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Residual Stress Relaxation in
Shot-Peened High Strength
Low Alloy Steel

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ABSTRACT

The relaxation of residual stress in a shot-peened high strength low alloy steel in response to applied loads has been investigated for both single-shot and cyclic loading. The near surface residual stress was measured predominantly by X-ray diffraction (first 10-20 μm) but supplemented for some conditions by measurements using high resolution, fine increment hole-drilling to yield depth profiling. The compressive residual stress showed a peak at about 50 μm below the surface. Under single-shot compressive loading, relaxation became significant when the combined surface and applied compressive stresses exceeded the proportional limit of the unpeened surface. The steel showed good resistance to residual stress relaxation under cyclic loading conditions, with only a 13% decrease despite cyclic load amplitudes at 50% of the 0.2% proof stress in compression. Significant relaxation did occur at applied stress amplitudes of about 80% of the 0.2% proof stress in compression. Whilst large single-shot or cyclic stresses would represent rare occurrences, they could lead to a marked loss in beneficial compressive stress and should be accounted for in structural integrity assessment.

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1 INTRODUCTION

High strength low alloy steels are used in a wide range of applications where strength to weight ratio is critical; e.g. tension wires, fasteners, aircraft landing gear, and in many structural components. However, the steels can be susceptible to hydrogen embrittlement¹ with the potential for failure in service. In addition to processing of the alloys to optimise resistance of the microstructure, reduction in the risk of cracking is achieved by limiting hydrogen entry (application of coatings and well controlled cathodic/galvanic protection) and by minimising tensile stress. In some applications, control of the stress is achieved by inducing large compressive residual stresses in the near-surface region by shot-peening. The latter has had considerable success and has been used in the power, aerospace and nuclear industries to enhance structural integrity. However, relaxation of the beneficial compressive residual stress in response to service loading is a possibility, especially where high amplitude fluctuating loads are important.

Residual stress relaxation in response to mechanical loading is not a new phenomenon and, indeed, has been exploited as a means of reducing undesired tensile residual stress in components². There has been a number of research investigations³⁻¹⁶ based on experimental measurement and modelling, including an incisive review by Lohe and Vohringer¹². More recently, Turnbull¹⁷ gave a brief overview of the literature on residual stress relaxation in shot-peened samples and broadened the scope to include an assessment of the impact of shot-peening on hydrogen uptake. The perspective that macroscopic or microscopic yielding is required for residual stress relaxation under the action of the combined applied and residual stress is self-evident but there was sufficient inconsistency in results that confidence in predicting behaviour for other alloys is limited. Furthermore, the use of X-Ray diffraction in these studies constrains assessment of the extent of relaxation to the near-surface, on the order of 10-20 μm .

Here, we report the results of an investigation of residual stress relaxation in a shot-peened ultra high-strength steel in response to single-shot and cyclic loading using both X-ray diffraction and high resolution, fine increment, hole-drilling to measure the near-surface residual stress and the variation with depth. The primary aim is to provide support to industry in assessing the possible implications for structural integrity.

2 EXPERIMENTAL METHOD

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). The dimensions of the tensile testpiece are shown in Figure 1.

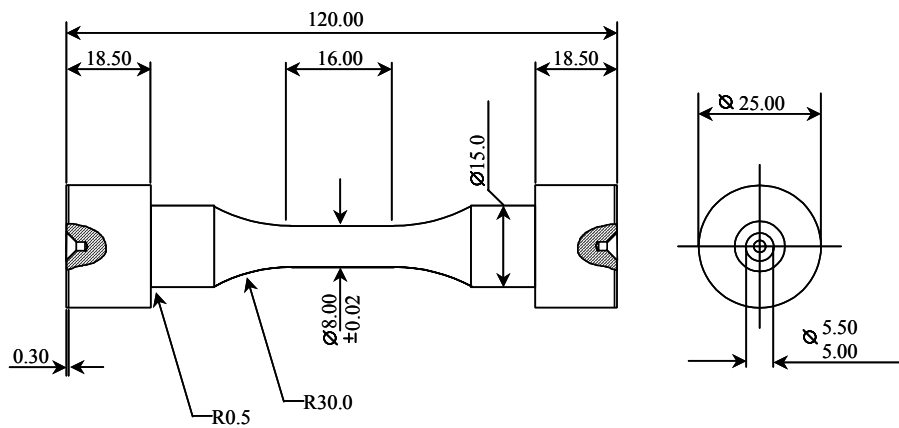
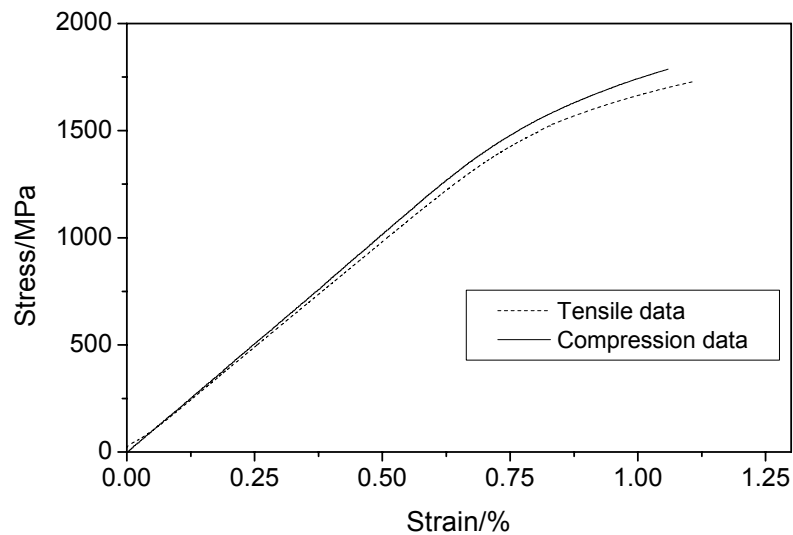


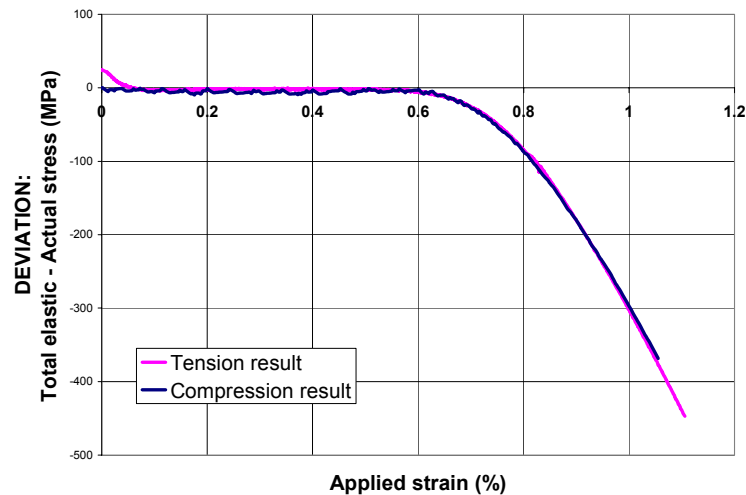
Figure 1. Dimensions of tensile test specimens

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 compressive stress-strain curve of the heat treated material was measured prior to shot peening (loading rate of about 2 MPa/s), and is shown in Figure 2 (a). Comparison is made with tensile data*. There was no distinct yield point for this material. The 0.2% proof stress in compression and tension were similar with a value of about 1800 MPa for the former and 1713 MPa for the latter.



(a)

* Tensile test results were provided by industry partner



(b)

Figure 2. (a) Stress-strain behaviour of 300M and (b) deviation from linearity.

The departure from linearity (proportional limit) in the stress-strain behaviour was also quite similar in compression and tension as evidenced by Figure 2 (b). However, the values deduced from the experimental data depend on the fitting procedure and the derivation of the proportional limit in relation to the relative change of gradient. We estimate a proportional limit in tension of 1245 MPa (strain: 0.64%) and 1352 MPa in compression (strain: 0.67%) but values as low as 1150 MPa in tension and 1300 MPa in compression could be envisaged with slightly different criteria in the analysis.

After final machining the specimens were shot-peened by Metal Improvement Company according to the specification: MI 230H, 8 to 12 Almen A, and 100% coverage.

2.2 Residual stress determination

The residual stress in the shot-peened test specimens was measured primarily by using X-ray diffraction (XRD), with a beam size sufficient to sample most of the gauge length, until testing on the particular specimen was complete. Then, for select specimens, the hole-drilling technique was adopted. From previous experience at NPL the X-ray diffraction method gives the strain in the first 10-20 μm or so for steels and thus measures only near-surface residual stress, whilst the hole-drilling measurements were carried out to depths of 500 μm and give information on the residual stress profile. For the X-ray measurements, a Siemens d500 diffractometer, with chromium radiation, vanadium filter and scintillation detector, was used.

The residual stress in the shot-peened specimens was determined by X-ray diffraction prior to application of stress, and the distribution of near surface axial and hoop residual stress in the 22 specimens examined is shown in Figures 3. The typical uncertainty in the actual measurement process would be ± 25 MPa for axial stress measurement and about ± 40 MPa for hoop stress measurement.

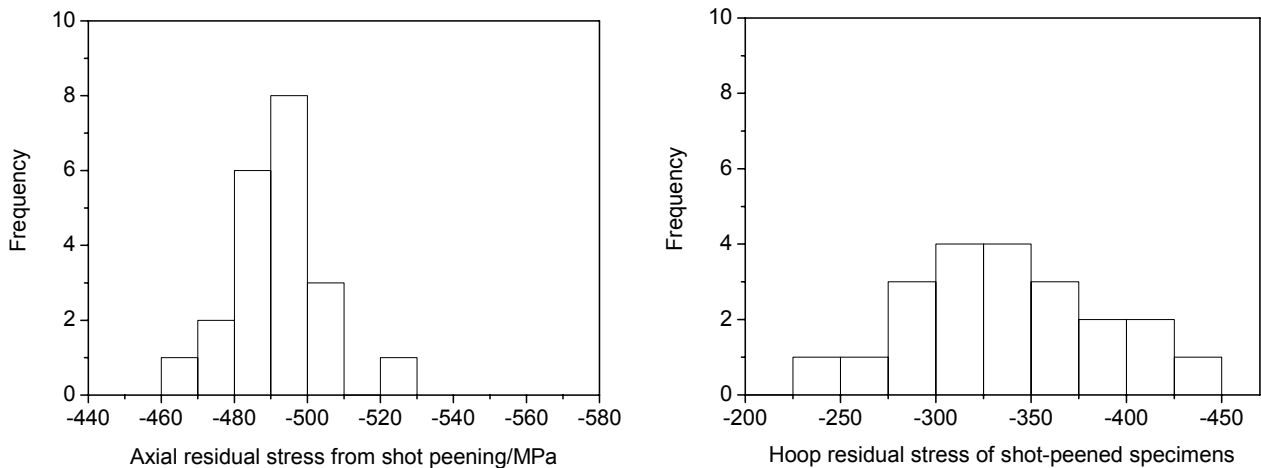


Figure 3. Variability of the near surface axial and hoop residual stresses induced by shot peening.

There is a reasonably tight distribution for the axial residual stress but a much more dispersed distribution for the hoop stress. A possible explanation for the scatter in the hoop stress values is due to the lack of a collimator during shot peening, which would normally ensure that the incident angle of the shot remained about 90° . On the small diameter cylindrical specimen this has probably led to varying impact damage, and subsequent variation in hoop stress values. However, there is also a possible contribution from uncertainty in X-ray measurement associated with the beam size and specimen curvature. Systematic testing with a collimated beam was not undertaken for all specimens as it is particularly time-consuming but for one specimen tested at various locations round the circumference, the average hoop stress was greater when compared with the previous measurements. In view of the variability in hoop residual stress, the focus on this study in relation to the X-ray measurement is on the axial stress component. As such, testing was undertaken with specimens with similar axial residual stress in the range -485 MPa to -503 MPa.

The hole drilling measurements were carried out by Stresscraft Ltd, according to the procedures outlined in NPL Good Practice Guide No 53¹⁸. 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, as shown in Figure 4. Surface preparation involved a light swab etch followed by neutralization and degrease; no abrasion was applied to the target sites. Gauges were bonded using Loctite 407. Orbital drilling was carried out at $8 \times 16 \mu\text{m} + 4 \times 32 \mu\text{m} + 8 \times 64 \mu\text{m}$ increments using an inverted cone WC cutter and the strain data analysed using the Stresscraft HD RS Int V5-1 Integral method spreadsheet. Within the data reduction

program, the strain data was subjected to a variable smoothing process and then reduced to axial direction stress (σ_1), circumferential direction stress (σ_3) and shear stress (τ_{13}) 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.



Figure 4. Hole drilling set-up

2.3 Load application

In service, structures and components may be subject to quasi-static loading, impact loading, low amplitude cyclic loading and occasional large amplitude cycles with often a complex load spectrum and history. It was not possible to cover all eventualities and for this study emphasis was given to single-shot loading, cyclic loading and cyclic loading followed by a single compressive overload. 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. Measurement under load would have been ideal but this is not readily feasible and it is commonplace to measure only the residual stress off-load. Several additional tests in compression were conducted in which a load equivalent to half the target compressive load was applied initially, the specimen unloaded and the single-shot load then applied. Though perhaps not incisive tests, the data for these are also reported. The cyclic loading was undertaken mainly in compression-tension with varying load amplitudes though with one additional test in tension followed by compression. A further test was undertaken for which the specimen received 10,000 cycles at ± 597 MPa (one third of 0.2% proof stress in compression) and then a single shot compressive load of -1223 MPa was applied.

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, prior to starting the test programme (details given in the Appendix). A

2620-602 extensometer (1923) with a 12.5mm gauge length was used to measure the strain in the specimens where appropriate.

On completion of testing, a few specimens were sectioned, ground and polished to a 1 μm finish, and then etched to reveal the microstructure.

3 RESULTS

3.1 Single-shot loading

The axial residual stress measured by X-ray diffraction after single-shot loading is shown in Figure 5. The value at zero applied stress represents the mean value of the residual stress in all the specimens prior to testing. The general behaviour conforms to that reported by Lohe and Vohringer¹² for shot-peened AISI 4140 steel insofar as the relaxation of residual stress with applied tensile stress was more rapid than for applied compressive stress. For the applied compressive stress, the onset of residual stress relaxation occurred at applied stress values close to -950 MPa . On the basis of the near surface stresses only, this corresponds to the situation where the combined stress (applied and residual compressive stress at surface) was about -1440 MPa , just in excess of the proportional limit for the unpeened steel. This should be compared with a 0.2% proof stress in compression of about -1800 MPa . When the applied stress was tensile, the onset of relaxation can be deduced to be in the range $1450\text{--}1500\text{ MPa}$, significantly greater than the proportional limit for the unpeened steel in tension (about 1245 MPa) suggesting that there is a constraint to deformation, at least in the near-surface region.

Within the general trend of results, as distinct from just the data-points at the specific applied stress, it is not possible to conclude with confidence that the preceding loading to half the applied load value, or applying 10000 cycles at one-third of the compressive yield stress, had a definitive effect on relaxation.

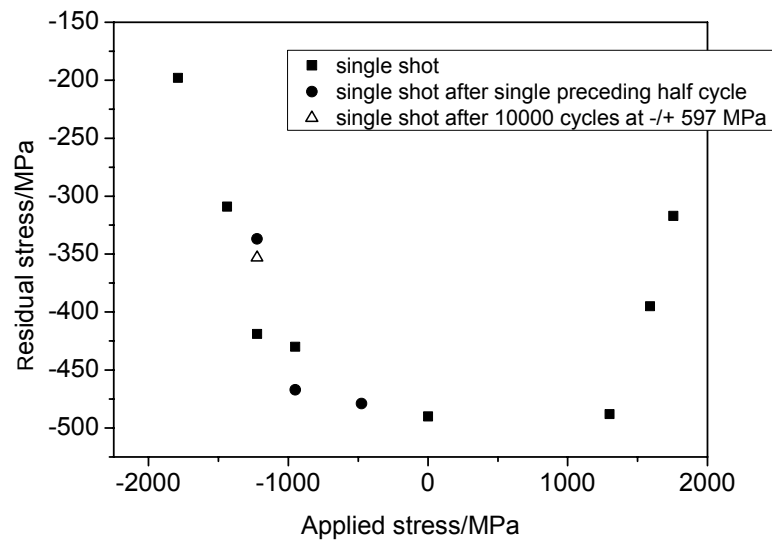


Figure 5. Relaxation of axial residual stress following primarily single-shot loading

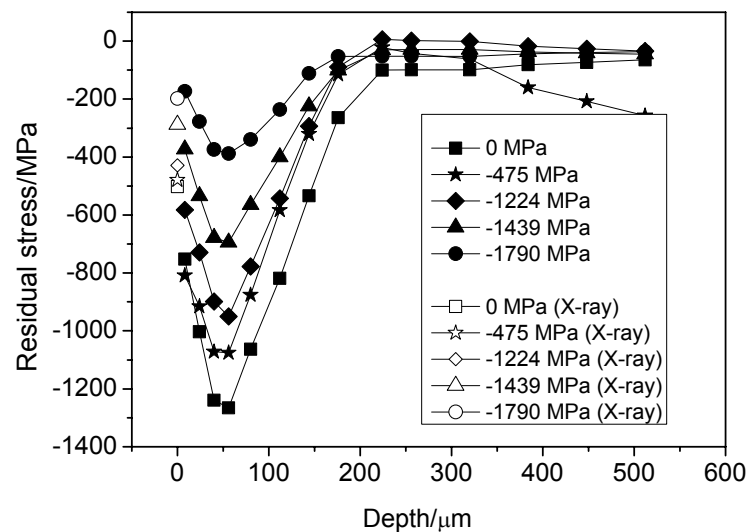


Figure 6. Depth profile of (axial) residual stress for varying applied compressive stresses.

The axial residual stress profiles measured by hole-drilling on a number of discrete specimens are shown in Figure 6. Extrapolation of the data to the surface gives reassuring agreement with the stresses determined from X-ray diffraction. The residual stress peaks at about 50 μm below the surface and is close to zero at a depth of about 250 μm . For these measurements, the stress does not quite go tensile, as would be expected in order to balance the near-surface compressive stresses, but this most likely reflect limitations of the technique in characterising the residual stress at significant depth in small diameter specimens, together with the small value expected. Such high residual compressive stresses, approaching -1300 MPa, are necessary to ensure that the

likelihood of a net tensile stress in the presence of absorbed hydrogen atoms is minimised.

In contrast to the X-ray diffraction measurements and near-surface behaviour, there is indication of relaxation of the peak stress at an applied compressive stress of -475 MPa. A similar result was obtained in a specimen that had been subjected to 130000 cycles (stress ratio = -1) at this stress amplitude. Since the combined applied and peak residual stress approaches the yield stress in compression some relaxation might be expected but with possible elastic constraint associated with adjacent material at lower combined stress levels. In both cases, the relaxation was modest and when account is taken of the variability associated with residual stress determination by hole-drilling it cannot be considered conclusive.

The progressive decrease in the axial peak compressive residual stress with high applied stress is not reflected in the hoop stress (Figure 7), which shows a response to applied load only when the magnitude of the applied stress is -1790 MPa suggesting a threshold for relaxation between this value and -1439 MPa.

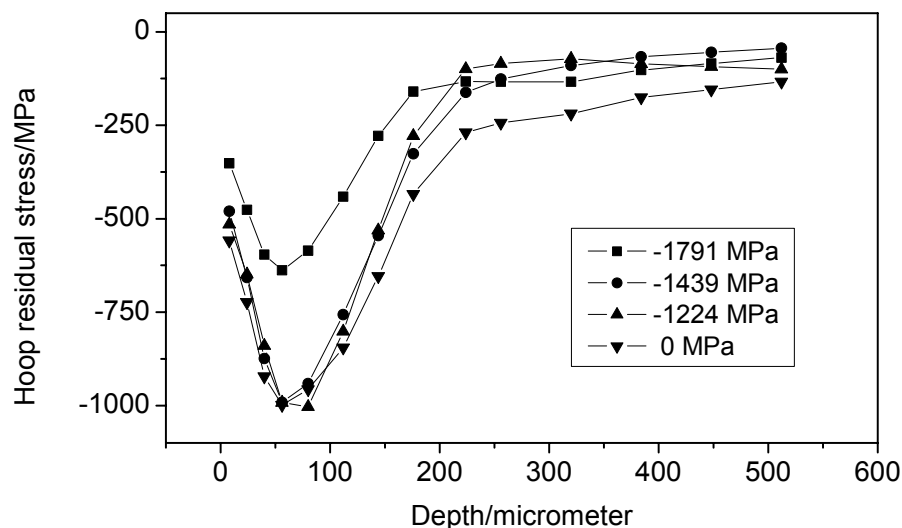


Figure 7. Depth profile of (hoop) residual stress for varying applied compressive stresses.

3.2 Cyclic loading

The single-shot loading tests reported in the previous section were designed to examine the change in the residual stress in response to occasional high service loads. Cyclic loading at low stress amplitude is more common. However, service loading is generally complex and there can be numbers of cycles of varying amplitude. Accordingly, the effect of stress amplitude on the residual stress relaxation was explored, mostly in compression-tension, for the conditions listed in Table 1.

Table 1. Cyclic loading conditions ($\sigma_{0.2c}$ and $\sigma_{0.2t}$ are respectively the 0.2% proof stresses of unpeened steel in compression and tension)

Cyclic stress range/MPa	Cyclic stress range in terms of proof stress
-/+ 474	-26% $\sigma_{0.2c}$ /+28% $\sigma_{0.2t}$
-/+ 597	-33% $\sigma_{0.2c}$ /+35% $\sigma_{0.2t}$
-/+ 950	-53% $\sigma_{0.2c}$ /+55% $\sigma_{0.2t}$
-1440/+1589	-80% $\sigma_{0.2c}$ /+93% $\sigma_{0.2t}$
+1589/-1440	+93% $\sigma_{0.2t}$ /-80% $\sigma_{0.2c}$

The value for the highest stress amplitude in the compression half of the cycle mode was chosen on the basis that it was close to the proportional limit for the unpeened material, and for the tension half cycle on the basis that it just exceeded the stress for relaxation in the single-shot test. The results are shown in Figure 8. For comparative purposes in this logarithmic plot, the initial residual stress values prior to cycling were arbitrarily set at 0.1 Hz. Over 130,000 cycles were accumulated at the lowest stress amplitude before failure of the specimen occurred in the gripping region at the sharp change in cross section. There was only a marginal decrease in the surface residual stress for this loading condition, which could be considered to be within measurement uncertainty. This would appear to be confirmed by the absence of any relaxation after 10,000 cycles at the higher stress range of -/+597 MPa.

At cyclic stress amplitudes of -/+950 MPa, for which the possible onset of relaxation was indicated by the single-shot test, there appeared to be a sustained decrease in the near surface residual stress value with increasing number of load cycles. A large number of cycles at such high stress amplitude would not be expected in most service applications so the number of cycles was limited to 1000. In reviewing the literature¹⁷ it was apparent that some degree of relaxation was invariably observed in the first load cycle (albeit all starting tension then compression) with either no further relaxation or a more progressive relaxation with increasing number of cycles. To resolve whether our own observations of a trend represented simply measurement uncertainty or test variability, repeat tests were undertaken for two other specimens. The results for all three are shown in Figure 9. They confirm that there is indeed a partial stress relaxation, albeit modest, but do not convincingly support an impact of increasing numbers of cycles beyond the first cycle. The explanation for the results of Specimen 1 may be associated with the borderline nature of the applied stresses for which the combined residual and applied stress is close to the proportional limit. Slight variations in testing conditions or measurement repeatability may account for the lack of apparent response on the initial cycle for Specimen 1. Of course, it may be argued that the trend is real in this test specimen and the differences from the other specimens may reflect some variation of residual stress distribution. The data simply indicate that any trend, should it exist, is not generic for this test condition.

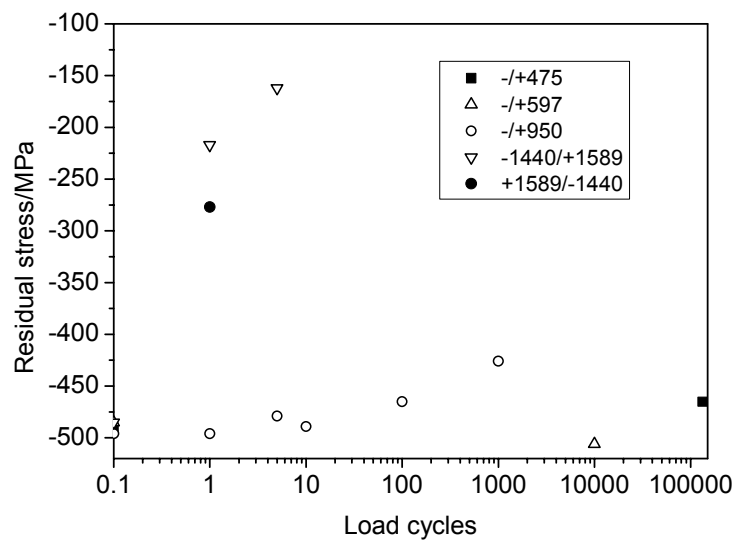


Figure 8. Relaxation of residual stress in response to cyclic loading. For comparative purposes in this logarithmic plot, the initial residual stress values prior to cycling were arbitrarily set at 0.1 Hz

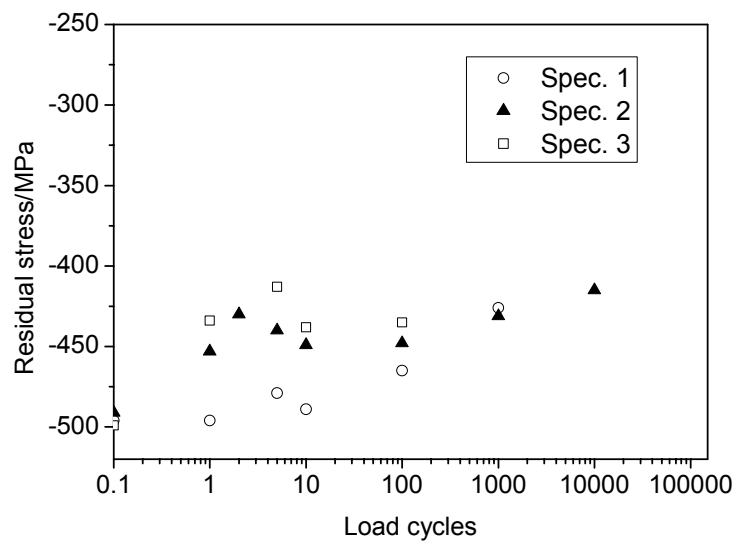


Figure 9. Assessment of repeatability of residual stress relaxation in response to cyclic loading at ± 950 MPa. For comparative purposes in this logarithmic plot, the initial residual stress values prior to cycling were arbitrarily set at 0.1 Hz.

At the highest stress amplitude, relaxation after the first cycle appears to be more significant than a single-shot compressive load of the same magnitude. Additional relaxation is expected in view of the observed relaxation under single-shot tensile loading at the corresponding tensile stress with a potential contribution from the Bauschinger effect. After 5 cycles, further relaxation was apparent. In service applications, such very high applied stresses would be rare events and a high cycle

number would be inappropriate. The application of a tensile stress and then a compressive stress appeared to give less residual stress relaxation compared to the inverse loading but the data are perhaps too limited to be conclusive. Nevertheless, the relaxation is still greater than for single shot loading in tension or compression for comparable maximum loads.

Determination of residual stress by hole drilling was undertaken for separate specimens at 100, 1000, and 10000 cycles. The test procedure and analysis was the same as that described previously, and the results are shown in Figures 10 and 11. The stresses at greatest depth are again poorly characterised, reflecting the challenge in measurement in small diameter specimens. There was a spread in results but the behaviour was again consistent with the X-ray measurements (axial stress). The important observation is that there is no systematic decrease in residual stress with number of load cycles, both near-surface and sub-surface.

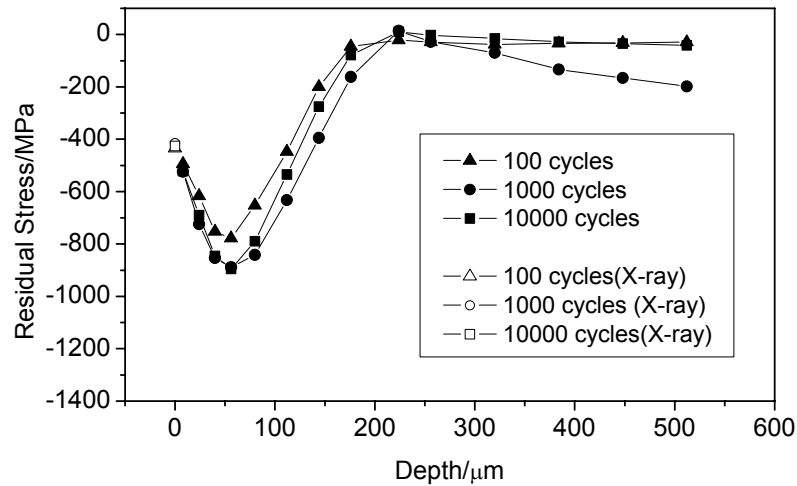


Figure 10. Depth profile of (axial) residual stress with number of loading cycles at ± 950 MPa

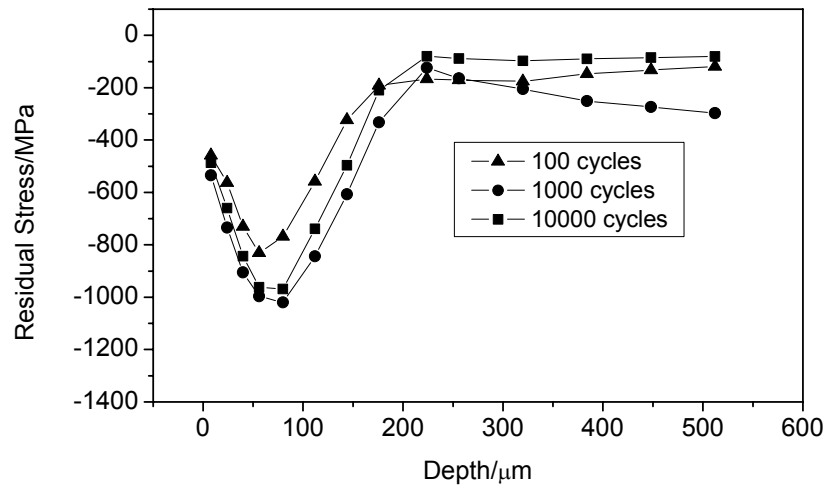
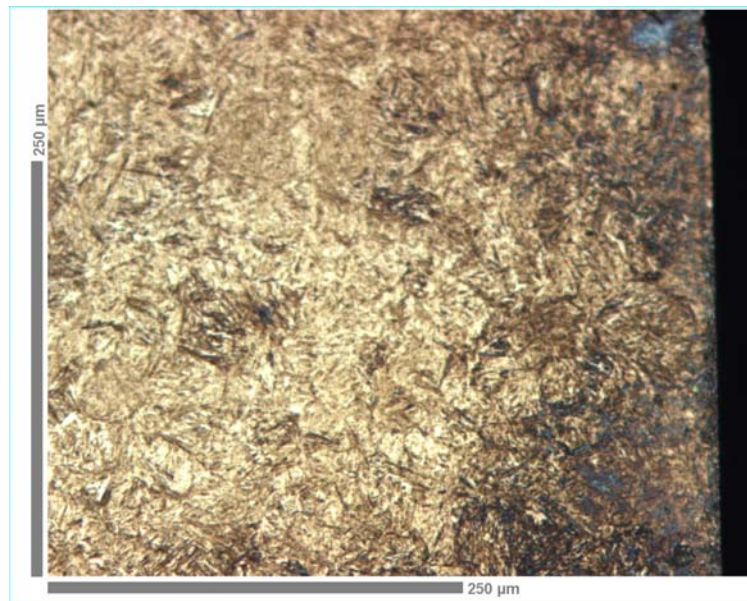


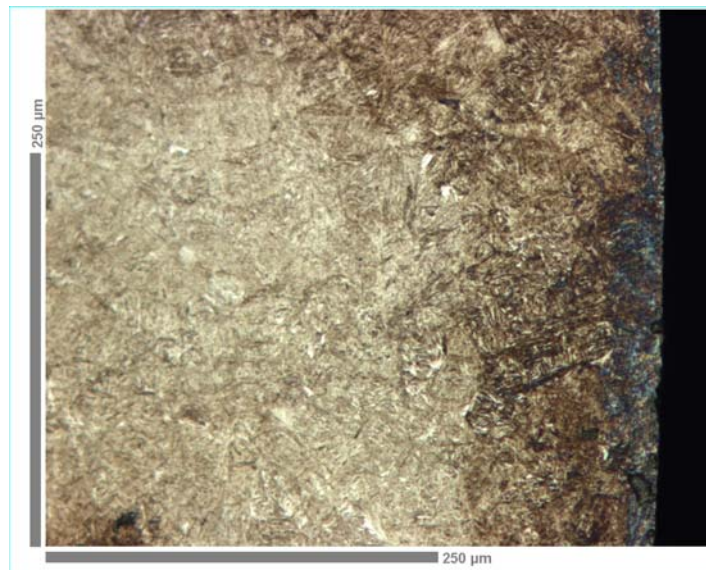
Figure 11. Depth profile of (hoop) residual stress with number of loading cycles at $-/+950$ MPa

3.3 Microstructural evaluation

Example images of the microstructure are shown in Figures 12 (a) and (b) respectively for shot-peened unstressed condition and after an applied stress of -1790 MPa. At this magnification, there was no significant difference in the martensitic laths between the shot-peened and core regions (recalling that the compressive residual stress tended to zero at a depth of about $250\text{ }\mu\text{m}$). Furthermore, there was no discernible influence of the applied stress within the limits of optical evaluation, though the captured images are perhaps not ideal.



(a)



(b)

Figure 12. Near-surface microstructure for shot-peened specimen (a) without applied stress and (b) after applied stress of -1790 MPa

4 DISCUSSION

A shot-peened steel will exhibit gradients of cold work, and hence deformation properties in the material, biaxial stress states, and a complex variation in stress, with a peak in compressive stress below the surface that can be markedly greater than the near-surface residual stress. Superimposed on this will be the applied stress. Additionally, it

is suggested¹⁴ that shot peening acts as a tensile pre-load, which results in a decrease of compressive yield strength as soon as the material is loaded under compression (Bauschinger effect). Thus, the common approach of comparing combined applied and residual stress with the uniaxial yield properties of an unpeened surface can potentially be misleading. In spite of that, there was close agreement between the combined compressive stresses at the surface (within 10-20 μm) and the stress corresponding to the onset of detectable macroplasticity in uniaxial compression (i.e. the onset of non-linearity in the stress-strain curve). Although the combined stress sub-surface peaks at 50 μm below the surface and would exceed the 0.2% proof stress before the proportional limit was achieved at the surface, the relaxation was not significant, perhaps reflecting elastic constraint of the adjacent material at lower combined stress levels.

In relation to applied tensile stress, the expected behaviour would be for the applied stress at relaxation to correspond approximately to the proportional limit on the assumption that the net tensile residual stress in the bulk of the specimen would be small. The perspective is that once deformation of the core occurs this would induce relaxation of the residual tensile stress in the core and a balanced reduction in the compressive stress must occur. In practice, relaxation did not occur until the applied tensile stress was significantly above the proportional limit for the unpeened specimen suggesting that relaxation was constrained by the adjacent near-surface region, which would be in net tension but at relative low stress levels well below the departure stress.

The overall behaviour of this system was similar to that for AISI 4140 steel¹² and also for a 7075-T1 Al alloy, as quoted in the review by James³. Thus, despite the potential limitations of the combined stress approach it does appear to have supportive evidence. However, the results of Smith et al¹¹ for a high strength steel in which relaxation occurred at much lower combined stresses, albeit with limited test data, suggest caution in extrapolating the principle too widely.

Under fatigue loading the general trend¹⁷, exemplified by work of Lohe and Vohringer¹², is for relaxation to occur in the first cycle and thereafter there is either no further relaxation with increasing cycles or a relaxation that could be described by a logarithmic creep law. By comparison, our results show that this steel is quite resistant to cyclic load induced relaxation, i.e. by microplastic flow, despite higher load amplitudes relative to the 0.2% proof stress (about 50%) when compared with Lohe and Vohringer (about 38%).

The experimental work in the literature is based wholly on constant amplitude loading. We have not been able to assess the impact of variable amplitude loading systematically but did undertake one test in which a relative high single-shot compressive load was applied after cycling the load at a smaller stress amplitude. There was no conclusive evidence for an influence of the preceding cyclic loading on the residual stress relaxation.

For a material that cyclic softens, progressive relaxation of residual stress with increased numbers of cycles might be expected and testing should then include evaluation for a large number of cycles. In contrast, a material that work-hardens would show any relaxation in the first one or perhaps first few cycles with then no value in prolonged testing. This material cyclically softens a little at high applied strain

amplitudes in the non-linear stress-strain region. However, there is little softening at more modest strain amplitudes* (Figure 13) and this is reflected in the relative insensitivity of residual stress relaxation to increasing numbers of stress cycles.

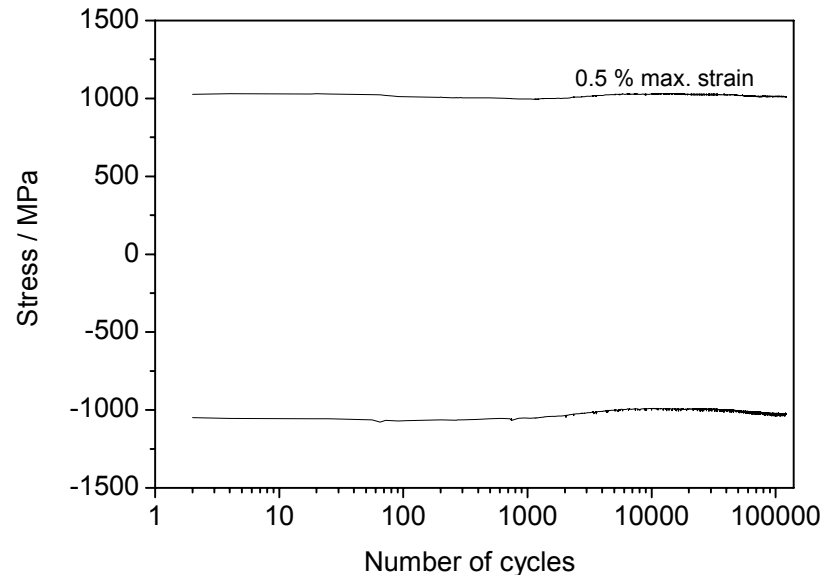


Figure 13. Variation of maximum tensile and compressive stress with cyclic straining of 300 M steel at $R=-1$.

However, high loads are expected in service, albeit very infrequently, and these do have a significant impact on residual stress relaxation although for the conditions tested they do not completely remove all residual stress. A high stress could be experienced early in service life on a random basis. At whatever time, the implications for structural integrity have to be accounted for. In that context, this means assessing the likelihood of failure from hydrogen embrittlement and fatigue.

In relation to hydrogen embrittlement, a number of factors should be considered in addition to the stress state and these have been summarised by Turnbull¹⁷. Coating failure is a necessary precursor to hydrogen entry. It would usually be highly localised and the exposure to the environment would be transient. Hydrogen entering the steel from a local source will undergo multi-dimensional diffusion with the character depending on the nature of the coating damage; e.g. scratch or local pore breakdown. This diffusion away from the source will cause delocalisation of the hydrogen atoms so that the concentration away from the immediate source is diluted. There will also be some reduction in hydrogen solubility in response to the compressive stress associated with shot-peening but, while welcome, the magnitude (about 20%) would be considered rather modest and in itself would be insufficient to establish confidence in structural integrity. The reduced diffusivity in the cold worked zone, because of the high concentration of traps, could be an advantage under intermittent exposure as it would limit the ingress of hydrogen to the sub-surface tensile stress region during the exposure period.

* Data supplied by industry partner

In the absence of residual stress relaxation the expectation is that a combination of local hydrogen uptake, from local coating damage and net tensile stress is feasible at least transiently but the high subsurface compressive stress would retard propagation of any initiated microcracks. The remaining concern would be pitting corrosion if pits were allowed to develop to a significant depth because the hydrogen is then generated closer to the tensile region and the removal of material by pitting would cause some local residual stress relaxation.

Following residual stress relaxation due to high applied stress, the integrity depends more on the performance of the coating, and coating maintenance then becomes the critical factor.

5 CONCLUSIONS

Shot-peening of 300M high strength low alloy steel leads to compressive residual stresses peaking at about -1300 MPa at $50\text{ }\mu\text{m}$ below the surface.

For a single-shot applied compressive load, significant relaxation of the near-surface compressive residual stress occurs when the combined applied and residual stress at the surface (less than about $10\text{-}20\text{ }\mu\text{m}$ depth) exceeds the stress associated with the proportional limit in the uniaxial stress-strain behaviour of the unpeened material.

In principle, relaxation of the peak stress would be expected at lower applied stresses, compared to near-surface relaxation, as the combined stress is more significant but while there is an indication of some modest relaxation the results are inconclusive. Elastic constraint of adjacent material may be a factor.

In tension, the stress required to induce relaxation in the near-surface region was significantly above the stress associated with non-linearity in the uniaxial stress-strain behaviour of the unpeened material suggesting constraint of more lightly stressed adjacent material at the surface.

The steel show good resistance to relaxation under cyclic loading with only very modest relaxation at stress amplitudes of 50% of the 0.2% proof stress. The relaxation tends to occur in the first cycle with no clear evidence for further relaxation with increased number of cycles.

At much higher stress amplitudes the relaxation is more pronounced and the magnitude of relaxation is greater than for single-shot loading at equivalent maximum loads.

Although such high stresses will be very infrequent in service, they could in principle occur early in life and this should be taken into account in structural integrity assessment.

6 ACKNOWLEDGEMENTS

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APPENDIX

ALIGNMENT OF TESTING MACHINE

The tests were performed on a servo-electric, 2-column Instron 8562 test machine with a frame capacity of 250 kN. The machine was equipped with a 100 kN load cell which was calibrated to Class 1 according to BS EN 10002-2: 1992. The machine was also equipped with an alignment fixture manufactured by Instron, which allowed the precise alignment of the load train, using a Nimonic 101 alignment cell, prior to the test programme starting. Figure 1 shows the variation of the maximum percent bending $\beta_{\max}$ with applied axial strain. This shows that prior to the test programme starting the machine was aligned to Class 5 according to the definition shown in Table I [1].

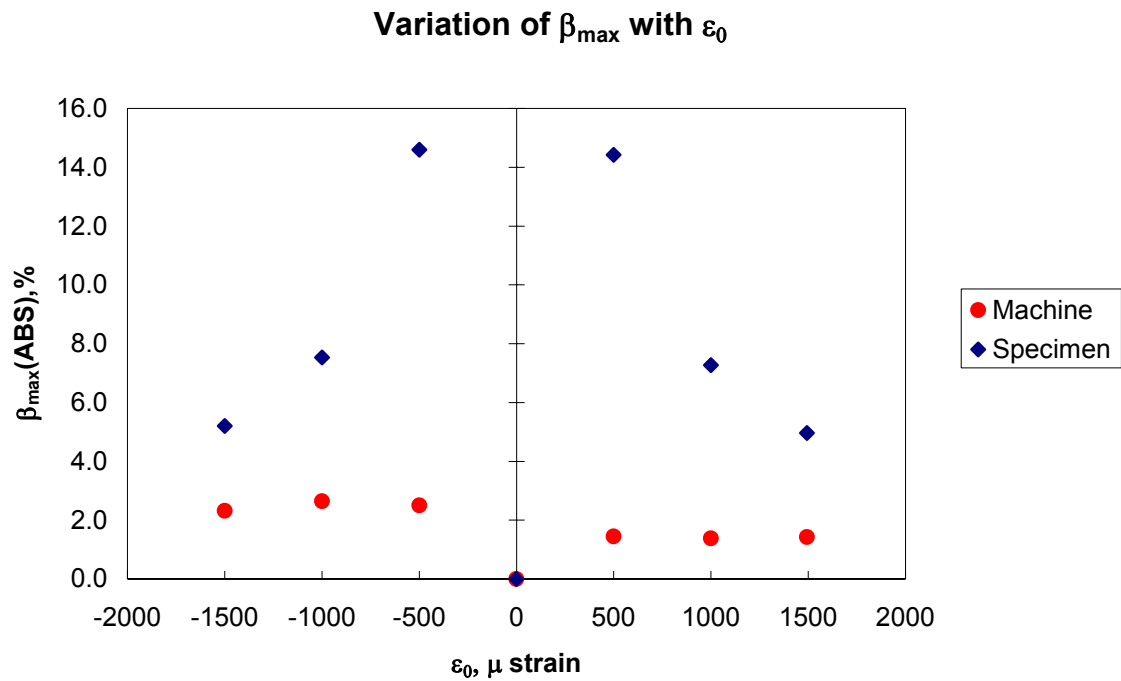


Table I Alignment Classes

Class	Axial Strain < 1000 $\mu\epsilon$	Axial Strain $\geq$ 1000 $\mu\epsilon$
2	$\beta_{\max.mc} \leq 20 \mu\epsilon$	$\beta_{mc} \leq 2 \%$
5	$\beta_{\max.mc} \leq 50 \mu\epsilon$	$\beta_{mc} \leq 5 \%$
10	$\beta_{\max.mc} \leq 100 \mu\epsilon$	$\beta_{mc} \leq 10 \%$
20	$\beta_{\max.mc} \leq 200 \mu\epsilon$	$\beta_{mc} \leq 20 \%$

1 F A Kandil, “*Verification of Alignment of Uniaxial Test Systems*”, VAMAS Report No. 42, ISSN 1016-2186, National Physical Laboratory, February 2003.