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The effect of laser shock peening on hardness and microstructure in a welded marine steel

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Abstract: Residual stress is generally considered as the main criterion in laser shock peening for enhancement of fatigue life. However, changes in material hardness, microstructure and surface roughness can also affect component performance. These three aspects are investigated in this paper for welded marine steel samples subjected to laser peening. After laser peening an increase in hardness was seen across the weld and parent metal, with the local hardness dependent upon the initial hardness of the region before peening. The increase was relatively higher for the weld metal which had lower initial hardness. The local surface displacement profiles reflected the number of laser peening layers applied, and the peening also affected the distortion of the specimen after welding.

1 Introduction

Laser shock peening (LSP) is a promising surface improvement technique that can increase the fatigue life of metallic components. In the laser peening process a laser beam is pulsed on to a metal surface that can either be protected by an ablative layer or kept bare, and that is covered by a water layer. The laser energy ionises and vaporises the surface layer such that it forms a plasma which absorbs the rest of the laser pulse energy. The pressure of the plasma rises significantly and is confined by the water layer to create a shock wave that plastically strains the surface material. Compressive residual stress is then imparted by the elastic relaxation of the surrounding material which pushes the surface material into compression.

Laser peening, as compared to traditional shot peening, induces deeper compressive residual stress. During laser peening multiple layers of peening are commonly used to ensure a uniform stress distribution with subsequent layers of laser pulses offset geometrically to the first layer. The impact of multiple layers of laser peening has been shown experimentally as well as numerically [1]. Various studies have examined the variability of stress during laser peening [2–3]. A particular conclusion is that in order to achieve consistent fatigue life it is important to have uniform spatial distribution of laser energy in the laser spot [4].

Some major advantages of LSP include the high depth of compressive residual stress generated with relatively little surface modification. Increasing the number of peening layers typically results in an increase of compressive stress in depth. Surface deformation during LSP increases with an increase in peen intensity and highest surface deformation occurs at the centre of the laser spot [5]. An increase in hardness has been seen for steels after laser peening [6].

This paper addresses the changes in material hardness, surface displacement profile, and microstructure of DH275 marine steel post welding and laser peening.

The influence of ablative tape on the specimen surface was studied using Electron Back Scatter Diffraction (EBSD). EBSD was used to examine the percentage of recrystallisation. It is generally understood that during laser peening a thin layer of surface metal is melted when the process is carried out without an ablative tape covering. Refinement of grain structure has been noticed previously during laser peening [7].

Laser peening in comparison to shot peening does less damage to the surface being peened, particularly in terms of surface roughness. However laser peening can cause macroscopic distortion, as has been noted for thin plates [3], and as is exploited in methods such as laser peen forming. This study found that the distortion increased with an increase in number of peening layers, which correlates with the resulting compressive residual stresses. Distortion caused by the welding was also present before peening.

2 Sample details

Lloyd's Register Group UK provided butt-welded specimens with base plate of 16 mm thickness as shown in Fig. 1. The specimens were laser and shot peened by Metal Improvement Company (MIC) UK. The material of the specimens is carbon manganese ship structural steel DH275.

Laser peening was carried out in two conditions: with three layers without ablative tape covering; or two layers with an ablative tape. Laser peening was performed according to specification AMS 2546 with the following details:

Peened location = Weld crown and root side face as well as specimen 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.

Shot peening was performed according to MIC process D0311 ISSA with the following details:

Peened location = Weld crown and root side as well as specimen edges, Peened area at weld crown and root face side = 136 × 90 mm^2, Peened area at edges = 256 × 16 mm^2.

The experimental yield and tensile strengths of DH275 steel are 436 and 560 MPa, respectively.

3 Experimental setup and procedure

3.1 Hardness measurements

To examine the hardening effect caused by laser peening, Vickers hardness measurements were carried out using a Struers micro-indenter on a butt-welded specimen that was laser peened with three peen layers without ablative tape. For this purpose a slice 70 mm long, 16 mm wide and 2 mm thick containing weld crown and root, heat affected zone (HAZ), and parent metal (PM) was extracted from the edge of a laser peened specimen, as shown in Fig. 2 using wire electro-discharge machining.

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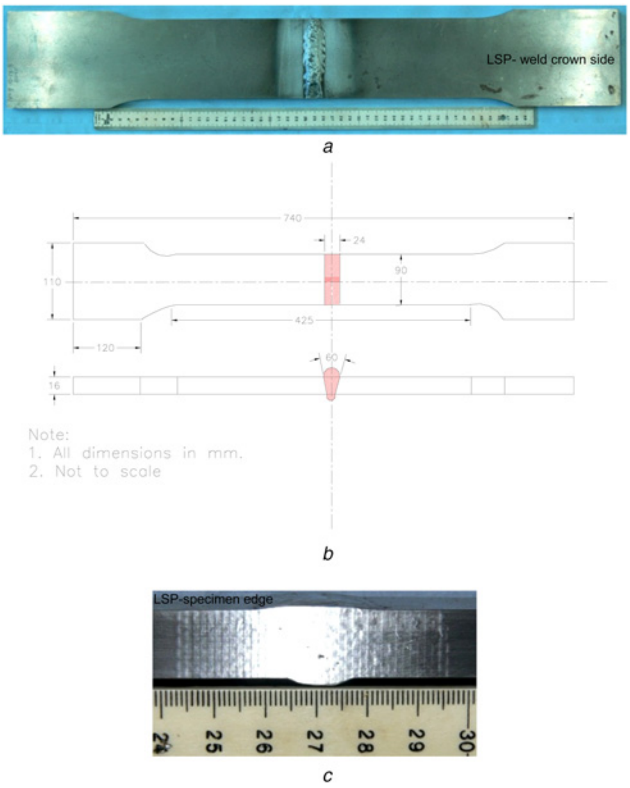


Fig. 1 *Butt welded specimens*
a Laser peened butt welded specimen
b Dimensions of butt welded specimen
c Close-up of laser peened region

Grit papers of grades ranging from 400 to 20 000 were used to polish the specimen to obtain a smooth surface that can be used for hardness indentation. Measurements were recorded with an indenter load of 5 kg and the spacing between measurement points was 0.5 mm. 0.5 mm was also left at the edges to avoid error in the measurements, so near surface data at the weld crown and root could not be captured. The whole slice was tested including the regions of weld, HAZ, peened parent metal and un-peened parent metal. Two opposite surfaces of the coupon were tested, one that was directly peened (i.e. surface ‘A’ in Fig. 2*b*) and another that was 2 mm away from the edge of the specimen (i.e. surface ‘B’ in Fig. 2*b*): however, that surface had the effect of peening on the top and bottom surfaces of the specimen.

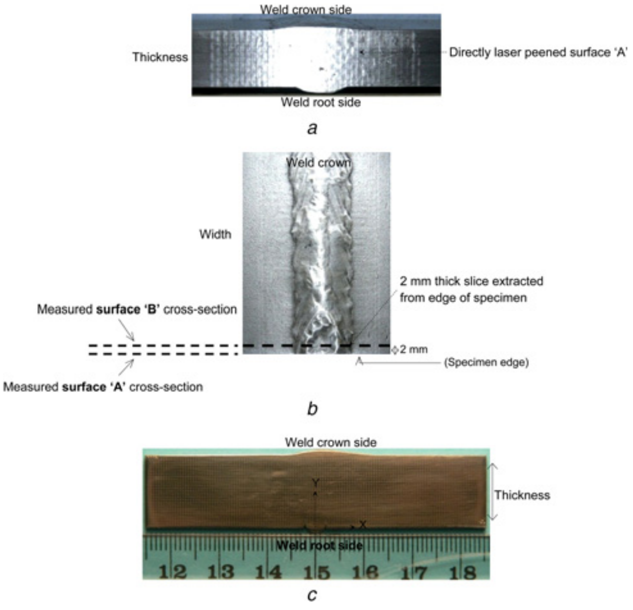


Fig. 2 *Sample for Vickers hardness measurements from the LSP-3 peen layer butt welded specimen*
a Peened location at specimen edge
b Location for extraction of slice
c Extracted test coupon used for hardness measurements

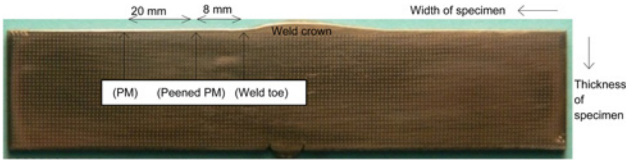


Fig. 3 *Measured locations for EBSD study*

3.2 Microstructure examination

Microstructural examination of the laser peened specimen (with three peen layers and without ablative tape covering) was carried out using optical microscopy and Electron Back Scatter Diffraction (EBSD). Abrasive paper, diamond paste and colloidal silica were used for the surface preparation of the specimen by polishing. Measurements were carried out on un-peened parent metal, peened parent metal and weld crown toe locations as shown in Fig. 3 with a step size of 1 µm.

It is generally understood that during laser peening without ablative tape covering a thin layer of parent metal is melted. The EBSD study was planned to investigate any evidence of re-crystallisation near the surface region depending upon the thickness of the affected layer. Measurements were carried out in a Zeiss Supra scanning electron microscope with results extracted using HKL Tango software. The minimum misorientation angle to separate sub-grains and grains was set as 2° and 15° respectively. Noise in the data was removed using Euler smoothing. The orientation spread is generally used to distinguish between deformed and recrystallised grains.

3.3 Surface displacement profiles

The surface profiles of the laser and shot peened specimens were measured using a Mitotuyo CrystaPlus 574 co-ordinate measurement machine (CMM) with a Renishaw SP25 (SM25-1) scanning probe of 4 mm diameter. The results enabled comparison of the surface profiles from laser and shot peening. Measurements were carried out on the weld crown and root sides for one half of the plate for all three types of specimens as per Fig. 4.

Three regions were identified for data acquisition – un-peened parent metal, peened parent metal, and peened weld toe – to examine the change in surface profile after the application of the peening techniques. The measurement spacing between points along the length and width of the specimens was 1 and

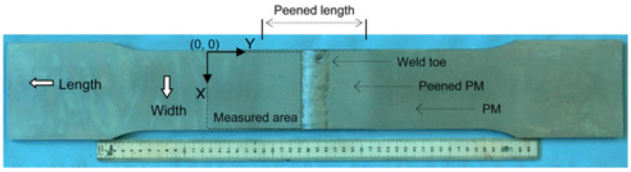


Fig. 4 *CMM measurement locations and directions (a shot peened specimen is shown)*

0.1 mm respectively. To examine the variation of surface profile at the centre and edge of individual laser peen spots, the distance between measured data along the width of the specimen was kept small. The measured distance along the length of specimen and from parent metal to weld toe was 50 mm for both laser peened specimens and 80 mm for the shot peened specimen. The larger distance for the shot peened specimen is because of its larger peened area compared to the laser peened specimens.

4 Results and discussion

4.1 Hardness measurement results

The hardness profiles at 2 mm away from the edge peened region are shown in Fig. 5. The measurement location refers to surface 'B' in Fig. 2*b*.

From Fig. 5 it is clear that hardness decreases below the surface (i.e. from Y = 0 to Y = 16 mm) on the weld root and crown sides. On the weld crown side the highest hardness is in the peened

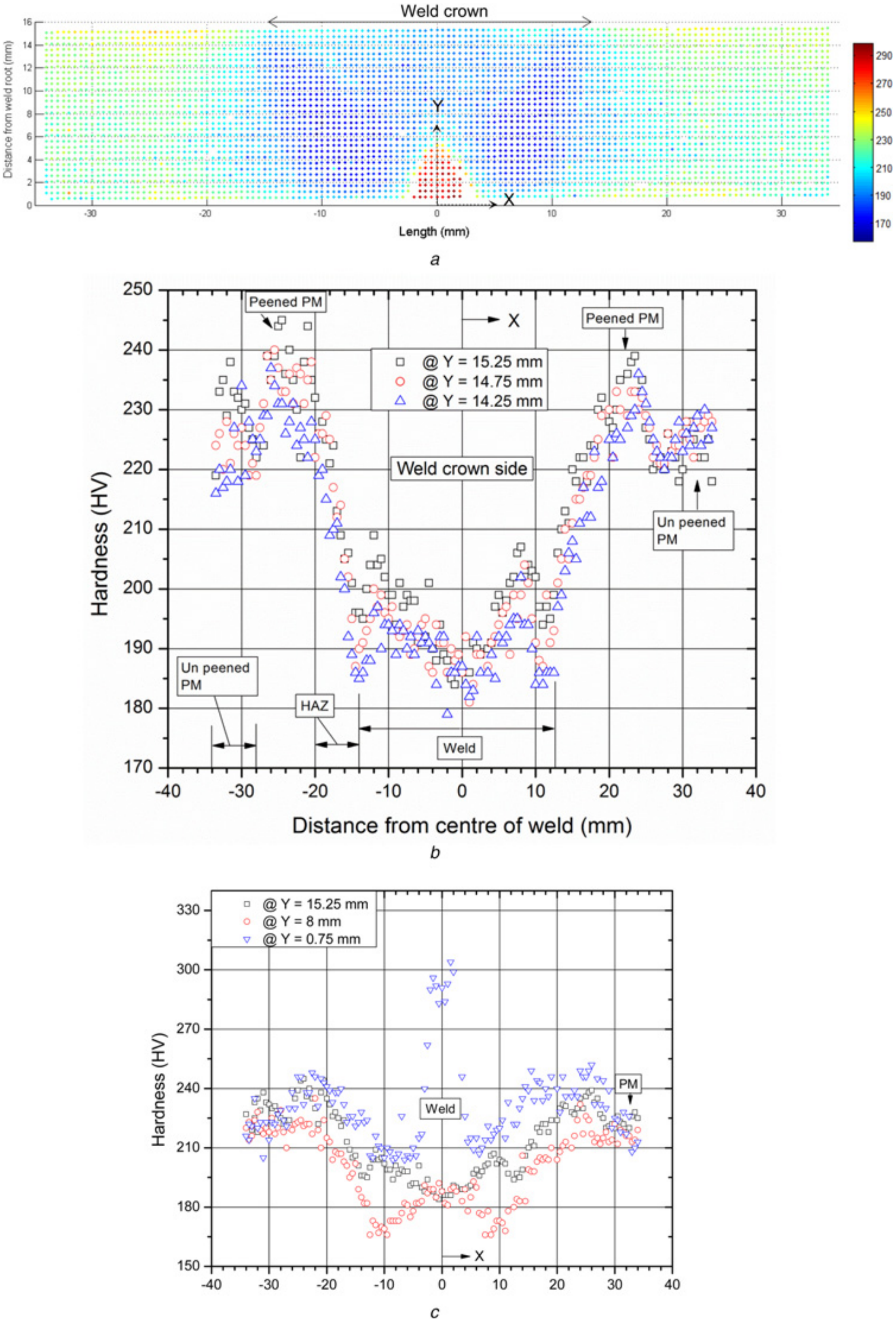


Fig. 5 *Vickers hardness line profiles for the LSP-3 peen layer butt welded specimen (Surface 'B' in Fig. 2b)*
a Hardness map
b Hardness line profiles on the weld crown side
c Hardness line profiles on the weld root side

parent metal, followed by the un-peened parent metal. On the weld root side the highest hardness is in the weld itself followed by peened parent metal and un-peened parent metal. Different hardness profiles can be seen from the line measurements carried out on the crown, root and centre of the weld. The softest region was found at the centre thickness of the specimen where there was no effect of the peening and where the weld thermal cycles have led to lower hardness. It can be seen that the hardness is lower on the weld crown side compared to the weld root. The shorter thermal cycle at the weld root has resulted in smaller grains, thus imparting higher hardness, as will be seen later.

The results of hardness measurements on the peened surface are shown in Fig. 6. The measurement location refers to surface ‘A’ in Fig. 2b.

On the peened surface ‘A’ the highest hardness is still in the weld root, followed by the peened region away from the weld in the parent metal. The hardness of the weld, except at the weld root, is comparable with the parent metal after peening.

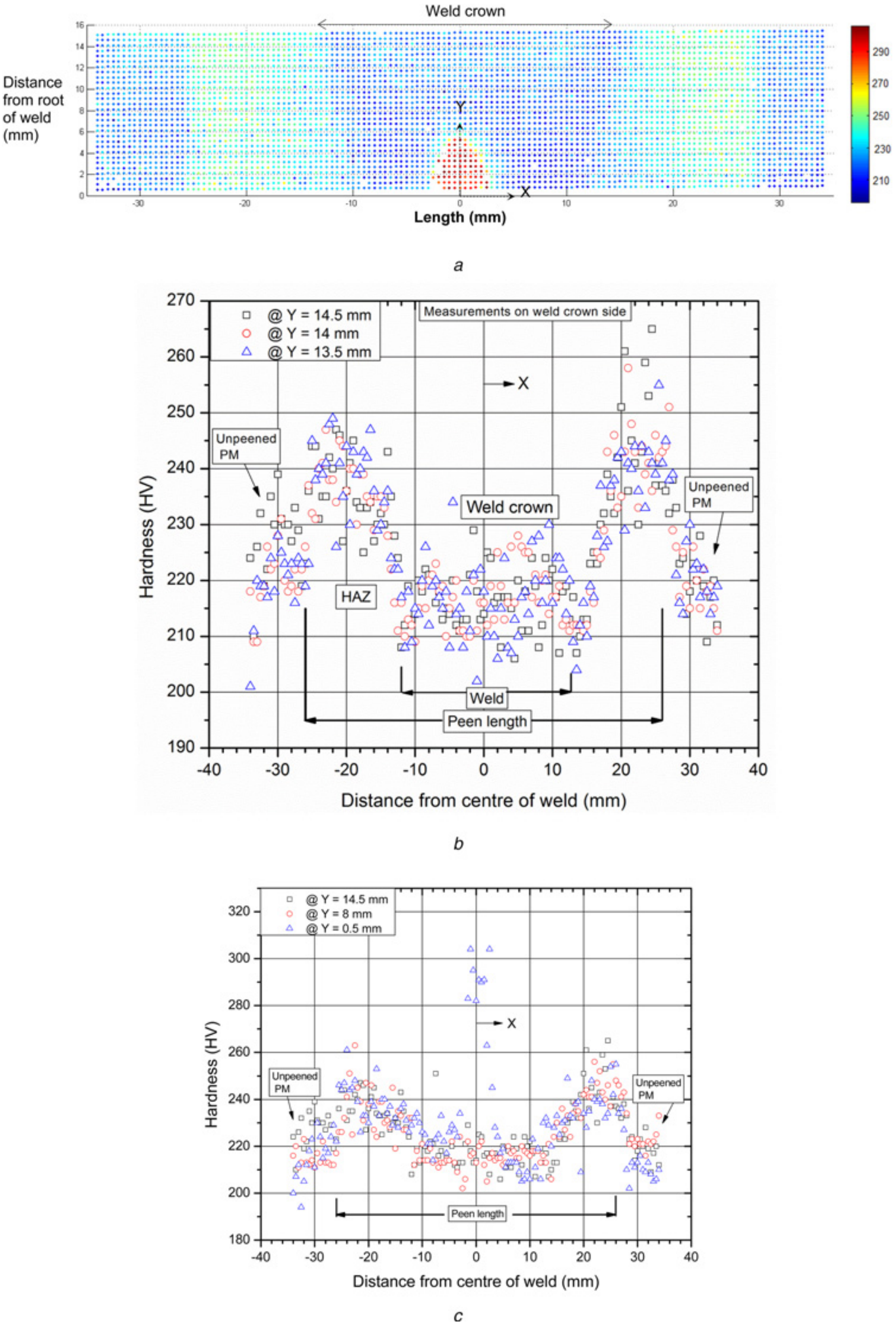
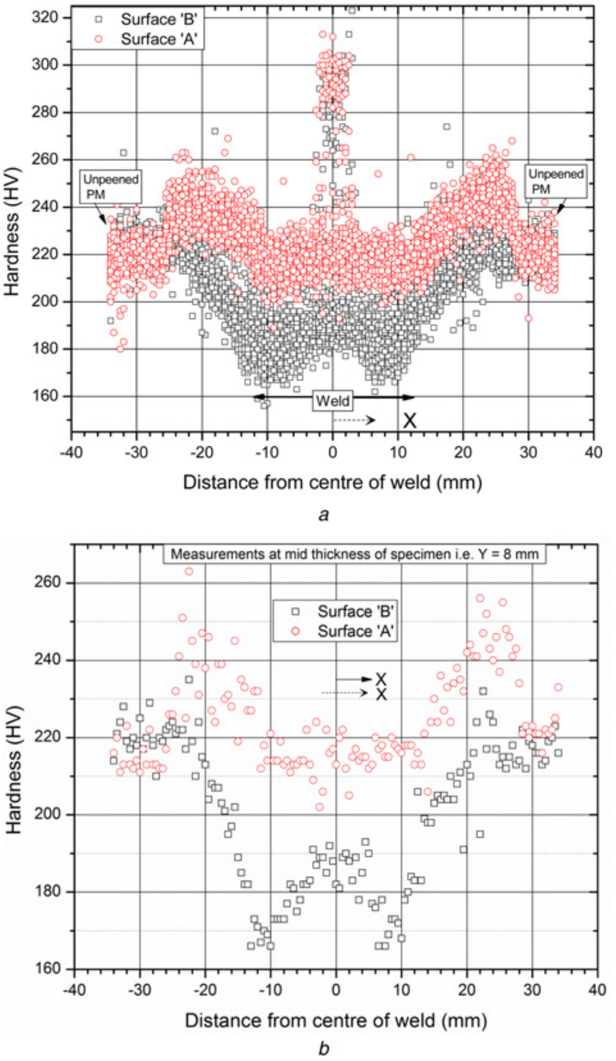


Fig. 6 *Vickers hardness profiles on the peened surface for the LSP-3 peen layer butt-welded specimen (Surface ‘A’ in Fig. 2b)*
a Hardness colour map
b Hardness line profiles on weld crown side
c Hardness line profiles on weld root side



a

b

Fig. 7 *Comparison of hardness profiles of two surfaces of the LSP-3 peen layer butt-welded specimen*
a Comparison of complete hardness profile of surface ‘A’ and ‘B’
b Comparison of hardness line profile of surface ‘A’ and ‘B’ at centre thickness (i.e. Y = 8 mm) of plate

The comparison of hardness of surface ‘A’ and ‘B’ (see Fig. 2*b*) is shown in Fig. 7.

After peening a considerable increase in hardness at the weld is seen as compared to the parent metal. On average the increase in the weld is about 35 HV and in the parent metal is 20 HV. The hardness of the parent metal is similar in both tests. The largest difference in the profile is seen at the centre thickness of plate followed by the weld crown side, whereas on the weld root side very little variation was observed. From the Vickers hardness tests, the average hardness of various regions of the specimen is indicated in Table 1.

It can be concluded in general that the peening has resulted in a high percentage increase in hardness of the softer region (i.e. the weld) as compared to the harder region (i.e. the parent metal). The significant hardening seen in the weld root pertains to the welding parameters and the thermal cycle experienced by the material.

4.2 Microstructural examination

Optical microscopy of different regions of the 3-layer laser peened specimen is shown in Fig. 8. The measurements were performed at the near surface regions. The parent metal shows a higher amount of pearlite. The weld regions have elongated grains, and at the weld root small grain sizes can be seen owing to the shorter thermal cycle.

Table 1 Average hardness of various regions of the specimen peened with three layers

Region	Hardness / HV
un-peened weld	185
un-peened parent metal	220
peened weld	220
peened parent metal	240

Fig. 9 shows the deformed and sub-structured grains from the material manufacturing process in the parent metal region, and shows the results following peening. There are no signs of melting of the near surface layer following peening: the recrystallised fraction may indicate recrystallised grains following melting of the surface layer. This suggests that with the selected laser peening parameters, without an ablative tape, that either there was no melting taking place, or it was confined to a microscopically-thin layer.

The substructured fraction refers to larger misorientation angles than the recrystallised grains; the deformed fraction shows the primary grain’s orientation [8].

The re-crystallised fraction at the weld crown toe region of the LSP-3 peen layer specimen is shown in Fig. 11. Relative to the other two locations i.e. parent metal (PM) and peened PM a higher fraction of deformed grains is seen at the weld crown toe region owning to the welding process. Some areas shown as white spaces in the Fig. 11 (a) could not be indexed owing to the surface condition of the test coupon.

4.3 Surface displacement profile measurement

The isometric surface profiles from the LSP-3 peen layer specimen at the weld root and crown sides are shown in Figs. 12 and 13 respectively. At the start of the peened region surface deformation can be seen. On the weld crown side surface deformation is highest at the toe of the weld, contrary to the toe on the weld root side. The variation in surface profile between the weld toe on the crown and root sides is likely to be caused by welding distortion. This particular observation is clearer from the line profiles as shown in Fig. 14. The surface deformation from the peening treatment can also be seen.

The peened area starts from the 43 mm Y-axis position in Fig. 13, where a depression in the surface is seen. The surface deformation is highest at the weld crown toe and is exacerbated by weld longitudinal distortion. In contrast to the LSP-2 peen layer specimen higher surface deformation is seen for the LSP-3 peen layer specimen. Fig. 14 gives the surface displacement line profiles at weld crown and root sides of the LSP-3 peen layer specimen across three regions of the specimen i.e. un-peened parent metal, peened parent metal and weld toe. Following peening the surface deformation increases in the parent metal. The higher deformation seen at the weld crown toe region has contribution both from weld distortion and peening. Additionally the lower initial hardness of the weld crown toe region may have resulted in more surface deformation relative to the parent metal having higher initial hardness when peened with similar peening conditions.

The measurements in the LSP-3 peen layer specimen showed surface depression of 10–30 μm at the centre width of the plate in the peened parent metal region relative to the parent metal region. On the weld crown toe region greater surface depression is seen, about 60 μm relative to the un-peened parent metal. Isometric views of the surface profiles (Fig. 13) showed the overall depression at the centre width of the plate, which is

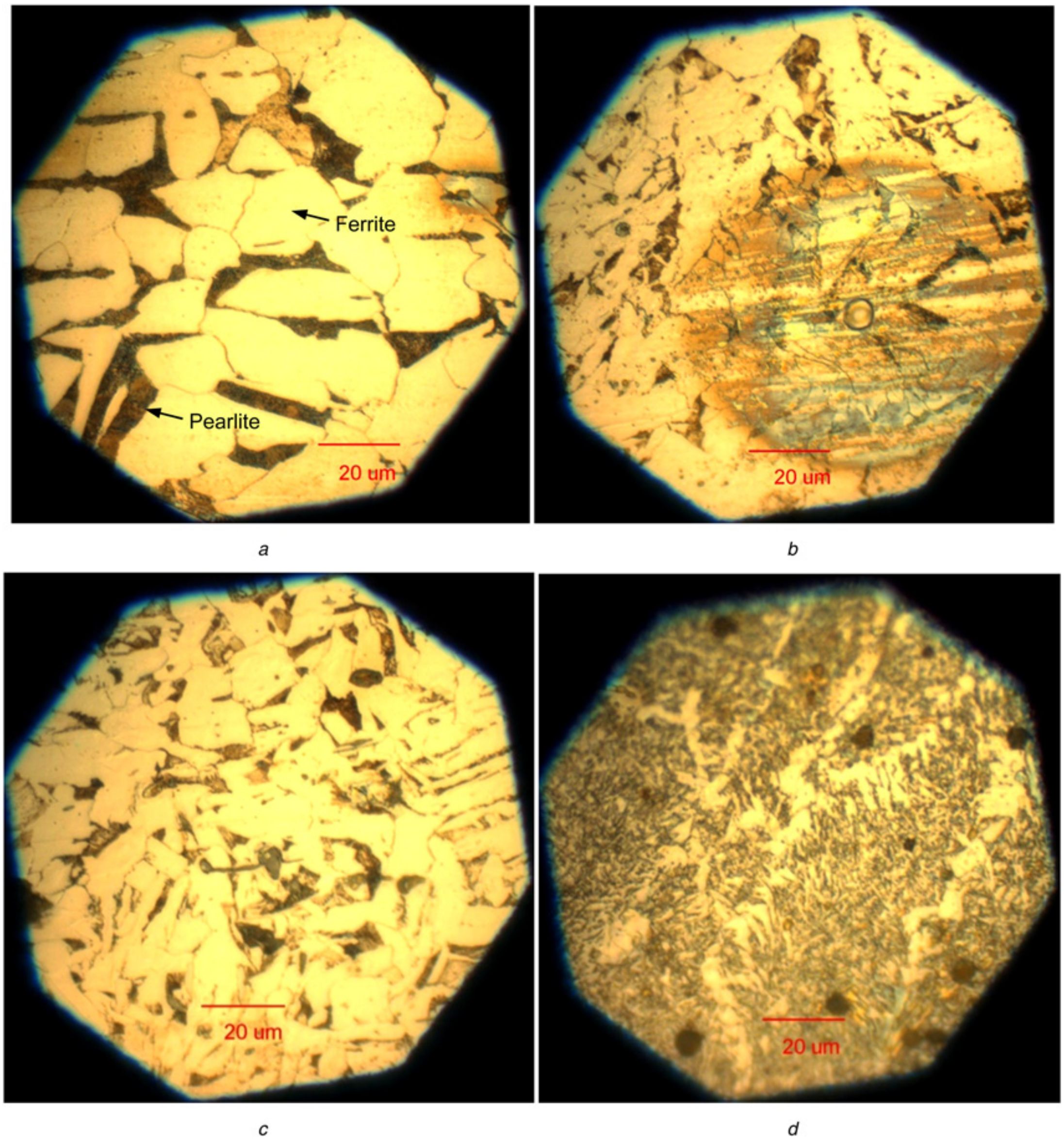


Fig. 8 *Microstructure examination of the LSP-3 peen layer butt welded specimen*
a Parent metal (non-peened)
b Weld crown
c Weld crown toe
d Weld root

formed into a curved shape. This symmetrical curve shape profile along the width of the specimen in the parent metal region on both sides of the plate is probably a consequence of the welding operation. Another interesting feature is the post peening difference in deformation at the edges and centre width of the specimen. The cause of this is considered to be the peening process where higher stresses and consequently higher surface deformation are seen in surfaces perfectly perpendicular to the laser beam as compared to inclined surfaces. Therefore during laser peening the surface at the centre width would be more flat as compared to the edges owing to its initial profile as discussed above. The influence of the incident angle of the laser with respect to the specimen surface i.e. higher stresses are seen on and near the surface region in case of higher incident angle [9].

The isometric surface profiles from the LSP-2 peen layer specimen at weld root and crown side are shown in Figs. 15 and 16 respectively.

Figs. 15 and 16 show an overview of the complete surface profile measured in the two LSP layer specimen ranging from parent metal to weld toe. Surface depression can be seen at the start of the peened region. Again in the case of the weld crown side surface deformation is highest at the toe of the weld which is contrary to the condition at the toe on the root side. This particular observation is clearer from the displacement line profiles shown in Figs. 17 and 18 below. The surface deformation following peening can also be seen.

The surface profiles of two laser peened specimens are compared at the weld crown toe and shown in Fig. 19. Higher deformation is seen in the LSP-3 peen layer specimen and suggests that an increase in number of peen layers has caused higher deformation. The CMM data was flattened to remove the shear component from the data set using Matlab software routine [10].

The parent metal regions have nearly identical difference between peak-to-valley positions along the displacement curve.

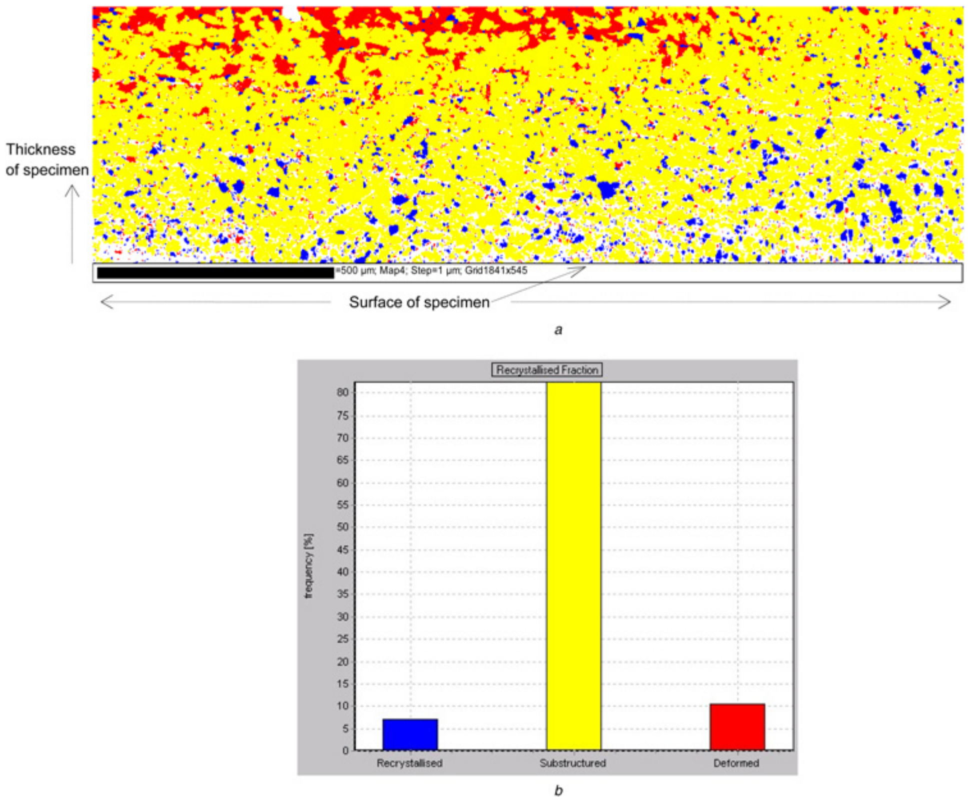


Fig. 9 *Re-crystallised fraction in parent metal of LSP-3 peen layer butt welded specimen (see Fig. 3)*
a Re-crystallised grain distribution in measured area
b Chart showing re-crystallised fraction

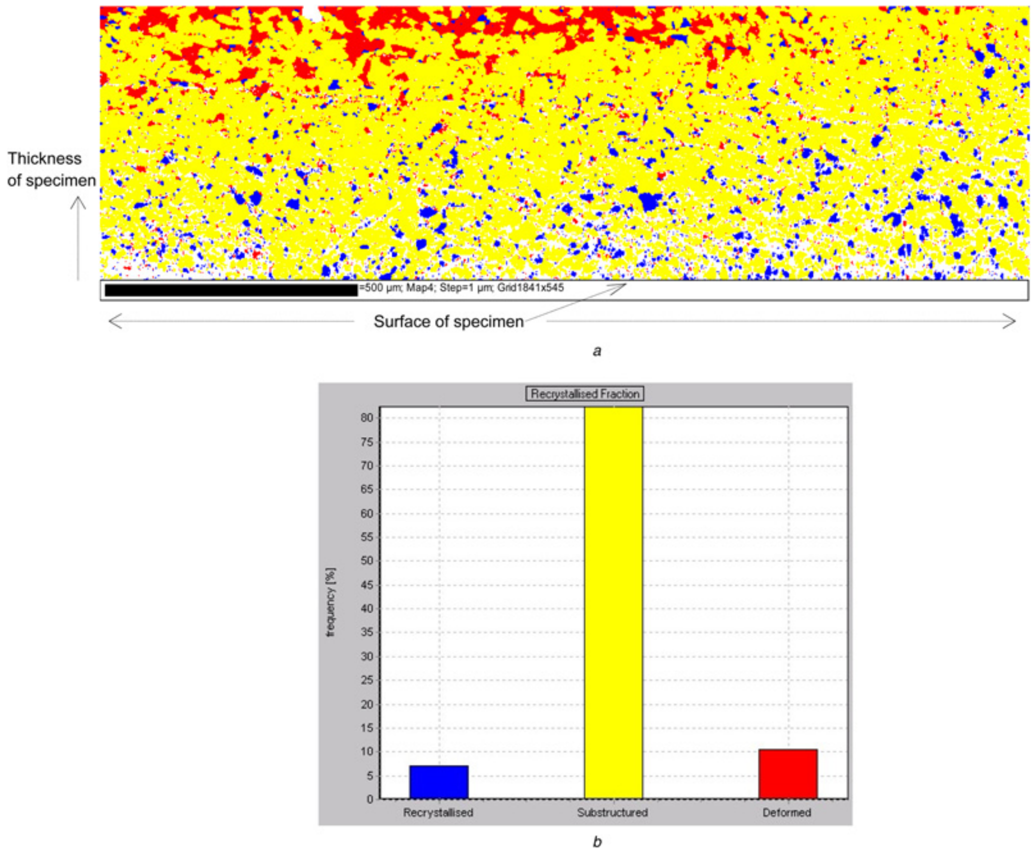
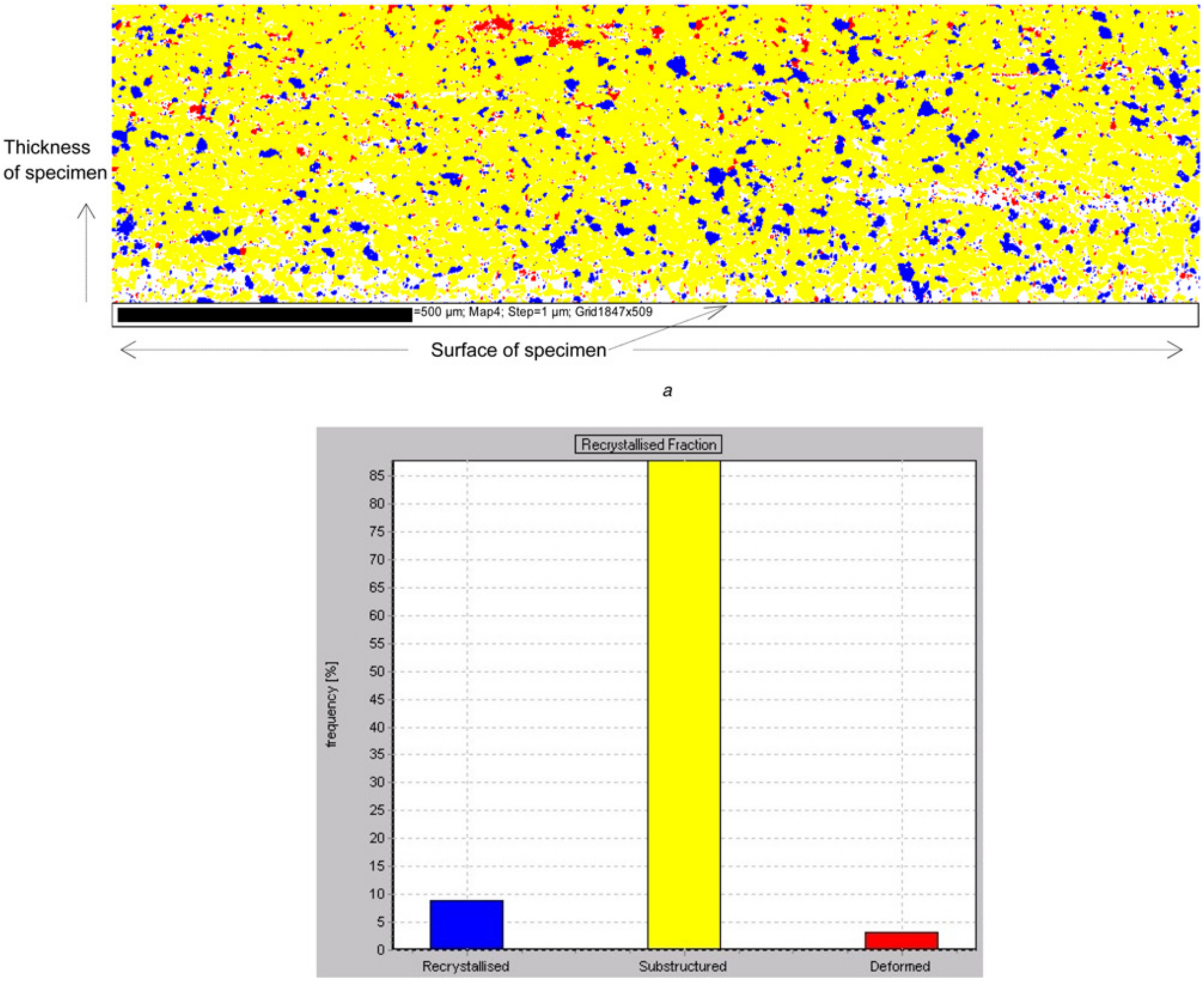


Fig. 10 *Re-crystallised fraction in peened parent metal of LSP-3 peen layer butt welded specimen (Ref. Fig. 3)*
a Re-crystallised grain distribution in measured area
b Chart showing re-crystallised fraction



a

b

Fig. 11 *Re-crystallized fraction at the weld crown toe of the LSP-3 peen layer butt welded specimen (see Fig. 3)*
a Re-crystallised grain distribution in measured area
b Chart showing re-crystallised fraction

The laser pattern for the two peen layer specimen can be seen in Fig. 20. In case of two peening layers the second peening layer is offset by about 50% in both directions and for three peening layers each peen layer is offset by about 33% to the previous peen layer. This peening process therefore generates four small square blocks of size $1.5 \times 1.5\ \mathrm{mm}^2$ in the case of two peening layers from a laser spot size of $3 \times 3\ \mathrm{mm}^2$. Similarly for three peening layers nine square blocks of size $1 \times 1\ \mathrm{mm}^2$ would be produced.

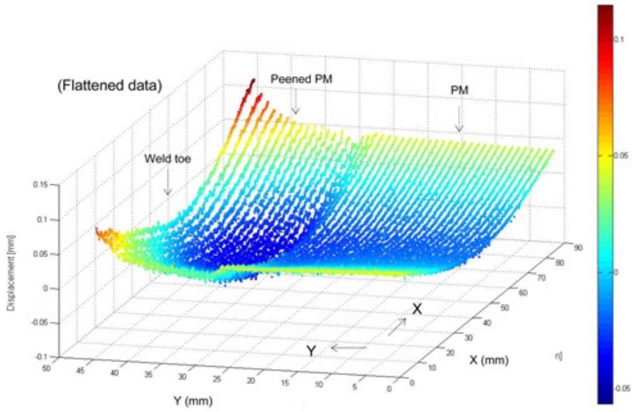


Fig. 12 *Isometric surface profile of LSP-3 peen layer butt welded specimen on weld root side*

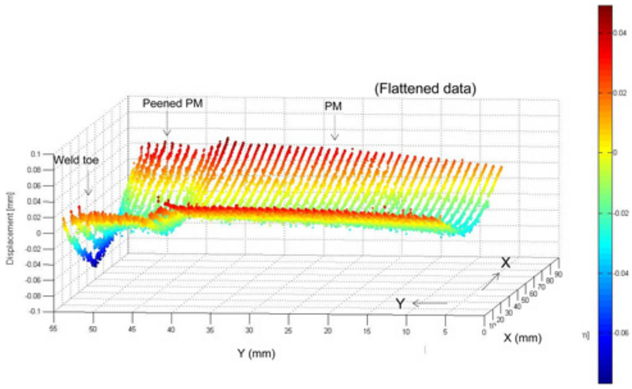


Fig. 13 *Isometric surface profile of LSP-3 peen layer butt welded specimen on weld crown side*

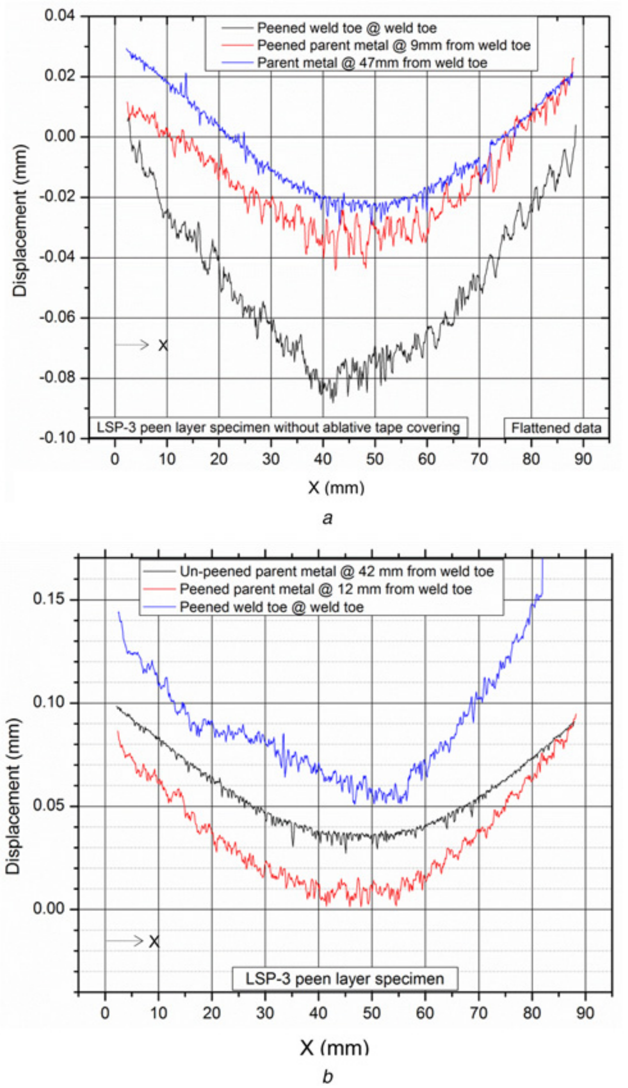


Fig. 14 *Surface profile along the specimen width (i.e. X-axis) from parent metal to weld toe region in LSP-3 peen layer but welded specimen*
a Weld crown side
b Weld root side

The surface deformation within and at the edges of the laser spots is shown in Fig. 21. Lower deformation is seen at the edges of the laser spots and higher deformation at the centre of

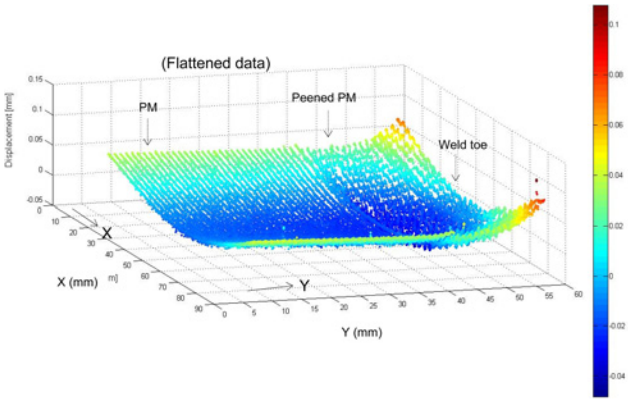


Fig. 15 *Isometric surface profile of LSP-2 peen layer butt welded specimen at weld root side*

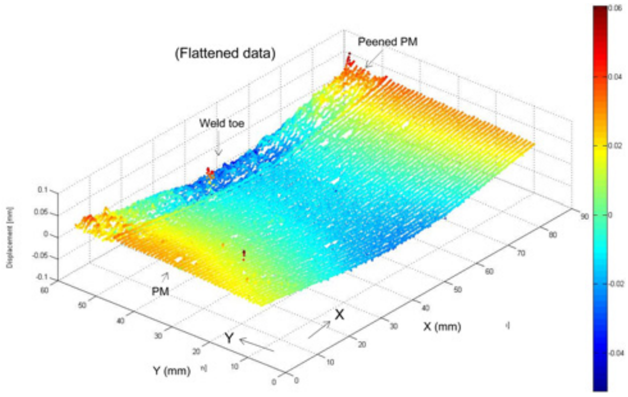


Fig. 16 *Isometric surface profile of the LSP-2 peen layer butt welded specimen at weld crown side*

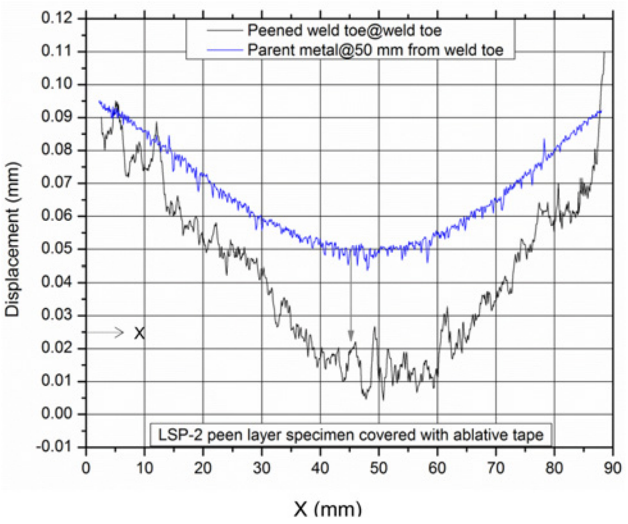


Fig. 17 *Displacement profile along the specimen width (i.e. X-axis) on the weld crown side of LSP-2 peen layer butt-welded specimen*

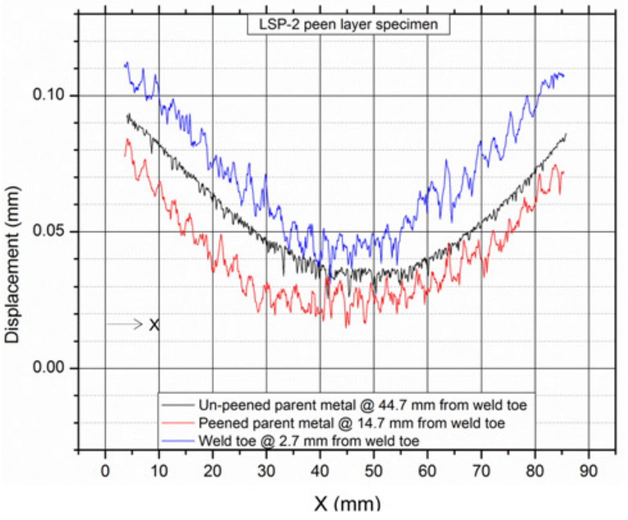


Fig. 18 *Displacement profile along the specimen width (i.e. X-axis) on the weld root side of the LSP-2 peen layer butt-welded specimen*

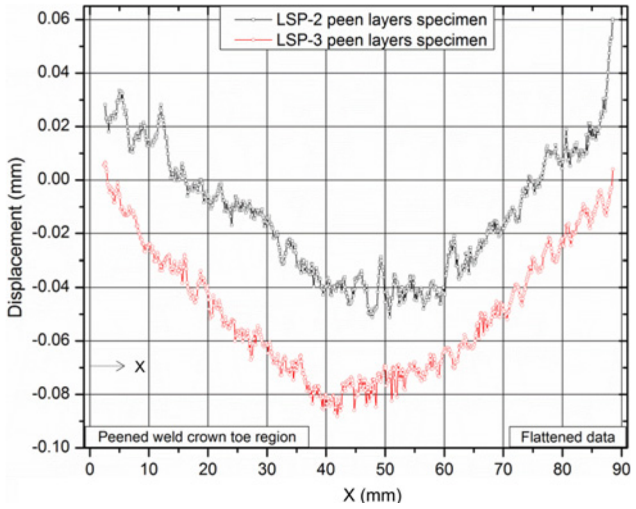


Fig. 19 *Surface profiles of the two LSP butt welded specimens along the width (i.e. X-axis) at the weld crown toe region*

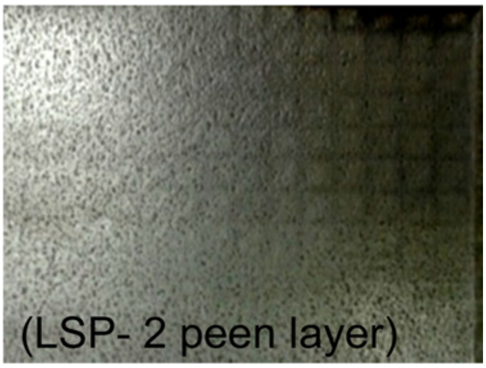


Fig. 20 *Laser peen pattern on the 2-layer specimen*

the spots. Peaks represent edges and valleys the centres of the laser spots.

The isometric surface profiles from the shot peened specimen at the weld root and crown sides are shown in Figs. 22 and 23 respectively. The surface deformation level of the peened region can be clearly seen relative to the parent metal region.

The displacement line profiles of the peened region compared to the parent metal are shown in Fig. 24. The peak to valley distance is considerably higher than the laser peened specimens showing higher surface roughness in the case of shot peening.

The measurements in the shot peened specimen showed a large peak-to valley variation across the specimen width. The indents formed by shot peening on a specimen surface have maximum surface penetration at the centre of the indented area and at the edge of the indent the surface is raised upward, therefore at those locations the surface displacement is above the parent metal. Surface penetration was higher at the weld crown toe region owing to the additional impact of weld longitudinal distortion. In the parent metal region the peak-to-valley variation is higher in the shot peened specimen as compared to the laser peened specimens. Although the material and manufacturing process of the base plate of all specimens was identical, the specimens to be laser peened were additionally milled which has resulted in better surface finish compared to the rolled condition.

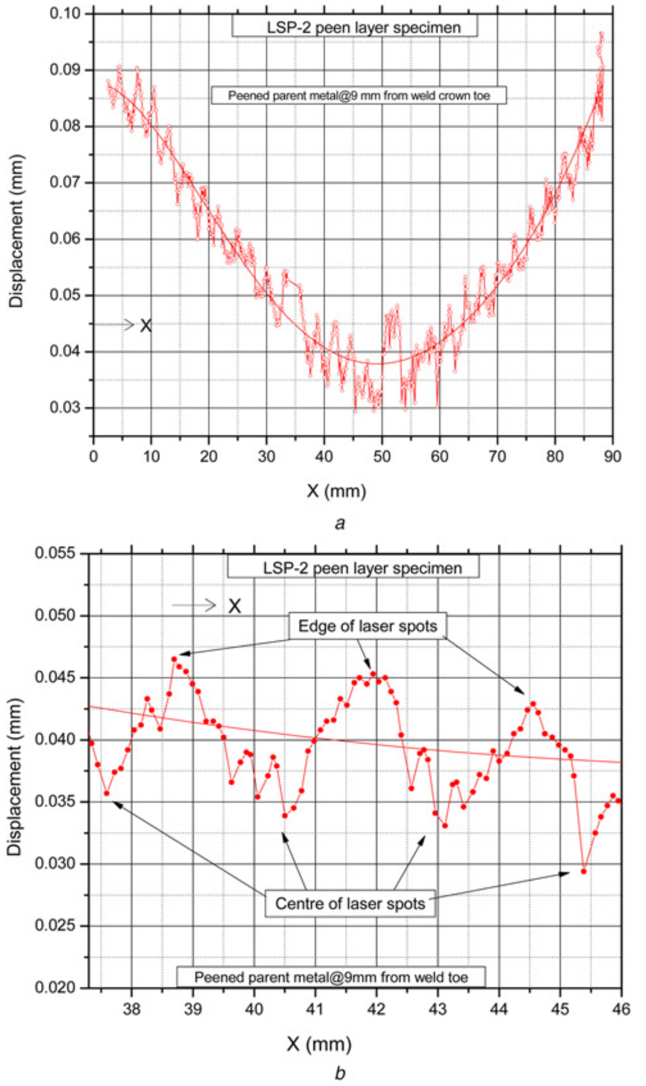


Fig. 21 *Surface profile across laser peen spots in the LSP-2 peen layer butt welded specimen*
a Along width X-axis
b Close up

From measurements in the peened parent metal region it can be concluded in general that the peening techniques deform the sample in addition to the deformation that existed from the welding process.

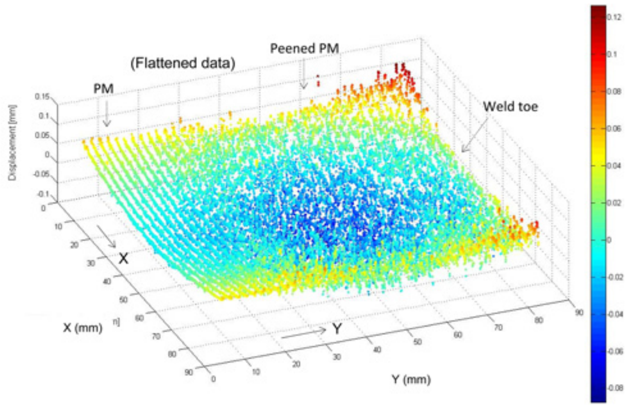


Fig. 22 *Isometric surface profile of shot peened butt welded specimen at weld root side*

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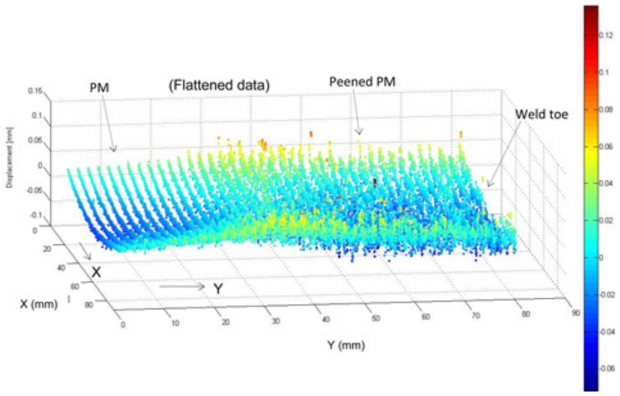

Fig. 23 *Isometric surface profile of shot peened butt welded specimen at weld crown side*

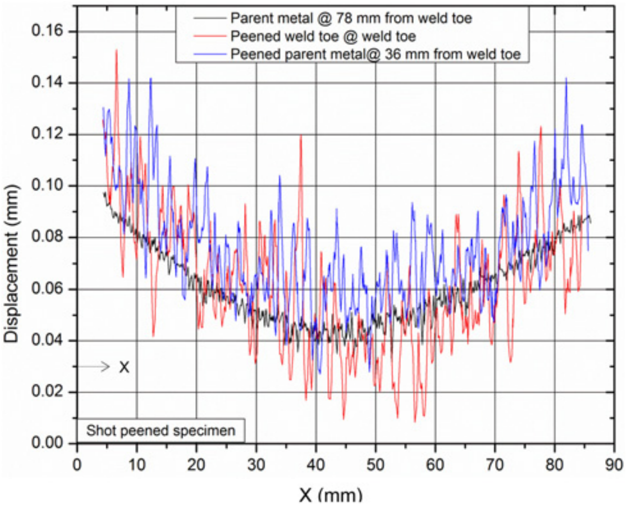

Fig. 24 *Displacement line profiles across the specimen width (i.e. X-axis) from parent metal to weld crown toe region for the shot peened butt-welded specimen*

This deformation was higher with laser peening compared to shot peening. However shot peening introduces higher roughness.

5 Conclusions

1. The surface hardening and deformation has been studied in DH275 marine steel subjected to laser shock and shot peening. The laser peening was seen to increase the hardness of both weld and parent metal, with higher hardening of the softer regions of the sample. The highest hardness after laser peening was in the weld root, followed by parent metal and the weld.
2. The surface displacement profiles revealed a curved profile across the width of the specimen caused by the combined effect of weld longitudinal distortion, peening and the original rolling. In the laser peened region higher surface deformation was seen compared to the parent metal. It was found that with an increase in laser peening layers the deformation also increased, and there was higher localised deformation of the surface.
3. An EBSD study of the LSP-3 peen layer butt welded DH275 steel specimen without ablative tape covering showed little evidence of recrystallisation from melting of the surface layer.

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