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Fatigue behaviour of geometric features subjected to laser shock peening: experiments and modelling

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Abstract

Finite element models, using the eigenstrain approach, are described that predict the residual stress fields associated with laser shock peening (LSP) applied to aerospace grade aluminium alloys. The model was used to explain the results of laboratory fatigue experiments, containing different LSP patch geometries, supplementary stress raising features and different specimen thickness. It is shown that interactions between the LSP process and geometric features are the key to understanding the subsequent fatigue strength. Particularly relevant for engineering application, is the fact that not all instances of LSP application provided an improvement in fatigue performance. Although relatively deep surface compressive residual stresses are generated which can resist fatigue crack initiation in these regions, a balancing tensile stress will always exist and its location must be carefully considered.

\textbf{Keywords:} Eigenstrain, Fatigue, Laser shock peening, Residual stress
1. Introduction

Laser shock peening (LSP) uses high power laser pulses (typical process parameters are power = 1-25 J, pulse duration = 18-30 ns, laser beam size < 10 mm) to generate an advantageous residual surface stress distribution in structural components (e.g. for airframe applications) [1]. The technique involves firing laser pulses at the surface of a component to introduce a surface compressive residual stress. Typically, an LSP treatment produces compression to a depth of 1-2 mm, which is about five to ten times deeper than that produced by conventional shot peening [1-4]. A significant advantage is that the laser parameters are more reproducible than their equivalents during shot peening, and this allows the process to be tailored to specific design requirements.

LSP is particularly attractive for application at geometric stress concentrations; by introducing a compressive surface residual stress, fatigue performance can be enhanced through the increased resistance to crack initiation. However, these are precisely the areas where the technique is most difficult to apply in practice, often due to “line of sight” restrictions or simply the difficulty in applying the ablative tape (used to transfer the laser shock to the substrate) around complex geometric features. Further, as will be shown in the paper, the interaction between the process and complex geometries can lead to unexpected results. The current paper examines such interactions in two aerospace grade aluminium alloys (Al 2024 and Al 7010). The analysis presented here shows how the eigenstrain technique may be used as an efficient tool for predicting the associated residual stress. This approach obviates the need for a completely explicit finite element (FE) analysis, which may be impractical, since in practice an array of multiple LSP pulses is generally required to treat the surface area of a component.
Surface treatment by LSP usually involves applying an ablative or sacrificial aluminium tape to the surface of a component. This tape is then vaporised by a laser pulse, producing a rapidly expanding plasma. The plasma is confined by a jet of water simultaneously sprayed on the surface [1-2] and the effect is to generate a high-amplitude, short duration shock (pressure) wave in the work piece [1-4]. As the stress wave propagates, localised plastic deformation occurs and, once the pulse has decayed, misfit between the plastically deformed material and surrounding elastic region generates a residual stress [2, 3]. Due to the short duration of the laser pulse (typically < 30 ns) no significant heating occurs in the substrate. Hence the generation of residual stress may be regarded as a largely mechanical process, involving the response of the material to a pressure wave [1-2]. An explicit FE analysis is generally required to model the residual stresses caused by LSP. However, in order to obtain the stabilised stress distribution, the FE simulation must be run until the stress waves caused by each laser pulse fully dissipate. Hence modelling the process in this manner is demanding in terms of computational processing times and cost [2-3].

Although the LSP technique offers significant potential to improve the fatigue resistance of engineering components, instances have been reported [5] where a subsequent fatigue benefit has not been found. Indeed, unless great care is taken, the balancing tensile stresses [1] may actually reduce fatigue life, therefore knowledge of the locations and magnitudes of these tensile stresses is required. For instance, in thin sections, care must be taken in the choice of the laser power to avoid “overpeening”, leading to a largely tensile field near the surface\(^1\). The beneficial effects of LSP on fatigue strength have been widely reported in the literature, for example using dog-bone [6] and open hole specimens [7]. There are also some investigations of the effect of LSP on fretting fatigue [6]. Titanium (Ti-6Al-4V) [6] and

\(^1\) For thin sections, it is possible to develop tension close to both the surfaces, if the stress wave reflection from the back surface is high enough to cause reverse plasticity in the initial compressive field underneath the LSP patch.
aerospace grade aluminium alloys (Al 2024 and Al 7010) [5] have been used in many studies, but limited research has been carried out using other alloys, including Ni-based super alloys [8]. The exact nature of the balancing tensile stress regions can be difficult to determine, because the residual stress arises as the result of the elastic response of the whole component to the localised plastic strain introduced by LSP. A knowledge of the precise interaction between the LSP parameters, the geometric features and the resulting tensile “hot spots” is required in order to model the fatigue strength.

It has been proposed that the improvements in fatigue life generated by LSP are dominated by a significant increase in life during initiation and early stage crack growth, [6]. Even so, a comprehensive understanding of the effect of LSP on fatigue strength is still lacking, and the influence of residual stress and surface conditions are very difficult to determine. Development of a comprehensive analytical method to predict the residual stresses generated by LSP and subsequent fatigue performance is difficult because of the complex interaction between the geometry of the component and the residual stress field. The authors have previously developed a hybrid eigenstrain approach (i.e. employing misfit strains, which act as sources of incompatibility of displacement) to determine the residual stresses generated by the LSP [2-4]. The current paper extends the method to model the stress field in open-hole specimens, both after treatment and during subsequent fatigue loads.

The eigenstrain technique is an efficient tool for modelling the residual stress state present in a component and the technique has been successfully used in a number of applications. For example, Korsunsky et al. [9] successfully constructed the residual stress induced by welding; Prime and Hill [10] determined fibre scale residual stress variation in metal-matrix composites; and Korsunsky [11] evaluated residual stresses in auto-frettaged tubes. The knowledge of eigenstrain distribution may be used to determine the residual stress rather than seeking the stress field directly. This has the advantage that the eigenstrain distribution is less...
Sensitive to component geometry than the resulting stress field. Previous analyses [2-4] have shown that the plastic strains are usually stabilised within a short time period and hence the eigenstrain distribution can be conveniently extracted from an explicit FE simulation by the modelling the effect of a LSP pulse as a dynamic pressure load. The residual stress distribution is then determined as the elastic response of the workpiece after incorporating the eigenstrain as an initial misfit strain in a static FE model [2-3]. It should be noted that the plastic flow caused by the shot has been captured in the eigenstrain extracted from the explicit simulation, so that the yield condition is unlikely to be exceeded in the implicit model.

Previous work [2-4] has shown that the eigenstrain caused by the array of shots in a single layer of LSP pulses can be simply modelled as that generated by a single LSP shot but applied over a wider area in an appropriate misfit strain FE model. This allows modelling of the effect of an array of LSP shots, arranged side by side, to peen a desired surface patch of a component. Thus, the residual stress distribution can be determined from a static FE model by incorporating the eigenstrain depth profile obtained from a representative simple array, thereby significantly reducing the computational cost compared to an equivalent wholly explicit FE analysis [3]. Similarly, the residual stress in a range of different geometries and for a range of peened areas (in a given material) can be simply derived using the knowledge of a single eigenstrain depth profile, related to a particular set of peening parameters. This has allowed modelling the effect of LSP treatment adjacent to geometric features (e.g. in the vicinity of a straight or curved edge) [4].

This paper investigates experimentally and numerically the degree to which the fatigue response of complex geometric features can be modelled by using an understanding of simple eigenstrain distributions. Thus, the model will be validated by comparing the predicted stress profiles in a particular specimen geometry with the corresponding experimental fatigue lives.
The results suggest that the eigenstrain approach is particularly useful in these cases (e.g. in the hole geometry investigated here). It will be shown that care must be exercised in the application of LSP at stress concentrations. In some cases, no fatigue benefit can result and performance may even be worse than the non-peened condition. Notably, the results show that LSP, when restricted to small patches around geometric stress raising features, may be more effective than LSP applied to larger areas.

2. Experimental Methods and Data

Fatigue tests were carried out on two aerospace grade aluminium alloys supplied by Airbus, Al 7010 T7451 and Al 2024 T351. The 0.2% proof strength of these two alloys is 340MPa and 430MPa respectively. Figure 1 shows the design of two open hole fatigue specimens, which were tested under cyclic tension. Two thicknesses of specimen were employed, 5 and 15 mm respectively. The specimens were initially machined into rectilinear blanks using CNC milling. LSP was then applied to the shaded regions indicated in Figure 1 on the front and rear faces only (i.e. no LSP was applied to the side faces). Where LSP was applied across the full width of the test piece this was designated a “full face specimen”. Alternatively, LSP was restricted to a central region of 20 x 20mm, to provide a “patch specimen”. As the final machining operation, the hole was drilled and reamed. A more limited set of specimens were prepared to the same geometry but peened across the full face using a conventional shot peening technique (MI 230H, 0.006 to 0.010 Almen) or tested in the “as machined” condition (i.e. without peening of either type). All fatigue tests were carried out in laboratory air at ambient temperature (20°C) using a load (R) ratio of 0.1 and 5 Hz sine waveform. A full inventory of experiments is included as Table I.

Figure 2 shows the results of the fatigue tests carried out on Al 7010. The peak net section stress (i.e. maximum load / minimum cross sectional area at the specimen mid length position) is plotted against the number of cycles to rupture. Three types of 15mm thick
specimen were used: ‘As-machined’, LSP, and shot-peened. The laser peening was applied using 4 x 4 mm shots with a laser pulse of 18 ns duration and an energy density of 4 Gw/cm². Three layers of shots were superimposed across the whole area of the array. This surface treatment was designated 4-18-3. No significant difference between the performance of the three types of specimen was apparent.

Figure 3 illustrates fracture surfaces from the three specimen variants tested at a common net section stress of 220 MPa. Essentially, all three specimens have failed in a similar mode, with multiple cracks initiated to either side of the hole, eventually coalescing to form through section cracks growing laterally to either side. Notably in all cases, crack initiation was most prevalent in the mid-thickness bore of the hole and no cracks initiated at surface corner locations). Therefore, from the combination of evidence from the measured fatigue lives and fractography, neither of the peening operations appear to affect the overall fatigue performance.

For the experiments on Al 2024, five different types of specimen were tested: (i) as-machined; (ii) conventionally shot-peened; (iii) LSP full face; all with a thickness of 15mm, then (iv) LSP full face and (v) 20 mm x 20 mm LSP patch on specimens of 5mm thickness. Figure 4 illustrates the actual surface appearance on the thin, full face and patch specimens respectively. Figure 5 plots the results obtained from the AL 2024 specimens. As with the Al 7010 alloy, LSP on the 15 mm thick specimens showed no benefit when compared to ‘as machined’ specimens. In contrast, conventional shot peening of thick specimens did appear to show a benefit with this alloy, with an apparent increase in endurance strength, although the increase in life was more significant at lower stress.
Turning to the thin (5mm) specimens, LSP applied over the full face of the specimen provided a similar response to either of the 15mm thick specimens. However, a notable improvement in fatigue performance was obtained with Al 2024 patch specimens at all applied stress levels. Figure 6 shows fracture surfaces for two 15 mm thick specimens (as machined and LSP full face respectively) tested at a peak stress of 220 MPa. As with the Al 7010 alloy, crack initiation occurs along the bore of the hole and away from the specimen surfaces. Finally, Figure 7 Illustrates the fracture surfaces obtained from the 5mm thick specimens. Comparing the ‘full-face’ and ‘patch’ treatments, it is clear that the total critical crack length (i.e. measured to either side of the hole) is shorter in the patch specimen. It will be shown later (Section 4) that this difference can be explained by the location of the tensile part of the residual stress field.

3. Modelling

As explained in Section 1, modelling of the residual stress distribution was carried out using an eigenstrain method. The first step was to establish the residual plastic strain distribution introduced by a single LSP shot. This was achieved by means of an explicit (i.e. dynamic) finite element simulation of the LSP process. The resulting stress distribution in the specimen was then modelled by the introduction of a misfit strain (or eigenstrain) over the entire treated region [2]. In the experiments reported here, three layers of LSP shots were applied. Hence, the required profile of plastic strain with depth is that caused by three successive LSP shots at the same location [3].

As explained in greater detail [2], the LSP process is modelled as a purely mechanical process caused by the shock wave generated by the ablation of the tape by the laser. Hence, in the explicit finite element model, a pressure pulse is applied to the surface of the specimen over the area corresponding to the laser pulse. The pressure is treated as uniform over the area of
the pulse. Whilst this is probably an approximation, it is difficult to make a more sophisticated assumption without a detailed multi-physics model of the plasma generation process. It remains to determine the time history of the pressure pulse applied. For simplicity, and because experimental results are limited, a simple triangular variation of pressure with time was assumed (Figure 8). The duration of the pulse is \( t_p \) and the peak pressure, \( p_{\text{max}} \), is assumed to be generated at half the total duration of the pressure pulse, i.e. \( p(t_p / 2) = p_{\text{max}} \). The pressure pulse duration is normally assumed to be four to six times that of the laser pulse [2, 12]. Here a value of \( t_p = 100 \text{ ns} \) was used, which can be compared to the laser pulse duration, \( t_L \), of 18 ns. The final parameter needed is the peak pressure. This may be chosen by considering the energy transferred to the work piece by the pressure pulse and comparing this to the laser energy.

Typically, only 5 to 10% of the laser energy is transferred to the substrate [2]. In the current application, a peak laser power density of 4 GW/cm\(^2\) was used, and the peak pressure in the simulation was adjusted so that 3% of the energy was transferred to the work piece\(^2\). This resulted in a peak pressure in the simulation of 3.15 GPa. A simple elastic, perfectly plastic material model was assumed, with a yield stress of 350 MPa. More sophisticated material models (e.g. including strain or strain rate hardening) could easily be employed. However, there is always a difficulty in setting the hardening parameters correctly. Strain rates during the LSP pulse are found to be in the region of \( 10^6 \text{ s}^{-1} \) and materials data at these rates of strain are difficult to obtain. Very high strain rate material data for the alloys used here was not readily available, therefore use of a more sophisticated material model could not be justified. In any case, even if strain rate hardening takes place, the high levels of yield stress are

\(^2\) The total strain energy and kinetic energy in the finite element model is readily available as an output from the explicit FE code.
unlikely to be sustained after the impact event, so that a quasi-static value is likely to be representative of the situation at the end of the process.

The assumptions of peak pressure and pulse duration in the modeling can be validated to some extent by comparing the results of the simulation with a simple experiment. One straightforward method of validation is to compare the experimental and predicted surface profiles obtained for the case of a single shot. Figure 9 shows a typical surface measurement profile obtained from an Alicona Infinite Focus microscope. Half of the LSP shot is shown, and the surface indentation caused by the shot is clearly visible. Figure 10 shows a comparison of the measured and predicted surface profiles, and it is evident that a good match can be obtained if the peak pressure in the simulation is set correctly. If pulse length and temporal distribution or material yield stress are also treated as free parameters, then other combinations might lead to a similar indentation depth. Hence the validation must be treated with some caution. It merely provides an indication that a broadly consistent set of parameters have been found.

The explicit finite element simulation of an LSP shot may be terminated as soon as the plastic strain has stabilized. Typically this is 1000-1200 ns (i.e. after 10-12 $t_p$) after the start of the pressure pulse. The plastic strain is found to be introduced almost exclusively underneath the shot itself [2] and not to vary significantly over the area of the shot. Hence, the plastic strain profile can be assumed to be a function of distance from the surface ($z$) only. Figure 11 shows the profile obtained for the current case. The plastic strain components in the x and y directions are identical and are shown here as ‘eigenstrain’. In the current configuration three layers of shots are used. Because the strain introduced is largely confined to the material directly under the shot, it is not necessary to consider interaction of adjacent shots, nor is it necessary to explicitly consider any offset between shots of subsequent layers [3]. Hence, the
effect of two or three shots can be explicitly simulated by applying the pressure pulses one after the other in the finite element model. Figure 11 shows the results obtained, it can be seen that the plastic strain is increased in magnitude and depth with each subsequent shot. It should be recognized that these results are obtained without strain hardening and the effect may be less significant with a work-hardening material.

Once the variation of plastic strain with depth has been established, this may be introduced as a misfit strain (or eigenstrain) in an implicit finite element model. A convenient means of achieving this is to specify a thermal expansion coefficient which varies with position in the work piece and then apply a fictitious unit temperature rise [2]. The residual stresses then arise in the model as the elastic response to the misfit strain. This is exactly what happens in the real process: a plastic misfit strain is introduced and the residual stress field arises from the elastic response of the work piece to this misfit strain. Herein lies a significant advantage of the eigenstrain approach: subsequent machining operations which change the shape of the component will not significantly affect the misfit strain introduced. Hence, the same eigenstrain distribution can be used in the remaining material. The residual stress field will, of course, change, as the different component geometry will affect the elastic response.

The method outlined above may now be exploited in the context of the surface treated fatigue specimens described earlier. Since the hole was introduced after the LSP treatment, we can consider the eigenstrain distribution to be uniform over the remaining area treated. Provided that the drilling of the hole does not create significant further plastic strain in the remaining material, it is not necessary to consider the interaction of the hole with the plastic strain field. Of course, the residual stresses in a specimen with a hole will differ from those in a flat plate, but the requirements of equilibrium, compatibility and the material constitutive law will be correctly enforced within the finite element code. Hence, the residual stress field will be
correctly modeled and it is not necessary to install the eigenstrain first in an undrilled specimen and then to model the drilling of the hole.

4. Predictions of residual stress

The method described in the previous section was used to predict the residual stress field present in each of the different Al 2024 specimens with laser shock peening applied (Section 2). It was assumed that the specimen was originally free of residual stress and the appropriate eigenstrain distribution was introduced to correspond to the area treated in the specimen. In practice there may be some near-surface residual stresses in the specimen caused by machining, but these are likely to be significantly smaller than those induced by LSP [1]. As is usual in finite element analysis, only half the thickness of the specimen is modeled, and symmetry conditions applied at the mid-plane. In the case of the 5mm thick specimen, the eigenstrain distribution is deeper than 2.5mm. Hence, an approximation was made by truncating the distribution at this depth. A comparison with the case where the two full eigenstrain distributions were superposed (so that they overlapped) shows relatively small differences in the residual stress profile.

Figure 12 shows two contour plots of the $\sigma_{xx}$ stress distribution in the 5 mm and 15 mm thick specimens with “full-face” LSP treatments. This is the stress component which combines with the applied stress to cause fatigue crack initiation. In both the ‘thick’ and ‘thin’ geometries, a compressive stress is introduced as expected at the specimen surface. In the thin specimen, this residual compression persists along the bore of the hole throughout the entire thickness, whereas the thick specimen exhibits some residual tension on the mid-plane. This difference explains the observed experimental results (Section 2 and Fig. 5). With the thin specimen, the residual compression helps to inhibit crack initiation and the recorded lives are longer than the ‘as machined’ condition. The thick specimen geometry does not produce
this life extension, as there are points along the bore of the hole where the residual stress is mildly tensile. It should be noted that in Fig 12, the surface compressive stress reaches 350 MPa in compression. This suggests that a small amount of additional plasticity has been caused by the interaction of the eigenstrain with the hole.

Figure 13 illustrates the effects discussed above in a more quantitative fashion. The \( \sigma_{xx} \) stress component at the 90\(^\circ\) position with respect to the applied loading is plotted as a function of depth. For the 5mm thick specimen geometry the stress component is purely compressive, whereas for the 15mm thick geometry, the stress rises to about 150 MPa at mid-plane. Also illustrated here is the significant difference between the full-face (40 x 40 mm) treatment and the patch (20 x 20 mm) case in the thin specimen geometry. The 20 x 20 mm patch generates residual compression of about 350 MPa, whereas in the ‘full-face’ case this is reduced to around 200 MPa. The reason for this becomes apparent when one considers overall specimen equilibrium and it illustrates a fundamental point. The definition of residual stress is a stress field that exists in the absence of external loading. Hence, the residual stress field on any section through the component must give rise to no resultant force and moment. It follows that it is not possible to introduce a compressive residual stress at one location in a component without a balancing tension somewhere else. The magnitude and location of this tensile region is of crucial importance: if it is located in a region of low stress and away from the surface, then the residual stress field may be beneficial to fatigue life. If it is not, then the fatigue life of the component may be reduced.

In the light of the observations made above, the results of Figure 13 may be interpreted as follows: for the thick specimen treated with full-face LSP, there is residual compression at the surface of the specimen. The balancing tension must therefore be carried towards the mid-plane of the specimen, and this gives rise to increased tensile stress along the bore of the
hole. There is therefore likely to be no improvement in fatigue life. If the peening is only applied to a patch, then some of the tension can be carried closer to the surface, in the un-peened regions and this gives rise to a slight improvement in residual stress profile. For the thin specimen, the residual tension must still be carried, and there must clearly be tensile stresses at the mid-plane. However, the eigenstrain interacts with the presence of the hole in quite a complex manner, and it appears (Figure 13), that the stress along the bore of the hole is wholly compressive. The best results were achieved with the thin specimen treated with a patch. Here there is a clear load path for the tension at the surface of the specimen in the lateral areas not treated by LSP. This means that a substantial residual compression can be established along the bore of the hole through the entire thickness of the specimen. This explains the fatigue life enhancement found in the experiments (Figure 5). It also accounts for the shorter critical crack length found experimentally in the specimens treated with an LSP patch (Figure 7a). Once the crack grows away from the treated area it experiences significant residual tension superimposed on the applied loading and hence the critical stress intensity factor for unstable crack growth will be experienced at a shorter crack length than will be the case in the ‘full-face’ treated case.

4.1 Effects of loading

The discussion above concerns the residual stress field which exists in the absence of any applied loading. Whilst this gives useful insight into the behaviour under fatigue loading, a crucial question remains: how will the residual stress field be affected by the loading itself. A simple first approximation is to assume that there is no further plastic deformation, in which case superposition may be used to give the stresses as the sum of residual and applied elastic fields. However, there will clearly always be a level of loading which gives rise to plasticity in the specimen and we would expect the residual stress field to change under these
circumstances. Hence, it is possible that the beneficial effects of the surface treatment might not persist under relatively high applied loading.

The eigenstrain method provides a simple means of investigating the point raised in the previous paragraph. The implicit finite element model includes the effect of surface treatment as a misfit strain, and the residual stress arises as a response to this. Hence, application of a live load to the model will superpose the effect of this loading on the residual stress field and plastic flow will take place once the yield condition is reached. With the current material model, application is particularly straightforward, since no work hardening has taken place and the yield condition is the same at all points in the model. Figure 14 shows the effect of applying a live load corresponding to an average net section stress 145 MPa. This represents the lowest peak load used in the experiments on the 5mm thick specimens. Figure 14a shows the load applied to an ‘as-machined’ specimen, and the effect of the stress concentration at the hole is clearly visible. A significant tensile stress is present right through the bore of the hole, and it is this which will give rise to crack initiation. In Figure 14b, the same load is applied to a specimen treated with an LSP patch (20 x 20 mm). It can clearly be seen that the tension is largely carried outside the patch, and that the bore of the hole is subjected to far lower tensile stress.

Figure 15 shows the effect of loading in more detail by plotting the variation of the axial stress component along the bore of the hole for different applied loads. Initially the stress is simply the superposition of the residual stress field and the applied stress times the elastic stress concentration factor, $K_t$. The $xx$ stress component becomes tensile at an applied stress of around 100 MPa (Fig 15), but the LSP still offers a significant benefit compared with an untreated specimen, as the tensile part of the stress range is reduced in magnitude. However, at applied loads greater than about 145 MPa, plasticity starts to occur and the protection
provided by the LSP treatment is diminished, as plastic flow reduces some of the beneficial misfit strains introduced by the process. Hence, we would expect treatment by a patch of LSP to show a large benefit at stress levels below 145 MPa, but a significantly reduced effect at higher stress levels. This is clearly evident in the experimental results shown in Figure 5.

5. Conclusions

The paper has presented experimental results concerning the fatigue response of Al 7010 and Al 2024 specimens with a centre hole geometry. The use of conventional shot peening and laser shock peening to potentially improve the fatigue strength was investigated. For the 15mm thick specimen, the surface treatments were found to have minimal or no effect. Initiation of fatigue cracks took place in the bore of the hole, in an area where the stress was not significantly affected by the surface treatment. For thin (5mm thick) specimens, there was some improvement, particularly when LSP was applied in a patch around the hole, rather than across the full face of the specimen.

A modelling approach based on the representation of the LSP process by an eigenstrain distribution was used to interpret the experimental results. This proved simple and effective and avoids the necessity to carry out explicit finite element simulation of each LSP shot, which would be computationally impractical. The method was able to explain the experimental results: residual compression was predicted in some areas of the specimen, but balancing residual tension at others. It is the location of this balancing tension which is an important feature in determining the fatigue life of a specimen. If the full face of the specimen is peened, then the tension must be carried towards the mid-plane of the specimen, and the bore of the hole will be exposed to these increased stress levels. If, however, a patch of LSP
is applied around the hole, the residual tension is carried outside the patch and it is possible to place the whole of the bore of the hole into residual compression.

The eigenstrain approach is also extremely convenient in investigating the effects of subsequent applied loading and the ‘shakedown’ of the residual stress field. For low loads, there is little or no plastic flow and the protective residual compression remains in place. For higher applied loads, plastic flow occurs and some of the benefits of the surface treatment can be lost. Hence, the eigenstrain approach provides an important tool for investigating the treatment of stress concentrations with LSP or similar surface treatments, such as shot peening. Once the characteristic eigenstrain distribution caused by the treatment has been determined, it may be applied over different regions of the work piece and the resulting stress distribution determined using a simple implicit finite element analysis. It is important to note that there will always be residual tension in addition to residual compression and the location of these tensile regions is an important consideration. If residual tension occurs in regions which are already subject to a significant tensile fatigue loading, then the improvement in fatigue performance offered by surface treatment may be compromised.

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References


Figure 1. Mid gauge section details of the full face (left) and patch (right) test specimens (total length of specimens = 330 mm, all dimensions quoted in mm)
Figure 2. Results of fatigue experiments on Al 7010 (all specimens 15mm thick).
Figure 3. Fracture surfaces for 15 mm thick Al 7010 specimens tested at a peak net section stress of 220 MPa: (a) As-machined, (b) LSP full face, and (c) Shot peened full face.
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Figure 5. Results of fatigue experiments on Al 2024.
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Figure 8. Assumed variation of pressure with time, caused by application of a laser pulse.
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Figure 10. Variation of surface displacement in the normal (z) direction with distance from the centre of the pulse (y): comparison of experimental results and model predictions.
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Figure 12. Comparison of $\sigma_x$ stress component (MPa) caused by LSP treatment in (a) 5mm thick specimen and (b) 15 mm thick specimen.
Figure 13. Variation of the $\sigma_{xx}$ stress component with depth along the bore of the hole (i.e. normal to the loading direction) for different specimen geometries and treatments.

Figure 14. $\sigma_{xx}$ stress component (MPa) in a thin specimen loaded to 145 MPa: (a) ‘as-machined’ and (b) treated with an LSP patch.
Figure 15. Variation of $\sigma_{xx}$ stress component with depth along the bore of the hole for different applied loads in a 5mm thick specimen with an LSP patch.
Table I. Details of fatigue tests performed.

<table>
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<td>as machined</td>
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<td>28116</td>
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<td>Al 7010</td>
<td>15mm</td>
<td>as machined</td>
<td>0.1</td>
<td>145</td>
<td>636037</td>
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<tr>
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<td>Al 7010</td>
<td>15mm</td>
<td>as machined</td>
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Denotes run out tests
Research Highlights (JIJF 3109)
Eigenstrain approach works well to model the fatigue of LSP treated specimens
Interactions between the LSP process and geometric features are important
Not all instances of LSP applications provide improvement in fatigue life
Eigenstrain method allows modelling the effects due to balancing tensile stress