

Measurement and Understanding of the Level and Effect of Residual Stresses Induced by the Laser Shock Peening Process

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ABSTRACT

This paper describes work undertaken to understand and quantify the benefits of laser shock peening (LSP) in improving the fatigue resistance of components when subject to high, near surface alternating stress fields. The process is known to introduce compressive residual stress fields down to depths of typically 1mm. The geometry of the component being treated is one factor that contributes to the magnitude and distribution of compressive residual stresses. In a simple geometry the measurement of the resulting residual stresses is relatively straightforward. However, practical application involves more complex geometries and the measurement of residual stress levels is more problematic. The first part of this paper describes how finite element modelling can be used to understand residual stress levels in a complex geometry following the application of LSP.

In order to maintain equilibrium, sub-surface tensile stresses must accompany the near surface compressive stresses induced by the LSP process. Account must be taken of these tensile stresses in the design process. The second part of this paper describes some work undertaken to predict the effect of the full through-wall residual stress levels on crack initiation lives. A programme of notched 3-point bend specimen testing is reported and an assessment method proposed for predicting fatigue lives. Depending on the applied stress levels crack initiation can occur near-surface or sub-surface. The proposed model can be used to predict both the crack initiation location and the cycles to failure.

1.0 INTRODUCTION

Laser Shock Peening (LSP) is a viable process to improve the fatigue resistance of components when subject to high, near surface alternating stress fields. LSP can introduce large compressive residual stresses up to and beyond a depth of 1.0mm. As a result the total near-surface stress, defined as the LSP-induced residual stress plus the applied tensile stress, is much less (more compressive) than the applied stress alone. The resulting reduced mean stress then manifests itself as an increase in fatigue strength or life of the component. LSP can be expected to be particularly effective when the stress field is localised such as at a high stress concentration. Applications of the process include the treatment of fan blade/disc contact at dovetail joints and the treatment of leading edges of fan and compressor blades to improve Foreign Object Damage (FOD) tolerance.

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Understanding the benefits of LSP requires knowledge of the magnitude of the entire through wall stress distribution. The measurement of through-wall residual stresses in complex geometries is problematic. Accurate measurements generally involve destructive techniques and correction of measured stresses following metal removal. Section 2 of this paper describes a method used to predict through-wall residual stresses in a complex geometry. The process involves the measurement of near surface residual stresses using X-ray diffraction techniques, metal removal by immersion etch and the correction of measured stresses to allow for metal removal using factors derived by finite element analysis.

In order to maintain equilibrium, the high near surface LSP-induced residual compressive stresses are accompanied by sub-surface tensile stresses. In the absence of a stress gradient these tensile stresses may actually reduce the fatigue strength of the material. Even in the presence of a stress concentration, the sub-surface tensile residual stresses can result in preferred sub-surface crack initiation. The effect of these sub-surface tensile stresses must therefore be considered when assessing the potential benefits of LSP. The significance of the sub-surface residual stress levels has been investigated using notched 3-point bend specimens. The specimens were subject to LSP and tested at a range of mean stress levels. The location of crack initiation was determined by fractography and noted. The position of crack initiation was also predicted by means of a simple analytical model. The model was based on a correlation of fatigue life with applied stress range. This programme of work and analysis is described in Section 3 of this paper.

2.0 THE USE OF FINITE ELEMENT MODELLING TO ASSESS THE EFFECT OF GEOMETRY ON RESIDUAL STRESS

2.1 Modelling Aims

LSP process parameters have typically been optimised on small flat plates approximately 50mm square and 8mm thick. The plates are subjected to LSP and the resulting residual stresses can be measured relatively easily using either hole drilling or X-ray diffraction (XRD) techniques. The latter approach often involves metal removal and subsequent correction of the measured stresses to give the through-wall stress profile.

The benefit of LSP on fatigue strength of the material is often derived using notched specimens. The measurement of residual stresses in the notch root is problematic using conventional techniques. Complex 3D components usually have to be sectioned before they can be subjected to residual stress measurement and the resulting pieces are often difficult to align in the test equipment. Destructive techniques such as XRD where layers of material are removed to allow measurements at depth require correction factors to allow for material removal. These corrections are well established for simple components [1] but are not so obvious for complex 3D geometries. Figure 1 provides an illustration of LSP induced stresses in a plate, a notched specimen and a more complex geometry. Due to symmetry only one quarter of the plate and the notched test specimen are shown.

The primary aims of the FE modelling are therefore:

- Estimate the residual stress profiles induced in test specimens and real component geometries by LSP based on flat plate measurement data.
- Quantify the effect of sectioning a component on residual stress levels.
- Produce realistic layer removal correction factors to apply to component geometries.

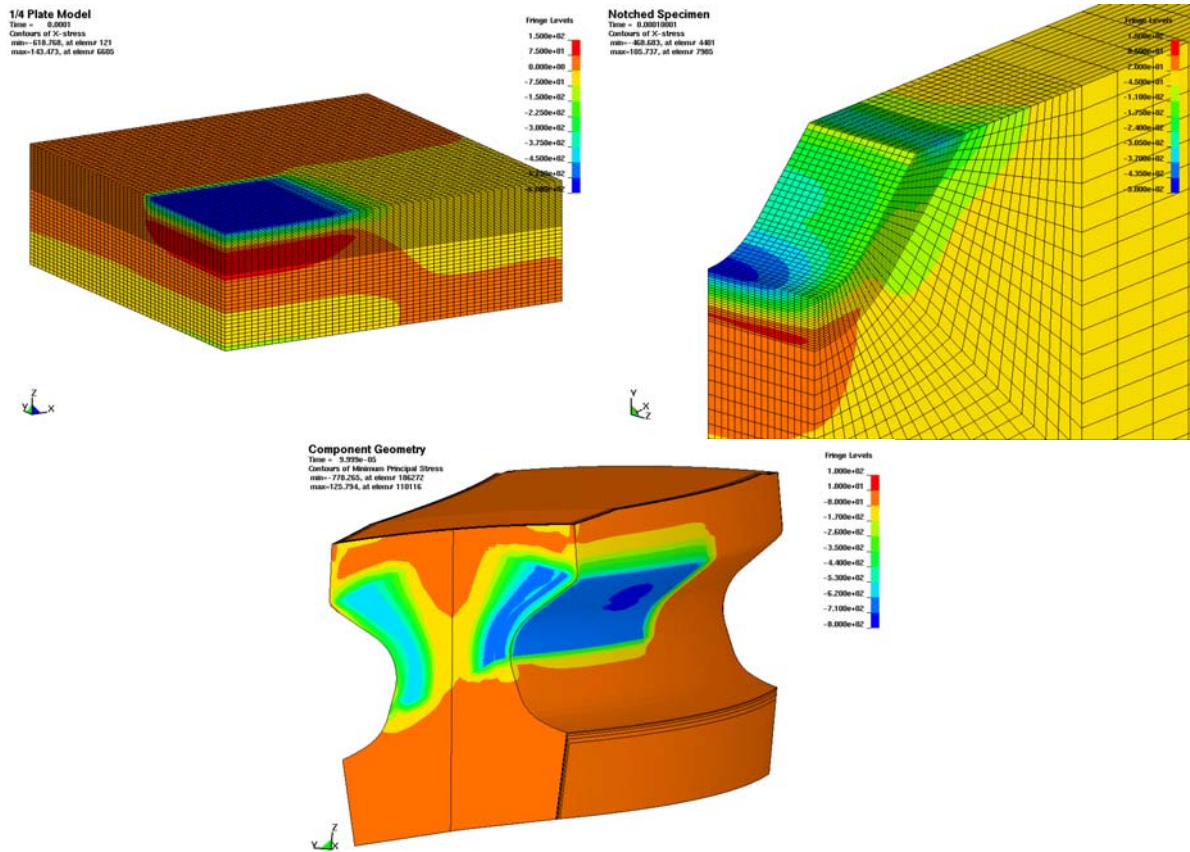


Figure 1: Residual Stress Model of Flat Plate (Top Left), Notched Specimen (Top Right) and Component Geometry (Bottom).

2.2 Residual Stress Modelling Method

The LSP process uses a high energy laser pulse producing a high amplitude shock wave. This creates plastic deformation, which leaves deep compressive residual stresses. Modelling the actual LSP process requires element mesh sizes of the order of 10 microns to capture the shock waves travelling through the material and material properties at very high strain rates. It is therefore not practical to model the LSP process in detail for complex 3D components. An alternative approach was used whereby 2D modelling was carried out to understand the local behaviour of the LSP process itself. Additional 3D modelling was then used along with initial strains to quantify the effects of different geometries. Hence a link was formed between the flat plate coupons, notched fatigue specimens and component geometries.

The local LSP induced residual stresses are formed very quickly compared to the time taken for the complete specimen or component to reach equilibrium. Instantaneous surface initial strains were therefore used to apply the LSP residual stress profile to 3D models, using the flat plate measured data and 2D modelling results for validation.

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The following list shows the steps taken for the 3D modelling:

- 1) Apply instantaneous surface strains to the flat plate model and allow the model to find equilibrium.
- 2) Note the resulting residual stress profile and repeat 1 iteratively until a set of surface strains have been obtained that give a residual stress distribution consistent with the 2D modelling and measurement data.
- 3) Simulate the layer removal process by removing layers of elements and compare results to 2D theory.
- 4) Apply initial surface strains, obtained for the flat plate modelling to the notched specimen and allow it to find equilibrium.
- 5) Apply the initial surface strains to the component geometry and allow it to find equilibrium.
- 6) Cut the measurement test piece from the component and quantify residual stress changes.
- 7) Simulate layer removal process and compare results to theory.

All the modelling work was carried out using LS-Dyna commercial software due to the ease of applying initial stresses and deleting elements. The 3D modelling methodology could be applied using almost any commercial FE solver.

2.3 Residual Stress Modelling Results

Figures 2 and 3 show the predicted results for the residual stress distributions into the depth. There are differences in the profile between the flat plate, notched specimen and different component locations indicating the influence of the constraining material around the area subjected to LSP. As expected the flat plate residuals are the same in both directions. The notched specimen residuals are less compressive in the through thickness direction. This is considered to be due the reduced amount of constraining material to support the high compressive stresses in this direction.

The component residuals show a maximum difference of approximately 160MPa at the surface for the 4 different locations and 2 directions. The trend is consistent with the understanding that the most compressive residuals are at the locations with the largest amount of material to support the compressive stresses. As one moves towards the locations closest to the edges of the component the amount of compression reduces.

The view of the component shown in Figure 1 shows only the part of the geometry that was cut from the full component. Cutting was essential to enable access to the X-ray diffraction measurement equipment. To assess if the cut boundaries were far enough away as not to influence the results the model was initially 'earthed' at the cut planes. Following the application of the residual stress profile the boundaries were set free and the change in stress observed. The sectioning was found to be sufficiently distant so as not to influence the results.

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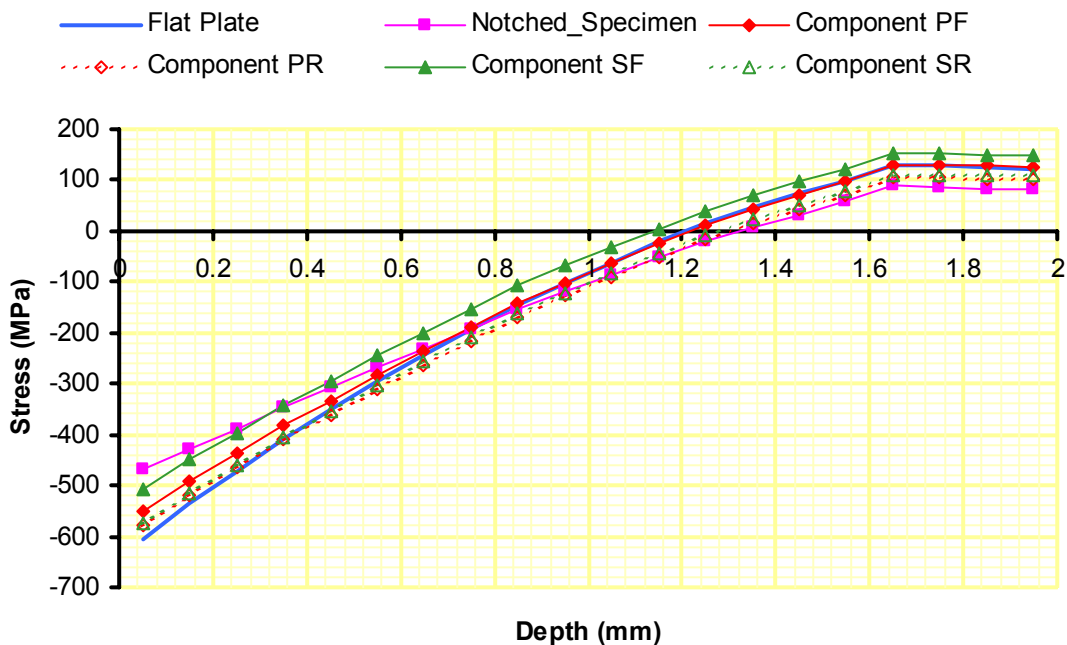


Figure 2: Flat Plate Residual Stress Profile Compared to Loading Direction Residuals in Notch Specimen and Component.

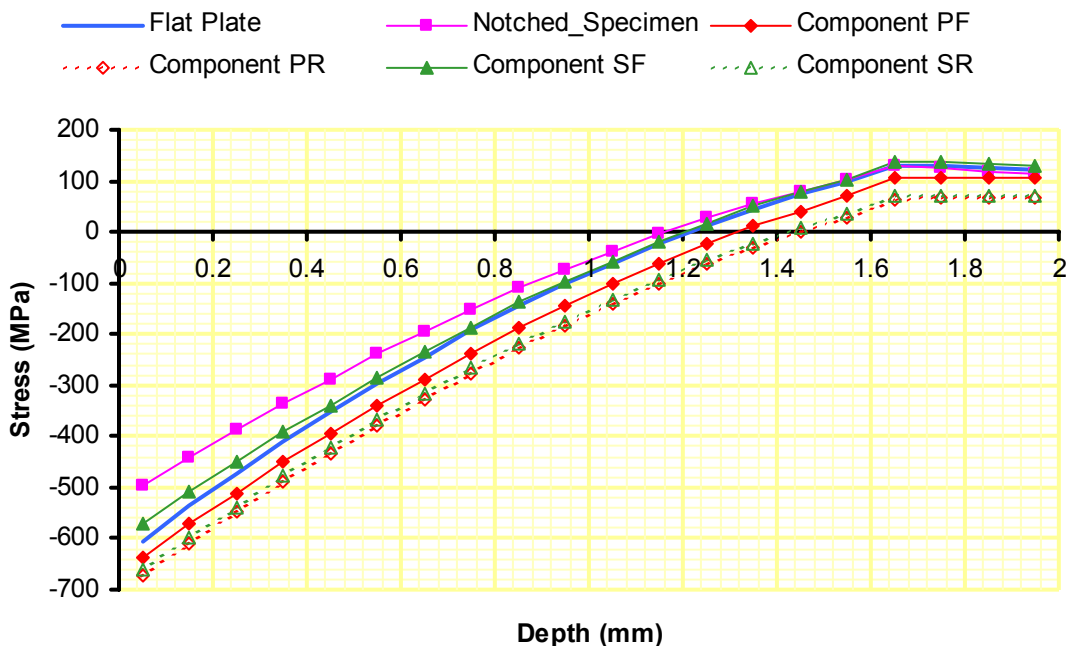


Figure 3: Flat Plate Residual Stress Profile Compared to Axial Direction Residuals in Notch Specimen and Component.

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2.4 Effective Plate thickness Technique for Layer Removal Correction

For a flat plate Moore and Evans [1] give the stress at the surface following layer removal as

$$\sigma_x(z_1) = \sigma_{xm} + 2 \int_{z_1}^H \frac{\sigma_{xm}(z) dz}{z} - 6z_1 \int_{z_1}^H \frac{\sigma_{xm}(z) dz}{z^2},$$

where z is perpendicular to the plate surface, z_1 is the distance from the lower surface of the plate to the point of interest, σ_{xm} is the measured stress in the x direction and H is the original thickness of the plate.

Assuming a quadratic function of the form $\sigma_{xm}(z) = az^2 + bz + c$, the error due to layer removal becomes

$$Error = a(H^2 - z_1^2) + (H + z_1) \left(2b - 6az_1 - 6\frac{c}{H} \right) + (2c - 6bz_1) \ln \frac{H}{z_1}.$$

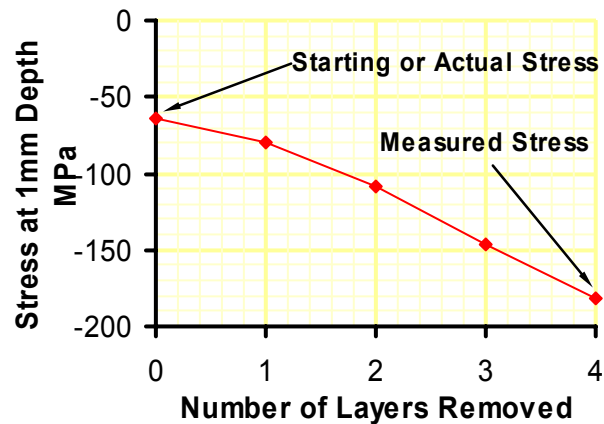


Figure 4: Example Showing How the stress at 1mm Depth Changes as Layers of Material are Removed.

The requirement for appropriate correction factors is highlighted by Figure 4. This figure shows the stress at a depth of 1mm for one of the component locations. As layers of material are removed the stress changes and by the time 4 layers have been removed such that the stress is now at the surface and can be measured it has changed considerably. The correction factor is therefore the difference between the measured stress and the starting stress.

The correction factors for the different locations on the component are only applicable for the given input profile. Rather than running the FE model for every measurement, an “effective thickness” method can be used that links the FE results to the standard flat plate theory. This method is as follows:

- Fit a quadratic equation to the as-measured residual stress profile, assume a plate thickness and derive the residual stress profile before metal removal.
- Compare the results from the flat plate corrected stresses to those directly from the FE model.

- Iterate to find the “best fit” plate thickness, i.e. the plate thickness that gives the smallest difference between corrected and FE model data.
- Repeat for each location and direction.

Once a best fit “effective thickness” has been established the correction factors from the flat plate theory agree very well with the full 3D model results. The resulting thicknesses are also fairly insensitive to changes in the starting input profile indicating their applicability to subsequent measurements.

For this particular component the effective thicknesses ranged from approximately 9 to 33mm. The effective thicknesses are logical on examination of the geometry, the smallest thickness occurring near an acute corner and the largest at the most central locations.

3.0 UNDERSTANDING THE INFLUENCE OF THE THROUGH-WALL RESIDUAL STRESS DISTRIBUTION

3.1 Experiments

A series of tests have been carried out using notched three-point bend specimens that were treated by LSP in the notch root region. The specimens measured 32mm deep x 62 mm wide x 10mm thick. A 4mm semi-circular notch was introduced to the specimens. The sides of the notch were then chamfered at 45°. The K_t for the specimens was determined by finite element analysis as 1.86. All specimens were manufactured from an alpha/beta processed Ti6Al4V (RR designation MSRR 8636 or 8672). Tests were carried out at four mean stress levels: 350, 420, 550 and 730MPa. the objective of the tests was to determine the cyclic stress ranges that gave a fatigue life of 10^7 cycles at each of the chosen mean stress levels.

3.2 Results

The results of the tests, plotted as half the total applied surface stress range versus cycles to failures, are shown in Figure 5.

For most of the specimen tests the point of crack initiation was identified by examination of the fracture faces. This position was described in terms of the distance from the specimen’s edge and the distance from the notch root. The results of the measurements are shown in Figure 6.

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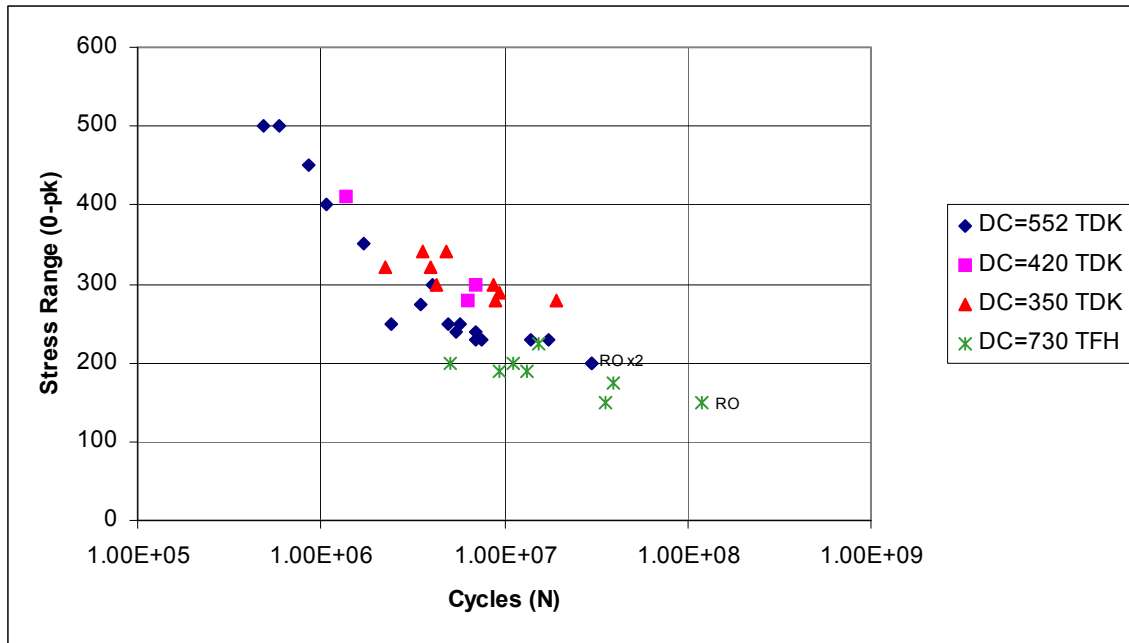


Figure 5 Results of LSP 3 Point Bend Specimen Tests.

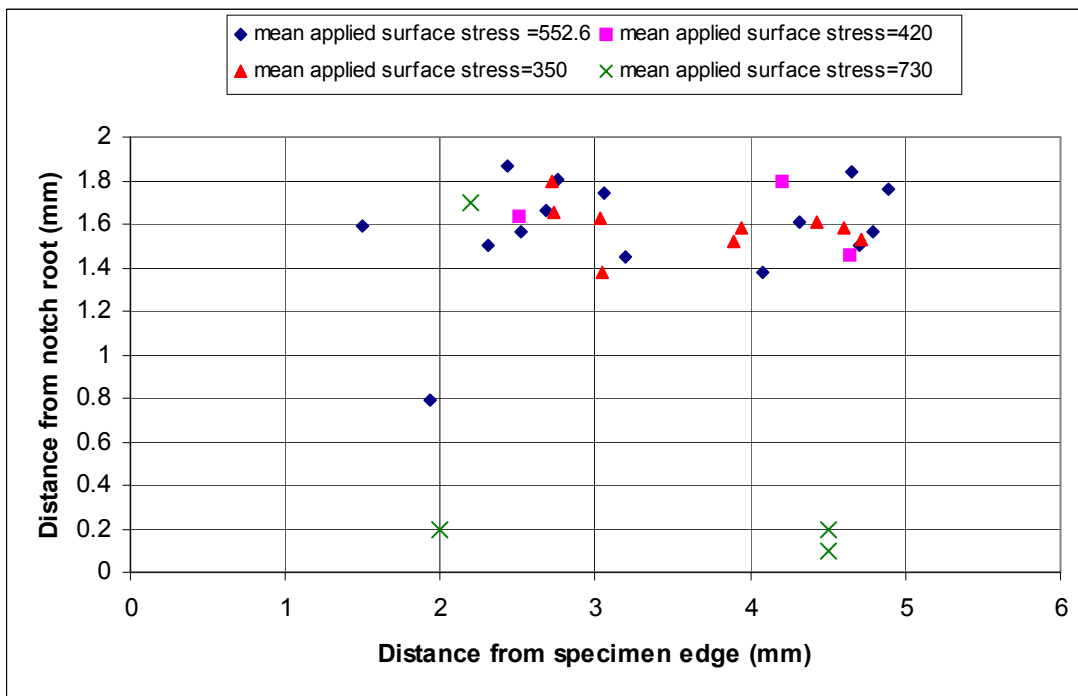


Figure 6 Position of Crack Initiation as a Function of Mean Stress Levels.

3.3 Analysis

Analysis of the test data requires an estimate of the residual stress levels induced by the LSP process. The resulting through wall residual stress distribution was derived based on measurements on plates using a combination of X-ray diffraction, neutron diffraction and hole drilling residual stress measurement techniques. Measurements were made down to depths of 3mm. Some judgement was exercised in predicting residual stresses at the larger depths. The resulting predicted residual stress distribution is shown in Figure 7.

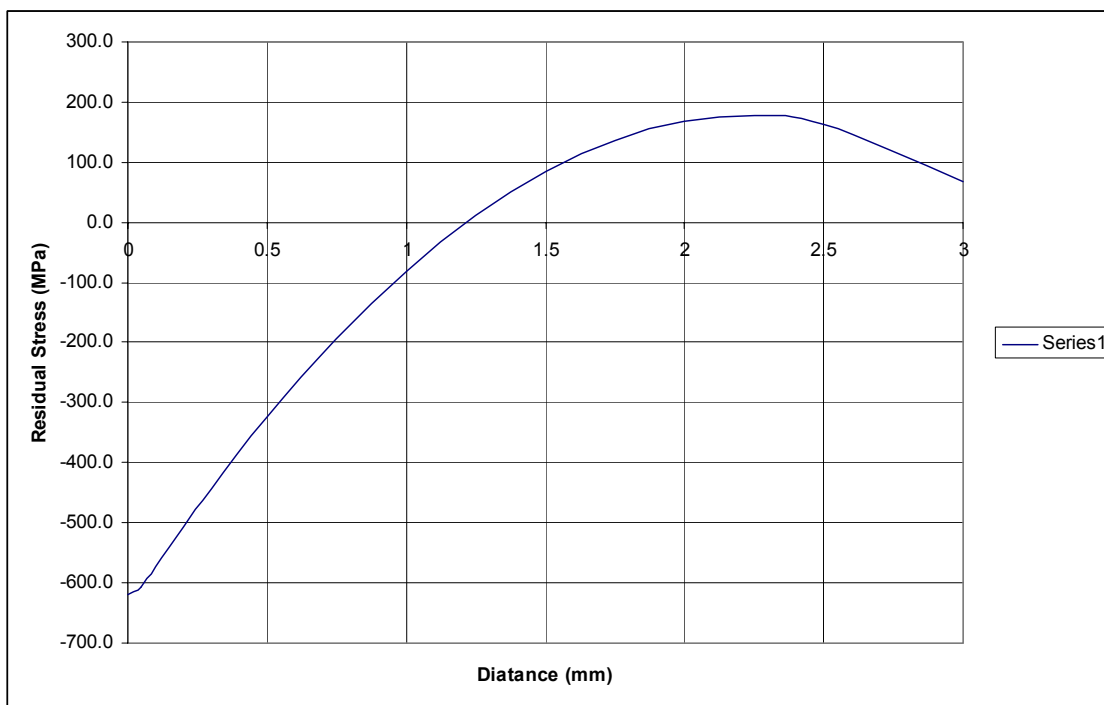


Figure 7 Predicted Through Wall LSP Residual Stress Profile.

The applied stresses, as determined by elastic finite element analysis of the specimen, were added to the residual stresses to determine combined stress levels. An example showing individual and combined stresses is provided in Figure 7. The graph reflects a mean stress of 730MPa and a cyclic stress of ±180MPa.

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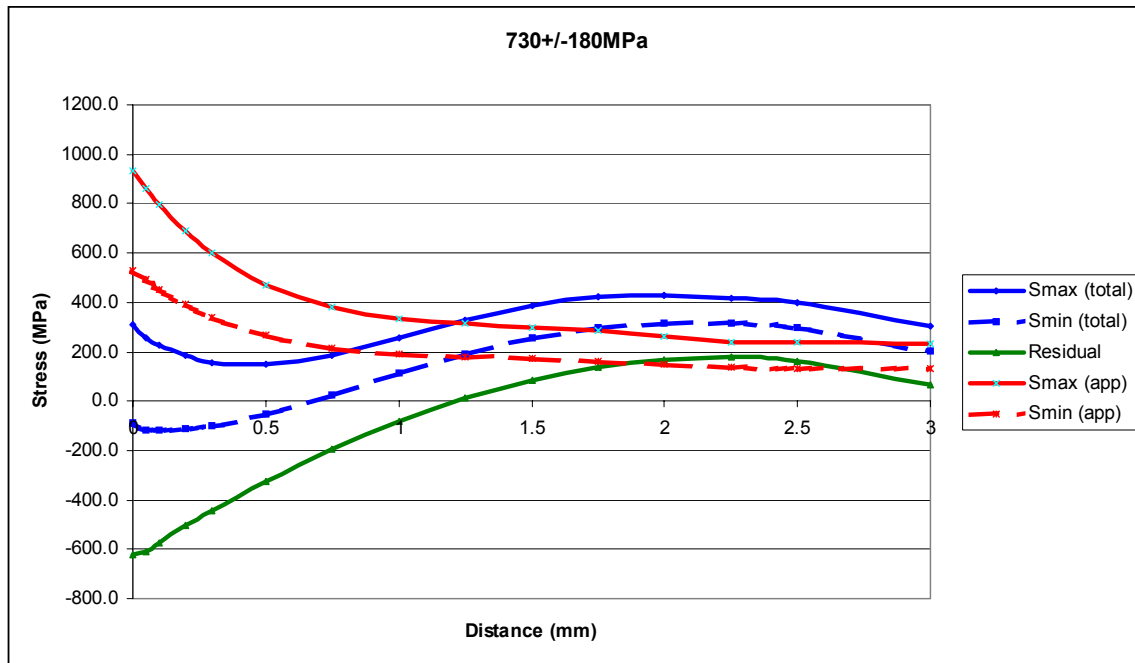


Figure 8 Example of Individual and Combined Through-wall Stresses in a 3PB Specimen.

The combined and applied residual stress distributions were then used to evaluate the Walker Strain parameter at a range of through-wall positions for all test conditions using the expression:

$$\varepsilon_w = \left(\frac{\sigma_{\max}}{E} \right) * \left(\frac{E * \Delta\varepsilon_{total}}{\sigma_{\max}} \right)^m$$

where: σ_{\max} is the maximum stress (steady plus alternating) (MPa), $\Delta\varepsilon_{total}$ is the total strain range ($\varepsilon_{\max} - \varepsilon_{\min}$), E is the elastic modulus (MPa) and m is an empirical fit to the 3-point bend experimental data.

The through-wall location having the maximum value of Walker Strain was considered to be the most likely failure location. Values of maximum Walker Strain evaluated for each test when plotted against fatigue life were found to collapse onto a single curve by fixing m as 0.38. The resulting curve is shown as Figure 9.

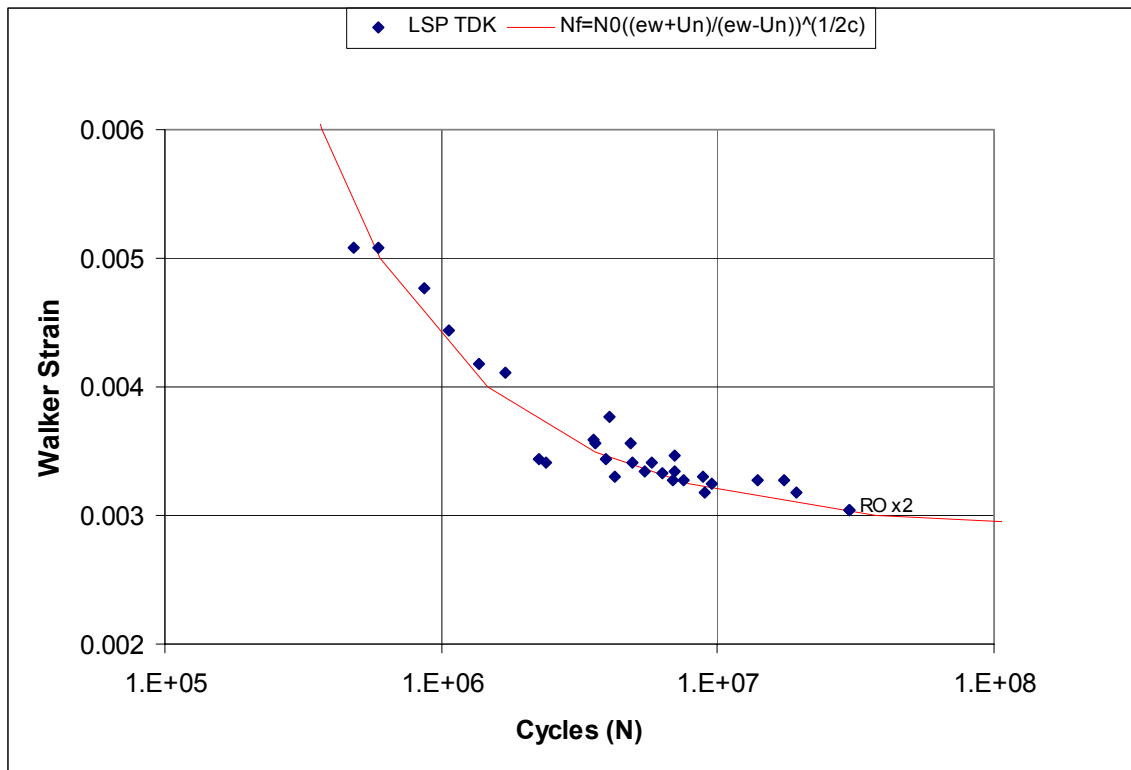


Figure 9 Walker Strain Plot – LSP 3 Point-bend Specimens.

Using the above approach the failure location for any applied stress range can be predicted. At mean stress levels of less than around 600MPa and for lives of between 10^5 and 10^7 cycles, initiation was predicted at approximately 1.5 to 2.0 mm from the surface of the specimen. At mean stresses above 600MPa crack initiation within 0.2mm of the specimen surface was predicted. The above prediction is illustrated in Figure 10. Values of Walker Strain are plotted for two mean stress levels and at cyclic stress levels that would give a life of 10^7 cycles. At a mean stress of 730MPa the maximum Walker Strain is clearly near the surface and near surface initiation is predicted. However, at a mean stress of 550MPa the sub-surface value of Walker Strain is at a maximum and sub-surface crack initiation is predicted. these predictions are consistent with the observed crack initiation sites shown in Figure 6.

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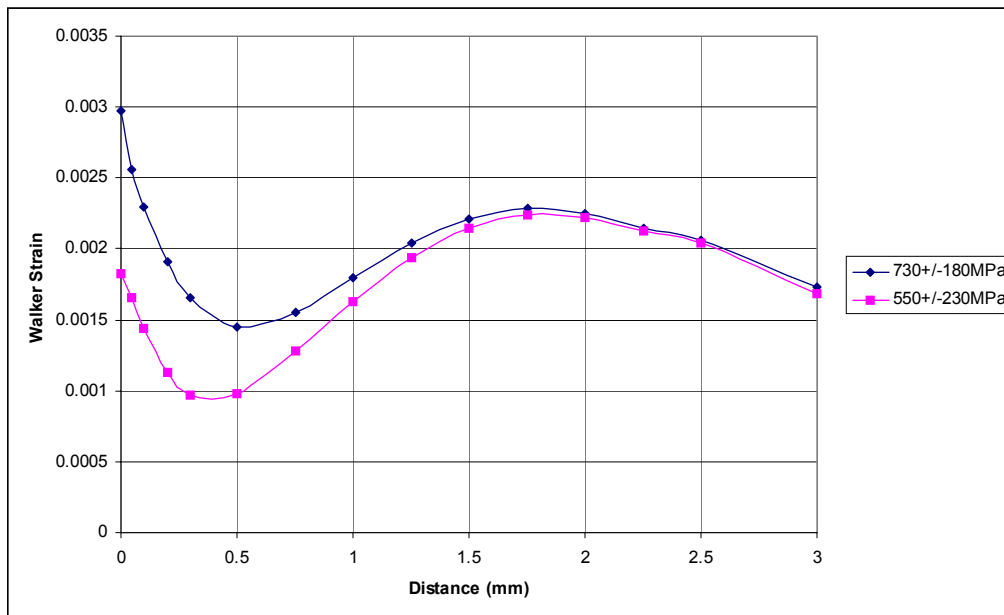


Figure 10 Plot of Walker Strain versus Through-wall Distance for Two Load Levels.

4.0 CONCLUSIONS

The use of FE techniques to aid in the understanding of residual stress problems is common practice, but is generally restricted to simple geometries using 2D techniques. Applying the FE technique to complex 3D geometries has enabled Rolls-Royce to gain a better understanding of the residual stress field produced by LSP on an engine component. An independent assessment of the XRD measured data has been possible and new procedures have been identified in order to obtain better residual stress measurements on engine components.

The balancing tensile residual stresses produced by the LSP process can threaten the integrity of a component if they are not properly accounted for. A simple method for quantifying their effect has been provided. The method requires an understanding of the residual stress field induced by the LSP process and the applied stress levels. The method is based on the results of a programme of testing on Ti6Al4V 3-point bend specimens.

5.0 REFERENCES

- [1] Moore, M.G., Evans, W.P., (8 August 1956), "Mathematical Correction for Stress in Removed Layers in X-Ray Diffraction Residual Stress analysis" SAE Residual Stress Committee

SYMPOSIA DISCUSSION – PAPER NO: 35

Author's name: J. Schofield

Discussor's name: S. Thompson

Question: General comment: Compensatory tensile stresses location must also be equated to the original residual stress profile of the component prior to the application of LSP.

Answer: Agreed.

