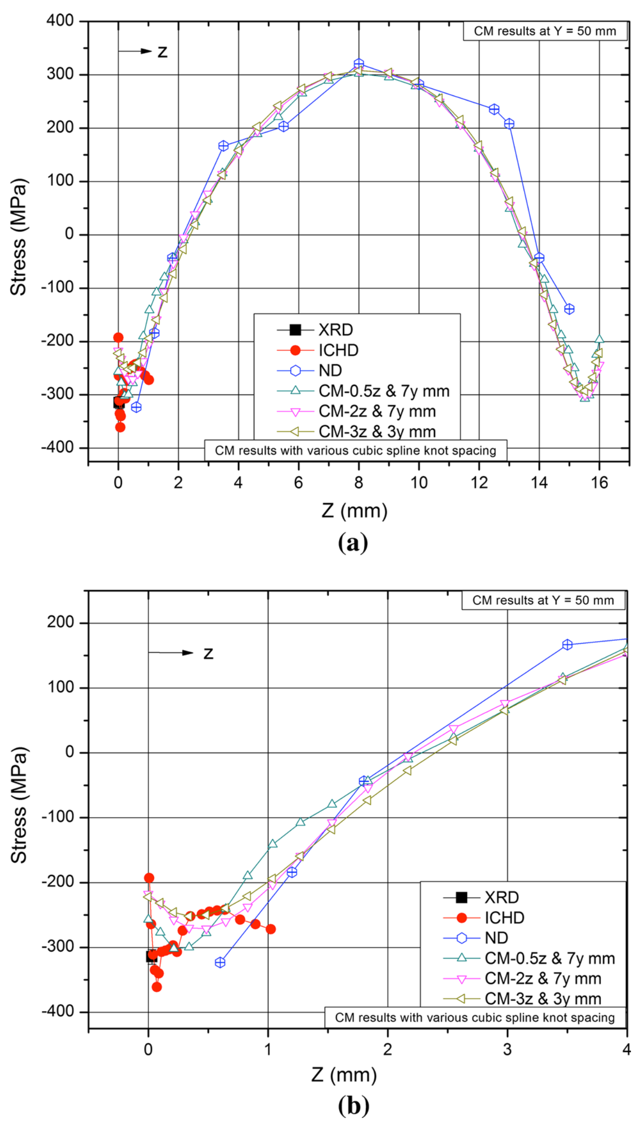

Fig. 10—Comparison of the contour method stress line profiles with XRD, ICHD, and neutron diffraction for the LSP-2 peen layer sample. (*a*) Through-thickness profile. (*b*) Detail of near-surface stresses.

From Figures 9 and 10, the influence of ablative tape and the number of laser peening layers on the residual stress can be seen. Ablative tape during laser peening protects the surface from thermal effects, and as a result, a high compressive stress is achieved on the surface. Also by increasing the number of laser peening layers, a greater depth of compressive stress is achieved.

The contour method stress line profile through the thickness of the shot-peened sample is compared with neutron diffraction and XRD results at the center width location in Figure 11. In the case of neutron diffraction measurements on the shot-peened sample, not all strain components could be captured at the weld crown toe location owing to limited beam time availability. The contour method stress profile matches the neutron diffraction strain profile with slight variation at the center region. The on-surface stress values obtained with XRD do not compare well. However, as will be seen shortly, the synchrotron XRD results are in better agreement with the surface XRD measurements than the contour method results, and it may be that at the weld

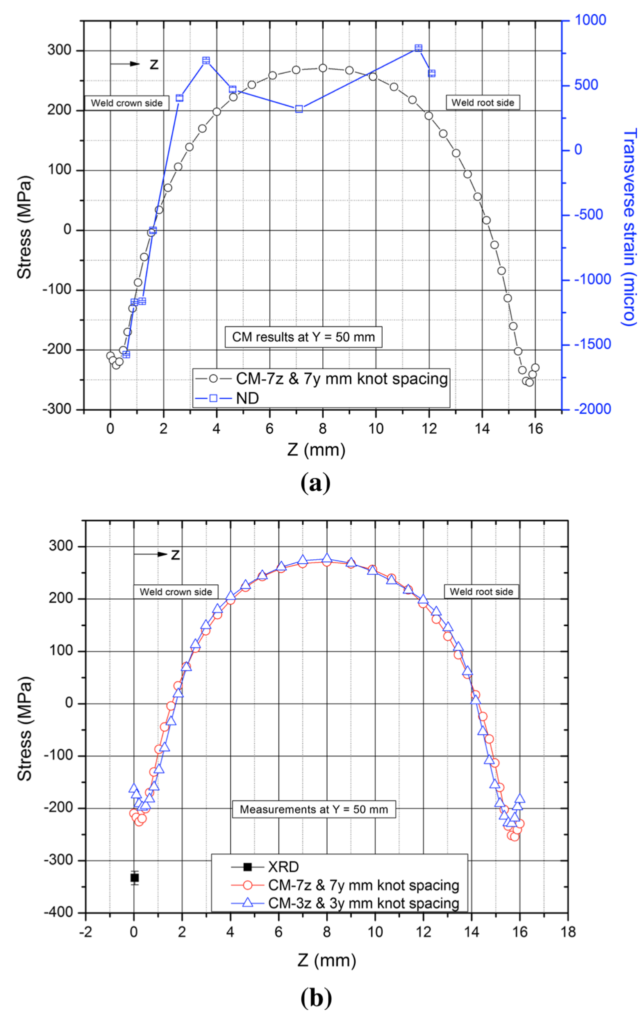

Fig. 11—Comparison of the contour method stress line profiles of the shot-peened sample with (*a*) neutron diffraction and (*b*) XRD.

toe location, the shot peening did not attain the desired level of compressive residual stress, and the XRD measurements made slightly away from the weld toe are more representative of the achievable level of residual stress from the shot peening.

The through-thickness residual stress line profiles of the laser-peened and shot-peened samples are compared at the center width location in Figure 12. From Figure 12, it can be seen that laser peening has imparted a greater depth of compressive residual stress compared to shot peening. In the case of shot peening, the depth of compressive stress is up to 1.5 mm below the surface. For the laser-peened sample with two peening layers, the compressive stress reaches 2.5 mm, and in the case of laser peening with three peening layers, it is up to 3 mm below the surface: the depth of compressive stress from laser peening increased with an increase in the number of peening layers. This is mainly because an increase in the number of laser peening layers also increases the depth of the plastic strain, which causes an increase in the elastic compressive stress.[18] When looking at the weld crown and root sides, some variation in the magnitude of the near-surface compressive stress can be seen, particularly for the shot-peened and LSP-2 peen layer samples. The observed drop in stress magnitude on the weld crown side of these two samples is explained by Figure 3: for these two samples, the contour cut passed through small portions of the weld, and as these small portions are not considered in the modelling step of the contour method: consequently, it caused a drop in the apparent surface magnitude of residual stress.

The change in the peak tensile stress at the center of the sample is small: the compressive stresses occupy a relatively small volume of material, so it would be expected that there would be a relatively small change in tensile stress to maintain force balance.

B. *Local Peen Spot Stress Measurements*

The stress profile across four laser peen spots on the LSP-2 peen layer sample was measured at the positions shown in Figure 7. The spot size is approximately 3 × 3 mm^2. The stresses were measured at the center and edge locations of four neighbouring laser spots: although it should be noted that the “edges” and “centres” of the spots as outlined in Figure 7(b) are for the second layer only, and have a different mapping relative to the first peened layer.

The results are shown in Figure 13. A higher magnitude of compressive stress was observed at the center location of the laser spots as compared to the edge for all four consecutive laser spots. This type of oscillation has been observed previously in an aluminium alloy with single-layer peening,[19] although in that case, only single coverage of peen spots was used.

The in-depth stress profile obtained for the laser peen spot labeled as no. 1 in Figure 7a is shown in Figure 14. Higher-energy X-rays are diffracted from greater depths in the material, allowing a profile to be constructed from the individual lattice reflections. In accord with the results in Figure 13, it is clear that the magnitude of the compressive residual stress is higher in the spot center compared to the spot edge.

The variation of stress across the laser peen spots can also be correlated to the surface displacement profile at those locations. It was noted that higher surface deformation occurred at the center of the laser spot compared to the edge. Figure 15 shows a case from the LSP-2 peen layer sample, with data obtained with a Mitutoyo CrystaPlus 574 CMM with a Renishaw SP25 scanning probe of 4 mm diameter. The distance between adjacent measurement points was set as 0.1 mm. More information about surface deformation associated with the laser peening can be found in Reference 20.

C. *Near-Surface Residual Stresses*

The stress profile along the weld crown toe of the LSP-2 and 3 peen layer butt-welded samples is shown in

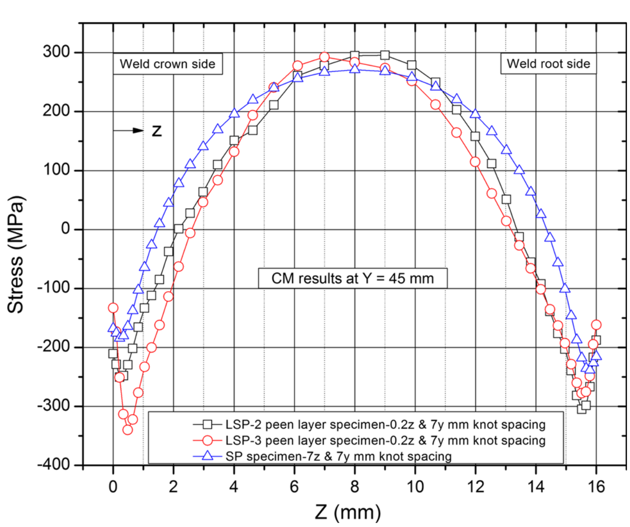

Fig. 12—Comparison of the contour method stress line profiles of laser and shot-peened butt-welded samples.

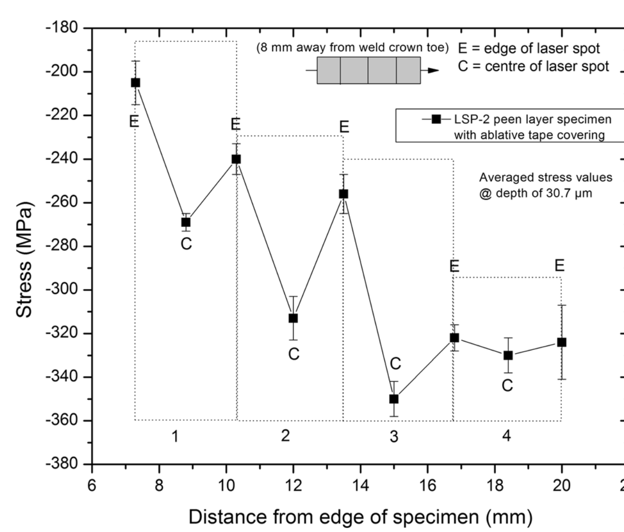

Fig. 13—Averaged stress profile at a depth of 30 μm across four laser peen spots in the LSP-2 peen layer sample, at the locations shown in Fig. 7(a).

Figure 16. The data are from the synchrotron X-ray measurements, at a depth average of ~30 μm. The plotted stress data represent the average values of eight hkl planes. It can be seen that by applying the ablative tape covering before the laser peening has resulted in higher compressive stress on the surface, despite the extra peen coverage for the three-layer sample.

Another feature that can be noted in Figure 16 is the trend of increase in surface compressive stress from edge to the center width of sample along the weld toe. It has been shown previously that higher surface compressive stress is achieved when the surface to be peened is perpendicular to the laser pulse.[21] A curved displacement profile exists at the weld toe, and hence owing to the effect of inclination angle, higher compressive stresses are imparted at the center width of the sample in comparison to the edges of the weld.

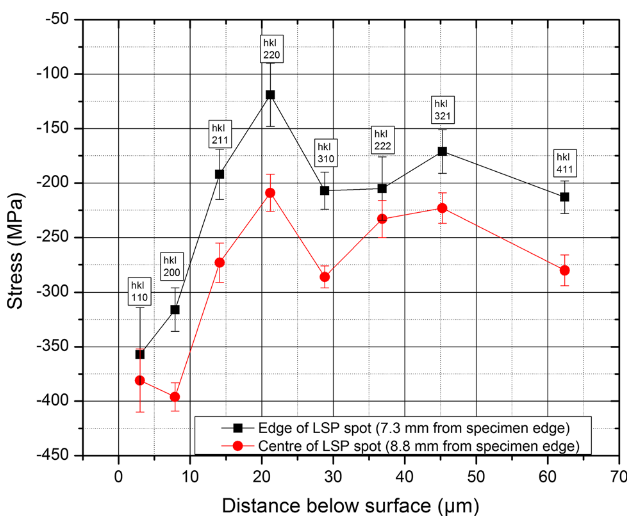

Fig. 14—Stress profile as a function of depth for laser peen spot no. 1 (see Fig. 7(a)) in the LSP-2 peen layer sample.

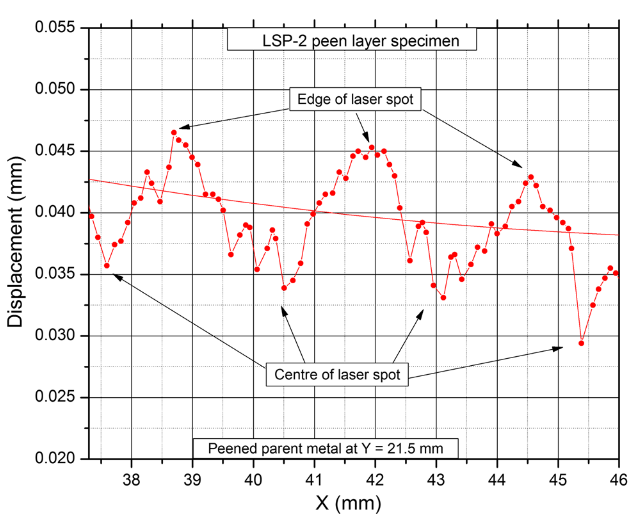

Fig. 15—Displacement profile across laser peen spots in the LSP-2 peen layer sample (axis definition as per Fig. 7(a)).

Figure 17 shows the stress profile acquired from individual hkl planes along the weld crown toe location (*i.e.*, along the *X*-axis). There is a large (and apparently systematic) variation in the results. However, the variation is likely to have two origins: the variation across the peen spots as shown in Figure 14, and the likelihood that the laser peen process has reduced efficacy at the weld toe because of shadowing effects.

This is confirmed by Figures 18 and 19. Figure 18 shows the stress profile across the weld crown, *i.e.*, from weld center to parent metal for the LSP-2 and 3 peen layer samples. For the shot-peened sample, the results are plotted from weld center to peened parent metal region. For the laser-peened samples, the peened distance is up to 27 mm from the center of the weld, and

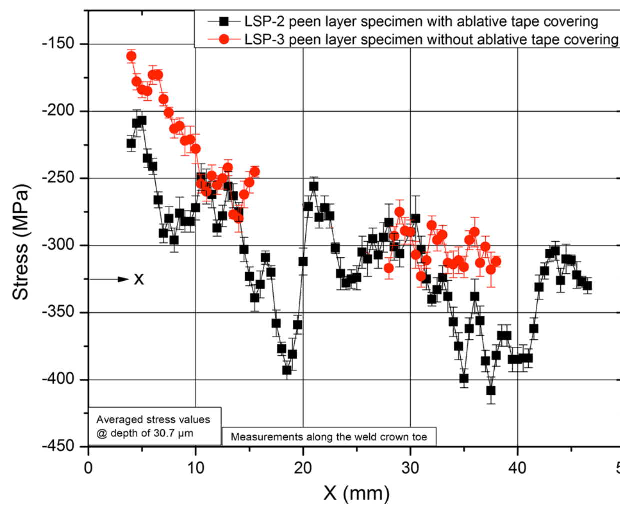

Fig. 16—Stress profile along the weld crown toe (*i.e.*, $Y = 12.5$ mm) for LSP-2 and 3 peen layer samples (see Fig. 7(a) for axes). The dataset is incomplete for the LSP-3 peen later sample owing to limited beam time.

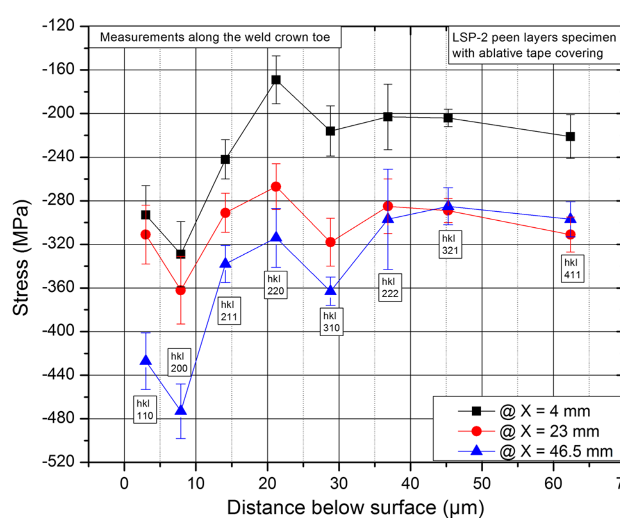

Fig. 17—In-depth residual stress profile at three locations along the weld crown toe location (*i.e.*, along the *X*-axis and $Y = 12.5$ mm) for the LSP-2 peen layer butt-welded sample.

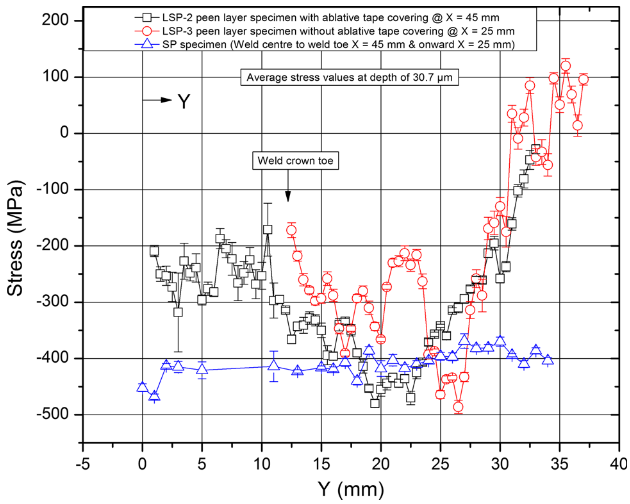

Fig. 18—Stress profile across the center of weld crown, *i.e.*, along the *Y*-axis.

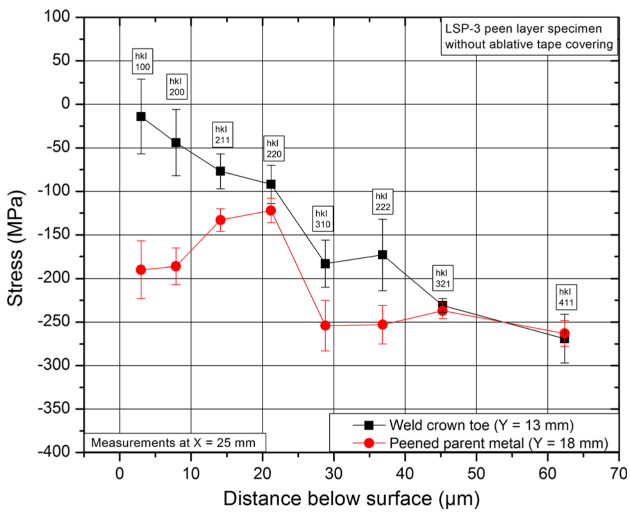

Fig. 19—Stress profile at the weld crown toe and peened parent metal region for LSP-3 peen layer sample.

after this distance, the compressive stress tends to decrease and terminate at about 7 mm beyond the peened location. For the shot peened sample, the peened area was greater, *i.e.*, up to 68 mm from the center of the weld crown. Note that in the weld crown, the shot peening has achieved a higher level of residual stress near surface, as the method is much less sensitive to the local surface profile than the laser-peened samples.

The stress profile from the individual hkl planes at the locations of the weld crown toe and the peened parent metal for the LSP-3 peen layer sample without ablative tape covering is shown in Figure 19. The near-surface stresses in the weld itself are low, as a result of the lack of ablative tape and the lower efficacy of the laser peening on the rougher weld surface.

V. CONCLUSIONS

We have investigated the application of laser shock and shot peening to introduce surface compressive residual stress into butt-welded marine steel DH275. Samples were laser peened with two or three peen layers: the samples with two peen layers used an ablative tape. Measurements were made using the contour method and high-energy synchrotron X-ray diffraction that allows for the depth profile of residual stress to be determined non-destructively. The following conclusions are drawn:

1. Laser peening introduced a greater depth of compressive stress compared to shot peening. The two-layer laser peening introduced higher levels of compressive stress on the material surface than the three-layer laser peening, which we attribute to the use of the ablative tape.
2. The shot peening produced higher at/near-surface compressive stress as compared to laser peening and a lower depth of compressive residual stress was attained for the shot-peened samples.
3. Mapping of the residual stress profile across several laser peen spots indicated that on a local (millimeter) scale, the stress fields were non-uniform. Higher surface compressive stress was present at the center of the LSP spots compared to the edges.

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