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Residual stress determination in laser-peened high strength low alloy steel - Comparison of methodologies and reproducibility

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Department for **Innovation, Universities & Skills**

Residual Stress Determination in Laser-peened High Strength Low Alloy Steel – Comparison and Methodologies and Reproducibility

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ABSTRACT

The residual stress in laser-peened 300M steel has been determined using X-ray diffraction (XRD) by two different organisations in order to assess the degree of reproducibility. In addition, complementary hole-drilling has been undertaken to allow comparison of near-surface residual stress using the two different techniques. Good agreement between the two laboratories was obtained in relation to the circumferential stress and between results determined by XRD and hole-drilling. For axial stresses, the hole-drilling gave smaller stresses in absolute terms and the agreement between the XRD-determined residual stress data was less ideal though there was no systematic difference.

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1 INTRODUCTION

Shot peening and laser peening have been used extensively in a range of applications to introduce near surface compressive stress and minimise the risk of fatigue or environment induced cracking. On the whole this has been a successful strategy but it is not often appreciated that relaxation of this beneficial compressive residual stress may occur in response to service loading[1,2]. For high strength low alloy (HSLA) steels a primary concern is the possibility of hydrogen induced cracking should a combination of coating damage and relaxation of beneficial compressive residual stress occur. In previous work[3] we have focused on the extent of relaxation of compressive residual stress induced by shot-peening. A similar study is being undertaken for laser-peened specimens[4] but during the process of making residual stress measurement for this alloy and also for stainless steels there has been concern about the reproducibility of residual stress measurements by X-ray diffraction (XRD) and the comparison of results from XRD and incremental hole-drilling. Accordingly, in undertaking measurements of residual stress for the laser-peened specimens the opportunity was taken to compare XRD results between two separate organisations.

2 EXPERIMENTAL METHOD

The full details of the experimental method were described previously[3] and here only a brief summary is given.

2.1 MATERIAL AND SPECIMEN PREPARATION

The material tested was a 300M high strength low alloy steel with a nominal chemical composition: C:0.38-0.46; Cr:0.7-0.95; Mn: 0.6-0.9; Ni: 1.65-2.0; Si: 1.45-1.8; V: 0.05 min; P: 0.01 max; S: 0.01 max. The material was supplied by the industry partner in heat-treated pre-machined form (details are commercially restricted). Tensile testpieces with a 16 mm gauge length and diameter 8 mm were used. After machining, the specimens received a magnetic particle inspection to BS.EN ISO 9943-1. No surface-breaking cracks, or crack-like indications, were observed. An etching inspection was also carried out to check for overheating during machining. No abnormalities were found. The 0.2% proof stress in compression and tension were not measured directly on this particular batch of specimens but previously[3] were noted to be similar, with a value of about 1790 MPa for the former and 1713 MPa for the latter.

2.2 RESIDUAL STRESS DETERMINATION

The residual stress in the laser-peened test specimens was measured using X-ray diffraction (XRD) complemented by subsequent hole-drilling. For the former, separate measurements were made with the parameters as listed in Table 1. Comparison of XRD measurements from the two laboratories (Manchester Materials Science Centre, MMSC, and NPL) was made on the specimens after application of stress. Note that MMSC was using a portable diffractometer specifically designed for residual stress measurement which incorporated a position sensitive detector, whilst NPL used a laboratory based multi-purpose diffractometer which incorporates a scintillation detector; hence, the difference in the test parameters in Table 1.

Table 1. Test parameters used by MMSC and NPL for the residual stress measurements

Parameter	Manchester	NPL
X-ray radiation (kV, mA)	Cr K-α (20,4)	Cr K-α (30, 40)
Bragg angle	154 °	154 ° Measurement range 148-160°
β-tilt angle	± 28°	NA
β-oscillation amplitude	3°	ψ oscillation of 3° at 90°/min
Collimator	1.0 mm and 1.0×5.0 mm	1.0
Exposure time×N	4 s × 10 (1.0 mm collimator) 2 s × 10 (1.0×5.0 mm collimator)	360 s × 17

The incremental hole drilling measurements were carried out according to the procedures outlined in NPL Good Practice Guide No 53[5]. Measurements Group type 031RE gauges were used, installed at the centre of each specimen gauge length with element 1 aligned with the axial direction and element 3 with the circumferential direction. Following analysis, the strain data were outputted in the form of axial direction stress (σ1), circumferential direction stress (σ3) and shear stress (τ13) components at selected depth increments. No allowance has been made for the curved surface. The uncertainty in hole-drilling measurements of residual stress using this procedure would be about ± 50 MPa.

2.3 LASER PEENING

The laser peening was carried out by Metal Improvements Company LLC, using high power density laser pulses (several GW/cm^2) fired at the surface of the metal that was coated with an ablative film (tape), and covered with a transparent tamping layer (water). As the laser beam passes through the transparent layer and hits the surface of the metal, a thin layer of the ablative layer is vaporized. The vapor continues to absorb the remaining laser energy and is heated and ionized into plasma. The rapidly expanding plasma is trapped between the ablative layer and the transparent layer by the inertia of the water, creating a high surface pressure, which propagates into the material as a shock wave plastically straining the near surface layer. The plastic strain results in residual compressive stress that can penetrate to depths of 100 micron or up to 8 mm, as desired, depending on the material and the processing conditions. In this instance, as the samples were only 8mm thick, parameters of 6-18-2 were used; 6 GW/cm^2, 18 nanosecond pulse width, 2 layers or passes of the laser and spot size of 3.85 mm ×3.85 mm.

2.4 LOAD APPLICATION

For the six laser-peened specimens available only discrete testing was possible with predominantly single-shot applied stress and one test under cyclic loading (10000 cycles at an applied stress range of -950 MPa to +950 MPa). For the single-shot loading, the load was applied in compression or tension from zero to the target load and the specimen then off-loaded to allow residual stress determination.

The tests were performed on a servo-electric, 2-column, Instron 8562 test machine with a frame capacity of 250 kN and with a 100 kN load cell calibrated to Class 1 according to BS EN 10002-2: 1992. Notably, the machine was equipped with a special alignment fixture that allowed the precise alignment of the load train, using a Nimonic 101 alignment cell. The test machine was classified as class 2 prior to starting the test programme, this equates to a machine bending contribution of less than 2% at an applied axial strain of 1000 $\mu\varepsilon$.

3 RESULTS AND DISCUSSION

The tabulated data for the different XRD measurements are listed in Tables A1-A3 in Appendix 1. The stresses applied to each specimen are given in Table 2.

Table 2. Stresses applied to each specimen. Specimen 1 was subjected to cyclic loading

Specimen no	Stress applied/MPa
1	-/+950
3	-1440
6	+1713
10	-1790
25	-1000
26	+1440

The data for the final residual stress after loading are summarised for the axial and circumferential residual stress in Figures 1 and 2 respectively. For the latter, only data from the 1 mm collimator data are shown but apart from one anomalous result (Appendix 1, Table A3, Specimen 6) there was little difference in circumferential stress for the two collimated beams.

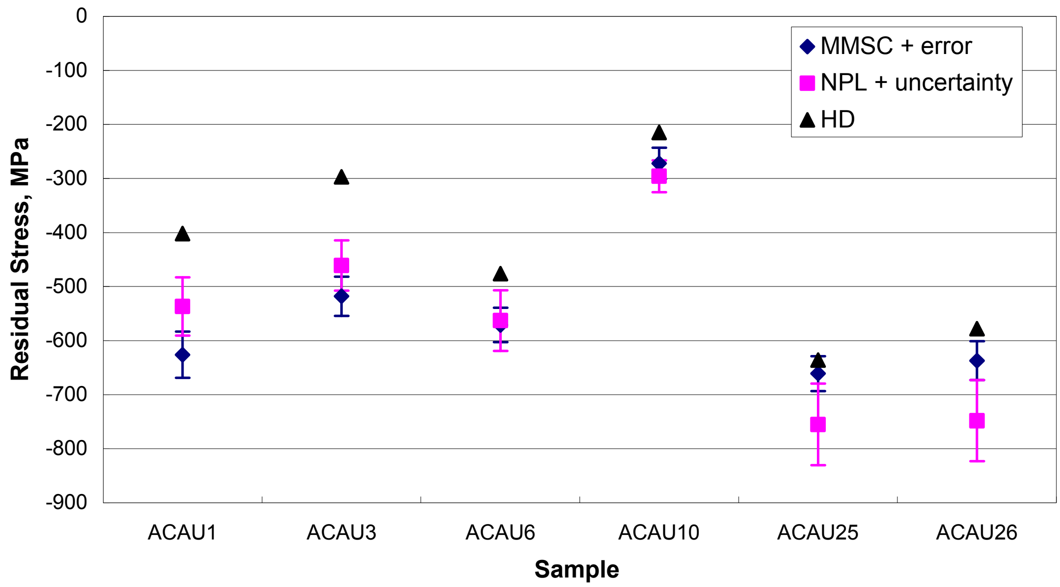

Figure 1. Comparison of axial residual stress values in shot-peened 300 M steel determined from XRD measurements from MMSC and NPL and from incremental hole-drilling data (at a depth of 8 µm in this case).

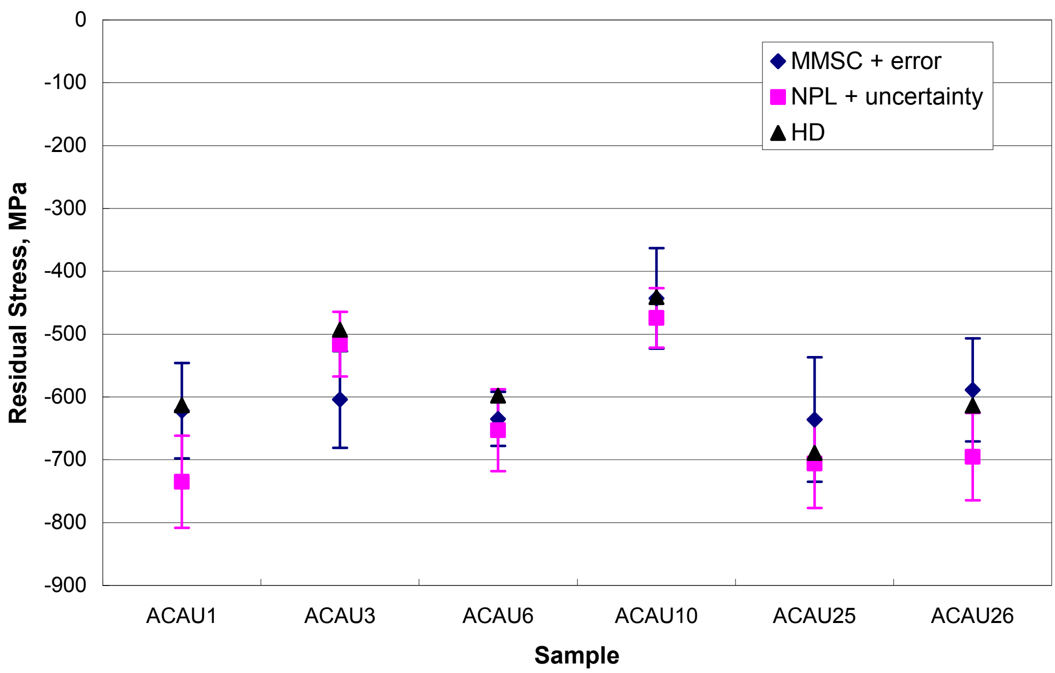

Figure 2. Comparison of circumferential residual stress values in shot-peened 300 M steel determined from XRD measurements from MMSC and NPL and from incremental hole-drilling data (at a depth of 8 µm in this case).

The error in relation to the results from MMSC arises from the fitting procedure. The uncertainty in the NPL is based on an uncertainty budget that incorporates that error and measurement repeatability. In the latter case, measurements were also made along an individual specimen to check for intrinsic variability in the testpiece since that could have affected comparison of data between the two laboratories. Except at one extreme location, the variability was less than ±50 MPa and within the span of uncertainty for the NPL data shown in Figures 1 and 2.

The measurements for the circumferential stress show very good agreement for the three sets of data. For the axial loading, the XRD results are relatively close. Though there are some differences, there is no systematic variation for the different specimens. Assuming a homogeneous stress state within the surface of the gauge length the results do infer that the uncertainty associated with an individual laboratory measurement for these conditions can be as much as ± 100 MPa, if the uncertainties in the two sets of data are combined. Nevertheless, the trend in the data is similar and provided a set of measurements was made within one laboratory the uncertainty would be less in relative terms.

The results for the hole-drilling do differ from the XRD data and the difference is systematic with the residual stress from hole-drilling consistently lower in absolute magnitude. The residual stress in these laser-peened specimens diminishes as the surface is approached[4]. Hence, at a depth of 8 μm the absolute stress would have been expected to be greater than for the XRD measurements, which sample the first 10 μm from the surface. The trend in the data with specimen history is similar but at this stage we have no intrinsic basis for assessing what the true value of the residual stress is.

4 CONCLUSIONS

A comparison of residual stress data derived from XRD measurements using two different laboratories indicates consistent trends in data for the six different 300M steel specimens evaluated.

There was good agreement between the laboratories with respect to the circumferential stress and this agreement extended to the hole-drilling measurement at 8 μm from the surface.

For the axial stress, the agreement between the XRD determined residual stress data was less ideal and the differences non-systematic. On an individual measurement basis, this could constitute an effective uncertainty of ±100 MPa.

The axial residual stress estimated from hole-drilling was consistently smaller, in absolute terms, than from XRD, despite the absolute stress decreasing towards the surface, but there is no a prior way of knowing at this stage which set of values is correct.

5 REFERENCES

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APPENDIX 1

Tabulated measurements of residual stress.

Table A1. Axial stresses

Specimen no	Initial residual stress /MPa	Stress applied/MPa	Final residual stress/MPa (Manchester)	Final residual stress/MPa (NPL)	Laser peening at depth 8 µm/ MPa (final)
1	-811±25	-/+950	-626±43	-537±23	-402±50
3	-797±31	-1440	-518±36	-461±46	-297±50
6	-697±18	+1713	-571±32	-563±28	-476±50
10	-725±35	-1790	-272±29	-296±45	-215±50
25	-650±34	-1000	-661±32	-755±54	-636±50
26	-695±24	+1440	-637±36	-748±33	-578±50

Table A2. Circumferential stresses 1mm collimator

Specimen no	Initial residual stress/MPa (Manchester)	Stress applied /MPa	Final residual stress /MPa (Manchester)	Final residual stress/MPa (NPL)	Hole drilling at depth 8 µm/ MPa (final)
1	-693 ± 109	-/+950	-622±76	-735±30	-613±50
3	-715 ± 100	-1440	-604±77	-516±56	-493±50
6	-585 ± 63	+1713	-635±43	-702±30	-618±50
10	-667 ± 91	-1790	-443±80	-474±41	-441±50
25	-600 ± 143	-1000	-636±99	-706±37	-689±50
26	-634 ± 111	+1440	-589±82	-695±19	-614±50

Table A3. Circumferential stresses 1mm×5 mm collimator

Specimen no	Initial residual stress /MPa (Manchester)	Stress applied /MPa	Final residual stress /MPa (Manchester)	Hole drilling at depth 8 µm/ MPa (final)
1	-608 ± 92	-/+950	-638±29	-613±50
3	-588 ± 84	-1440	-509±59	-493±50
6	-420 ± 27	+1713	-601±28	-618±50
10	-604 ± 70	-1790	-393±72	-441±50
25	-616 ± 147	-1000	-589±90	-689±50
26	-568 ± 113	+1440	-496±70	-614±50