

## Residual Stresses in Ultrasonically Peened Fillet Welded Joints

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**Abstract:** Fatigue cracks mostly initiate at areas subjected to high tensile residual stress and stress concentration. Ultrasonic peening is a mechanical method to increase fatigue life by imparting compressive residual stress. In this study residual stresses are characterized in fillet welded ship structural steel plates with longitudinal attachments. As-welded, ultrasonically peened, and specimens peened then subjected to accelerated corrosion testing were measured. Residual stress characterization was performed by the contour method and neutron diffraction.

### Introduction

Lloyds Register Group UK supplied three fillet welded marine structural steel specimens of 25 mm thick base plate with 15 mm thick longitudinal attachments welded on both sides. The specimens were received as-welded, ultrasonically peened, and following accelerated corrosion tested after ultrasonic peening. The specimens in as-received form are shown in Fig.1. The material of specimens according to International Association of Classification Studies (IACS) is marine grade carbon manganese ship steel DH36, which is used in commercial ship construction. Ultrasonic peening was performed at four weld toe locations of attachment corners only as these areas are more susceptible to fatigue cracks. The UP groove is 3 mm wide and 0.5 mm deep.

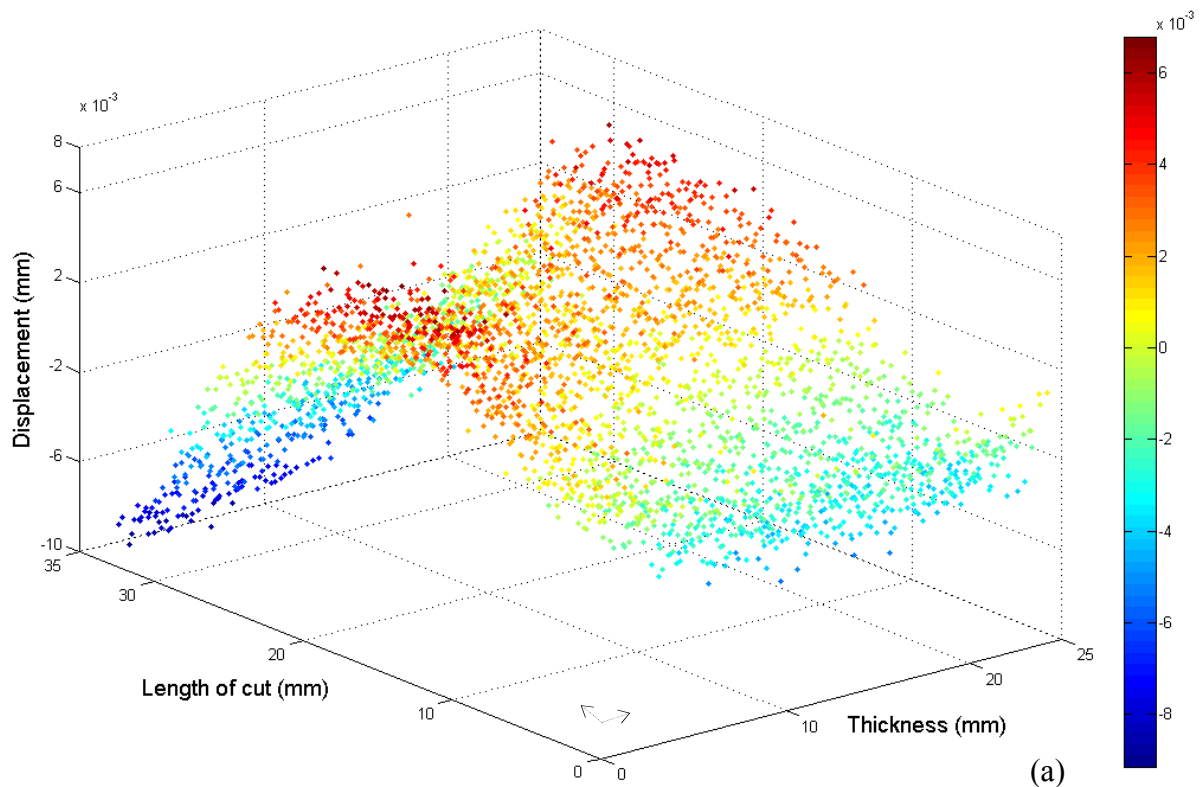


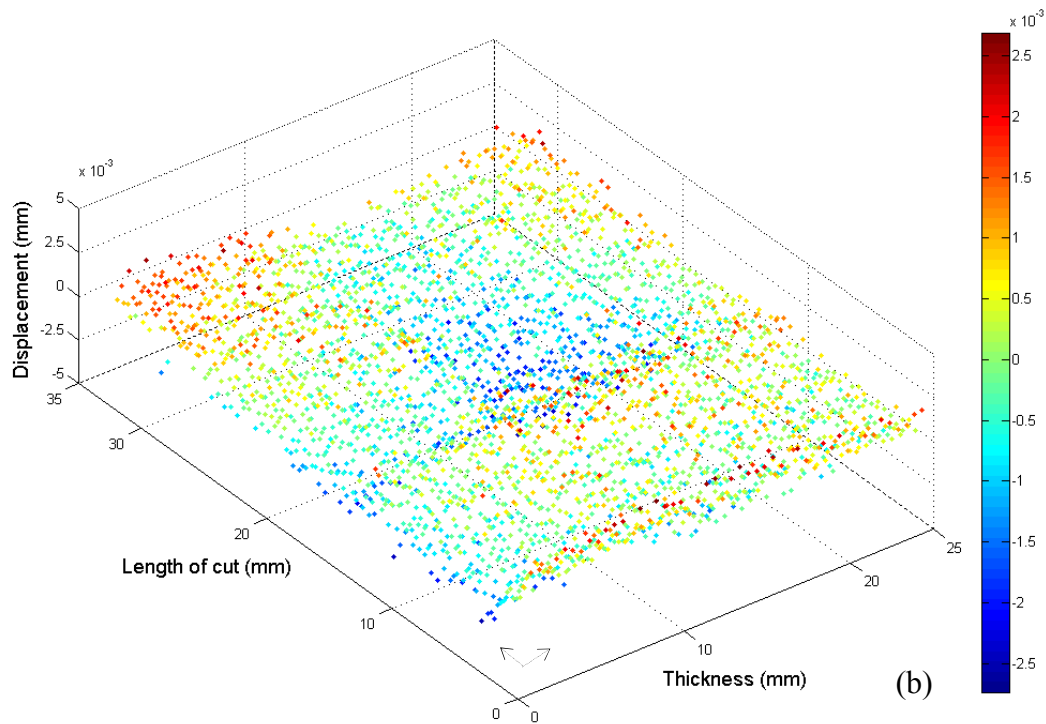
**Fig.1,** Fillet welded specimens (a). Ultrasonically peened, (b). Peened and corrosion tested condition

### Experimental Setup and Procedure

Residual stress characterization was performed by the contour method and neutron diffraction. Contour method measurements were carried out at The Open University UK and neutron diffraction experiment at ENGIN-X, ISIS. The detail and procedure of these measurements are summarized as below;

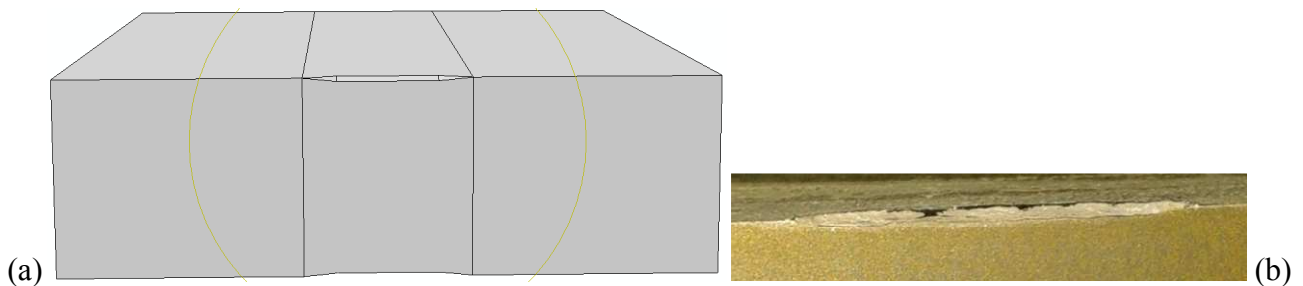
**Contour Method Measurements.** The contour method of residual stress measurement uses a wire electric discharge machine (WEDM) to cut the component in which the stress state is to be determined. WEDM is generally designed for manufacturing of mechanical parts/components for which multiple passes are made to obtain the desired surface profile: typically a “rough” cut is followed by several fine cuts. The EDM energy for the fine cut, giving good surface finish, is usually low. For application of the contour method a single cut is desired. The quality of contour results is highly dependent on the specimen cutting, particularly with regard to various artefacts associated with the WEDM cutting process [1]. Using small thickness sacrificial layers (composed of similar material) at critical locations (i.e. EDM wire entry and exit points, and the start and end of the cut) tends to reduce such cutting artefacts [5]. Therefore the need arises to select machine cutting parameters which are best in respect of surface profile/shape, roughness, data scatter range and induced residual stress. For this purpose a series of WEDM cutting tests were undertaken on stress-free material blocks of ship structural steel DH36. The WEDM cutting tests looked at different machines, wire diameters, machine default and modified settings. Tests were carried out without and with sacrificial layers made of DH36 steel and a low melting point alloy. One particular cutting condition was selected which was based on a reduced pulse duration setting as it gave best surface roughness, a flat cut and no notable cutting artefacts along the wire travel and cut path directions. Fig.2 shows averaged surface profiles measured using a co-ordinate measuring machine pertaining to machine default setting and the finally adopted setting. Sacrificial layers made of DH36 steel were used at the EDM wire entry and exit locations as well as at the start and end of the cut for both of these cuts. For DH36 steel a significant improvement in surface roughness was achieved from the WEDM default setting value of  $2.6\ \mu\text{m}$  to the reduced pulse duration setting of  $1.6\ \mu\text{m}$ . It is suggested to use a WEDM cutting condition for the contour method that gives the best surface roughness; and that the level of roughness achieved in WEDM cutting process is directly proportional to pulse duration time.





**Fig.2**, Isometric view of surface displacement profiles for (a). Machine default setting and (b). Modified setting

In addition to selection of the best cutting parameters, to obtain accurate results from the contour method it is essential that the cut geometry be modelled as near to reality as possible. This practice also helps to produce good near-surface residual stress results. Therefore the contour cut surface of both ultrasonically peened specimens was modelled by taking into account the actual cut portion of the UP groove and is illustrated in Fig.3 below for the UP specimen. The FE model used a non-uniform mesh along specimen thickness with refined mesh for near surface locations.



**Fig.3**, Contour cut surface of ultrasonically peened specimen (a). Model and (b). Actual cut surface

The measured surface contours were processed using Matlab analysis routines for data aligning, averaging, cleaning and smoothing with cubic splines. Linear elastic finite element analysis was performed using Abaqus with its 8-node brick element along with modulus of elasticity  $[E] = 210$  GPa and Poisson's ratio  $[v] = 0.3$ .

**Neutron Diffraction Measurements.** The stress free reference for the neutron diffraction experiment was obtained from measurements of 10  $d_0$  cubes of size  $3 \times 3 \times 3$  mm<sup>3</sup> which were extracted using WEDM from the as-welded fillet weld specimen at locations of weld, heat affected zone (HAZ) and at a distance of 7 mm below the weld toe. Three cubes were taken from the weld, four cubes from the HAZ and three cubes from a distance of 7 mm below the weld toe. For measurement of the  $d_0$  cubes, a gauge volume of  $2 \times 2 \times 2$  mm<sup>3</sup> was used. The centre of

measurement locations for the specimens is depicted in Fig.4. Measurements were made through the thickness of the weld toe at the attachment corner of two ultrasonically peened specimens and one as-welded specimen. For specimen normal and transverse strain components a gauge volume of  $2 \times 2 \times 2 \text{ mm}^3$  was used, whereas for the specimen longitudinal strain component a gauge volume of  $5 \times 2 \times 2 \text{ mm}^3$  was used to be more representative of the weld toe. The measured locations are at the centre of the weld toe at the attachment corner. The  $d_0$  measurements revealed that in the welds there is a higher directional dependence in the measured lattice parameters as compared to the HAZ and at 7 mm below the weld toe. This directional dependence in weld is about  $0.0009 \text{ \AA}$ . The individual measurement of cubes for all three regions showed better consistency, therefore average directional dependent lattice parameter values were used for residual stress calculation along with bulk material elastic modulus  $E = 210 \text{ GPa}$  and Poisson's ratio  $\nu = 0.3$ .

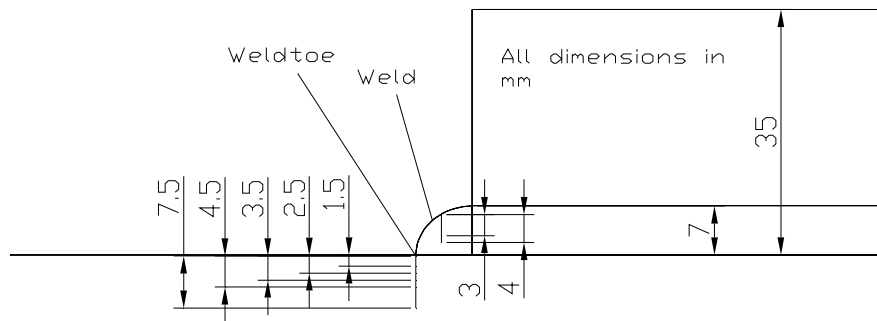
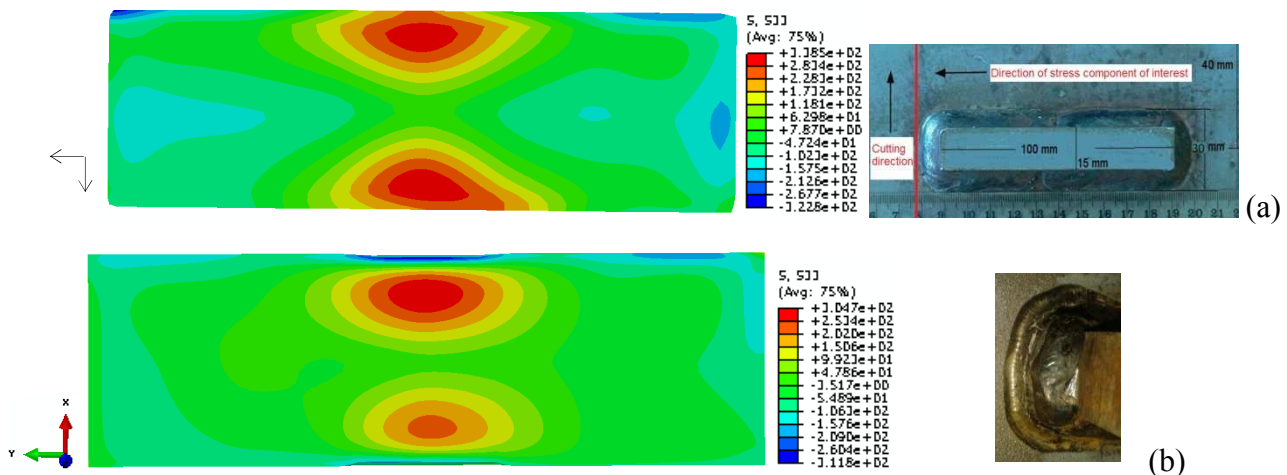
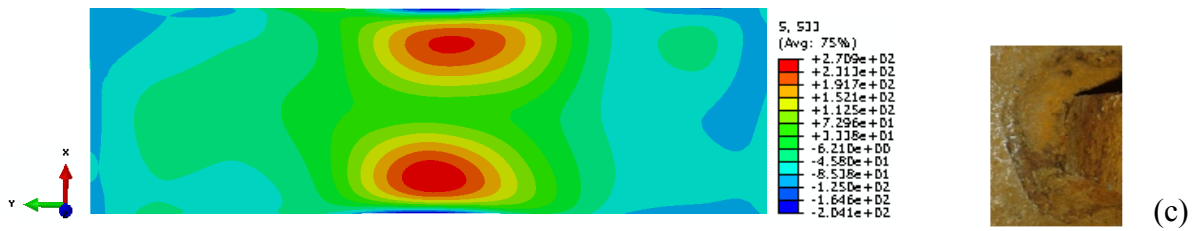


Fig.4, Measured locations for neutron diffraction experiment

## Results and Discussion

Fig.5 shows contour measurement residual stress results for the three specimens tested. The tensile residual stresses from the weld attachments are clearly visible in all cases. For the specimen subjected to UP (Fig.5b), the near-surface compressive stresses introduced by the peening are clearly observable. The peening has the effect of mitigating the surface tensile residual stress, with subsequent benefit to the fatigue performance. Following accelerated corrosion testing, there is little difference in the overall residual stress profile from ultrasonic peening (Fig.5c). There is still a measurable compressive residual stress at the surface.

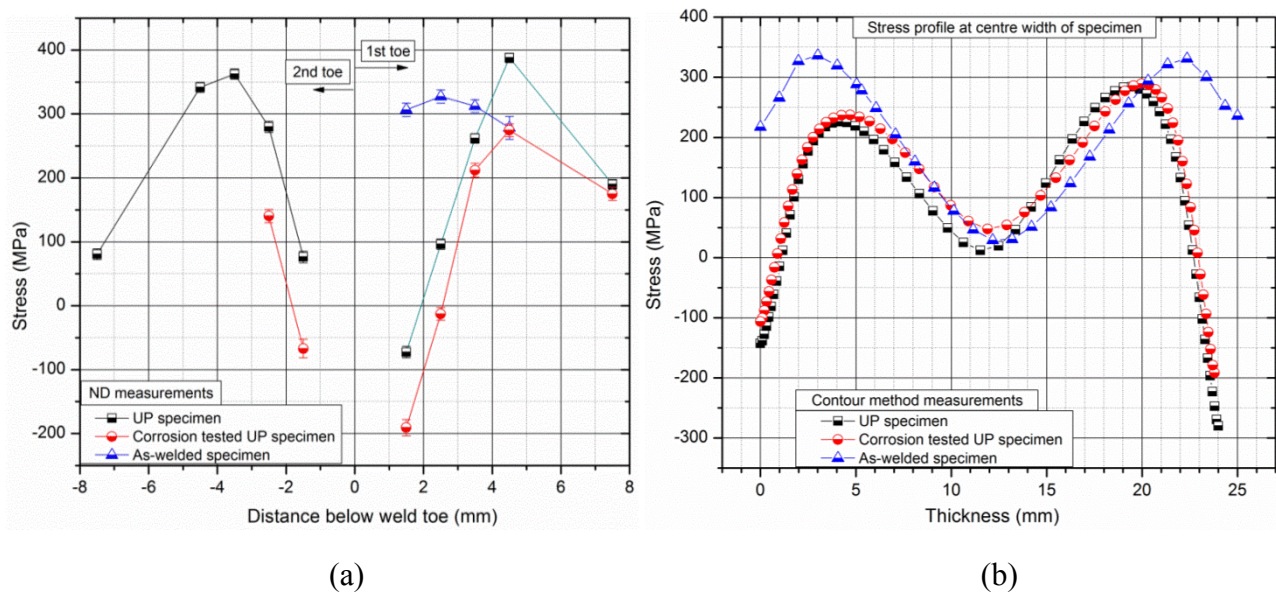




**Fig.5,** Comparison of the contour method stress maps for (a). As-welded, (b). UP and (c). Corrosion tested UP specimens

Fig.6 (a) shows neutron diffraction results below the weld toe, for the locations shown in Fig.4, and Fig.6 (b) shows a profile from the contour cut for comparison. Fig.6 (b) shows in detail that the effect of the corrosion has been to remove a layer of compressively-stressed material: however the overall profile of residual stress is essentially unchanged.

In the case of the ultrasonically peened specimen, the contour cut passed through the two UP groove locations on the upper and lower sides of base plate. On one side of the plate the cut passed through the centre of UP groove and on other side it passed through the edge of UP groove towards the weld: this asymmetry occurred because of slight misalignments in the weld attachment locations and the precise positioning of the UP line relative to the weld bead. Thus variation in cut location resulted in some difference of peak tensile stress at both weld toes as shown in Fig.6 (b). Additionally the compressive stresses at both weld toes are different because of variations in the peening process, as shown in both the contour method and neutron diffraction results. The surface of the corrosion tested UP specimen after removal of rust was uneven, which may have been caused by different exposure rate of artificial sea water and formation rate of corrosion product. This non-uniform surface resulted in a partially filled gauge volume for near-surface measurement using neutron diffraction, as well as incorrect estimation of measurement locations. However if the first measurement point is ignored and the following points are shifted, there is overall comparable results to the contour method.



**Fig.6,** Comparison of longitudinal residual stress profile of as-welded, UP and corrosion tested UP specimen (a). Neutron diffraction and (b). Contour method

## Conclusions

Residual stresses have been determined in fillet welded ship structural steel plates with longitudinal attachments. As-welded, ultrasonically peened, and specimens peened then subjected to accelerated corrosion testing were measured. Residual stress characterization was performed by the contour method and neutron diffraction. The contour cut process was optimized to obtain the best surface profile, in terms of roughness and flatness of the cut. Results show that the welding introduces tensile residual stresses into the material, which are mitigated by the ultrasonic peening treatment. However the ultrasonic peening for this case needs to be optimized to obtain reproducible results as different magnitudes of residual stress are observed at the different weld toes. Corrosion removes a layer of residually-stressed material from the surface, but the overall profile of the residual stress remains essentially the same.

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