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Abstract

In this study, residual stress fields, including the near-surface residual stresses were determined for an Al7050-T7451 sample after laser peening. The contour method was applied to measure one component of the residual stress, and the relaxed stresses on the cut surfaces were then measured by X-ray diffraction. This allowed calculation of the three orthogonal stress components using the superposition principle. The near-surface results were validated with results from incremental hole drilling and conventional X-ray diffraction. The results demonstrate that multiple residual stress components can be determined using a combination of the contour method and another technique. If the measured stress components are

congruent with the principal stress axes in the sample, then this allows for determination of the complete stress tensor.

Keywords: Near-surface residual stresses, contour method, superposition principle, X-ray diffraction, incremental hole drilling, laser peening

Introduction

Mechanical surface treatments, including shot peening and laser peening (also called laser shock peening), are widely applied to safety-critical components, especially in aerospace applications. Sections under loading, particularly those prone to failure owing to geometric discontinuities, are subjected to mechanical surface treatments against fatigue initiation. The resistance against failure can be increased by inducing compressive residual stress fields near the surface, where most failures initiate. Beneficial compressive stresses will superimpose with the structural or applied loads so that the crack initiation and propagation can be delayed or even inhibited. Therefore, residual stresses after any surface treatments play a crucial role in terms of improvement in service performance. Hence, characterization of these near-surface residual stress fields is very important to assess the impact of the applied surface treatments.

Laser peening has become an important surface treatment technique, applied to components to improve their properties against failure types including fatigue and stress corrosion cracking [1]. The surface of the sample to be treated may be covered with a sacrificial layer of black paint or thin aluminium foil to protect the surface from the thermal effects of the plasma [2] or laser pulses can be sent directly to the sample, where it is very hard to do a surface preparation before laser peening such as applications in nuclear power plants [3]. Laser pulses with selected power density and duration, which are different depending on the laser peening system used, are delivered to the sample surface by mirrors or fibre optic cables. The laser pulse instantaneously vaporizes the surface layer to create a high temperature (about 10000 K) and high pressure (several GPa) plasma [2]. The target material is covered with a confinement medium, usually water, to increase the efficiency of the plasma. The plasma generated by a laser pulse induces a mechanical momentum onto the material and shock waves are formed. The shock waves penetrate into the material and cause plastic deformation through dilation, which induces a compressive residual stress field after subsequent elastic relaxation. Even though instantaneous temperature of the plasma reaches very high levels, owing to very short duration (generally in nanoseconds) and the surface protection, the process is considered as a mechanical surface treatment method and thermal effects are generally ignored. The resulting compressive residual stresses, especially at the surface, enhance fatigue performance by acting against structural and applied loads. Compared to conventional shot peening, the laser peening treatment is proven to give a deeper compressive stresses with better surface finish, which leads to improved fatigue performance [4].

The contour method is a recently-invented destructive residual stress measurement techniques, being used since the early 2000s [5]. A full 2D stress map can be obtained by the method with a single cut, which makes the technique unique. Despite its advantages, there are two main limitations for the method: the full 2D residual stress map can be obtained only for one stress direction; and the residual stress in the near-surface region is very challenging to obtain reliably [6]. However, multiple stress components can be obtained by additional approaches such as the eigenstrain theory [7] and multiple cuts [8]. Introduced by Pagliaro *et al.* [9], the superposition principle can also be employed to obtain multiple stress components with the contour method. The application of this principle necessitates additional residual stress measurements using other techniques, such as X-ray diffraction or hole drilling [10]. Near-surface residual stresses perpendicular to the cut surface by contour method were investigated in detail by the authors previously [11]. It was concluded that, with the help of cutting trials to optimize cutting parameters and improved data analysis, especially for the near-surface region, reliable near-surface residual stress measurements are possible with the contour method. However, only one stress component was obtained near the surface in that study.

In this work, multiple stress components including the near-surface region were obtained for an Al7050-T451 sample after laser peening. The contour method was combined with X-ray diffraction to employ the superposition principle to obtain multiple orthogonal stress components. The near-surface residual stress results are compared to complementary measurements from incremental hole drilling results and X-ray diffraction.

Materials and methods

Sample preparation

The sample used in this work was fabricated from Al7050-T7451 aluminium alloy. After production, it was solution heat-treated, stress relieved by stretching, and over-aged, as the T7451 notation indicates. The material properties of the alloy are listed in Tab. 1. The stepped sample used in this work (Fig. 1a) was designed to investigate the fatigue performance of the material after laser peening: results from the fatigue study are reported elsewhere [12]. The transition region was laser peened between the gauge section and the shoulder of the specimen, where the thickness changes from 28 mm to 42 mm. The cross-section of the sample shown in Fig. 1b also highlights the laser peened region. The peening of the sample was carried out by Metal Improvement

Company (MIC), Earby, UK with a sacrificial ablative layer and water overlay. A 4 × 4 mm[2] square laser spot was used. The laser power density in GW/cm[2], the pulse duration in nanoseconds and the number of peen layers were 4-18-3 respectively, in the notation widely used in the literature. The number of layers indicates the number of laser hits on a particular location, and is equivalent to a coverage of 300%. The overlapping was achieved by 30% offsetting in both *x* and *z*-directions, as shown in Fig. 1b.

Table 1 Mechanical properties of the Al7050-T7451 [11]

Al7050-T451	*E [GPa]*	*Poisson's ratio*	*YS [MPa]*	*UTS [MPa]*
	72	0.33	460	520

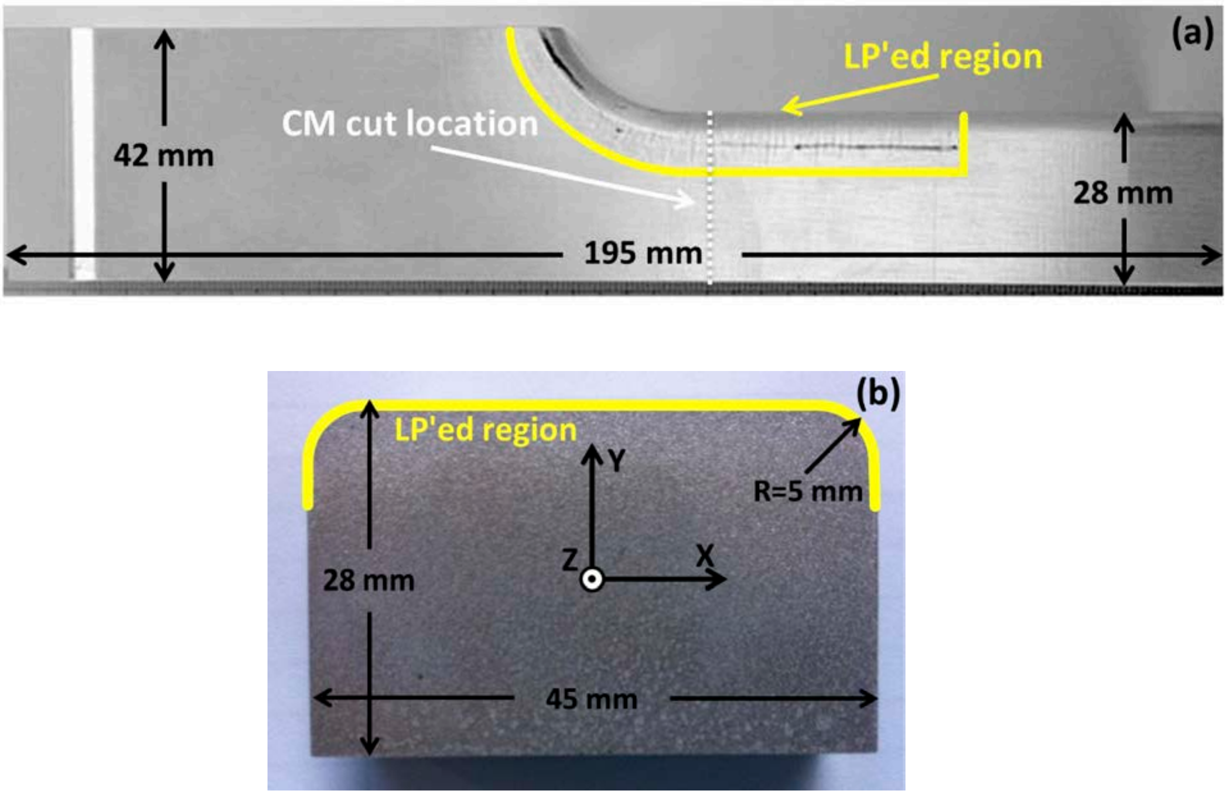

Figure 1: Side (a) and cross-sectional (b) view of the stepped sample used in this study. The laser peened (LP'ed) region is indicated by the continuous line and the location of the contour method (CM) cut is shown by the dotted line.

Residual stress measurements

X-Ray diffraction

X-ray diffraction experiments were conducted using a Stresstech X3000 diffractometer according to guidelines provided by the NPL Good Practice Guide [13]. A 2-mm-diameter collimator was used to define the sampling area, to have a similar area for comparison to incremental hole drilling. A Cr anode was used to obtain diffraction peaks from the {311} lattice planes, which reflects the macroscopic behaviour of aluminium most closely [14] and is recommended for samples with texture and large grain size owing to its high multiplicity [13]. The penetration depth in aluminium is around 17 μm with a Cr anode. The diffraction angle 2θ was $\sim$139°. The detectors' ψ tilt angles were from –40° to +40°. Peaks from different tilt angles we rerecorded and fitted by the cross-correlation method: from the change in peak positions the residual stresses were calculated by the $\sin^2\psi$ method [13].

Incremental hole drilling

Incremental hole drilling experiments were conducted using a set-up developed by Stresscraft, UK. As in all destructive techniques, the method is based on stress relaxation upon material removal. Stresses are relaxed by introducing a hole, and the consequent relaxed surface strains are used to calculate the original relieved residual stress at each increment. The measurements were done based on the methodology recommended in the UK NPL Good Practice Guide [15]. A 2-mm-diameter hole was introduced by an orbital driller in controlled depth increments. At each increment, strains were measured by a three-gauge rosette attached to the sample surface. The measured strains were evaluated by Stresscraft RS INT software version 5.1.3 employing the integral method developed by Schajer [16].

Contour method

The contour method is a destructive method used to obtain residual stresses. The sample with residual stress to be determined is cut into two halves by a wire electro-discharge machine, and the stresses normal to the cut surface are relaxed. The elastic surface deformations on the cut surface owing to the stress relaxation are measured by a co-ordinate measuring machine or laser profilometer. Data analysis is required to eliminate, or at least minimize, any artefacts arising during the cutting or contour measurements. Finally, the surface contours are inputted into a finite element model as a set of displacement boundary conditions, and the pre-existing normal residual stresses perpendicular to the cut surface can be obtained.

The near-surface stresses are very challenging to obtain by using the contour method. It was suggested by Prime *et al.* [6] that near-surface results obtained using the contour method should not be reported unless extra effort was spent for improved accuracy. Therefore, several cutting trials were conducted to minimize cutting effects and a new data analysis routine based on [17] was developed to obtain near-surface stresses. The results were compared with different techniques to increase confidence in the results. The fundamentals and the application of the contour method employing the new data analysis method to the laser peened stepped sample were given previously by the authors [11]. The other stress components can be obtained by superposition principles, as described in the next section, originally introduced by Pagliaro *et al.* [9].

Multiple near-surface stress components via the superposition principle for the contour method

Bueckner's principle for a cracked body [18] is the basis of the contour method. According to the application of Bueckner's principle to the contour method, the original residual stress state, σ^A, will be equal to the final stress state at the cut surface, σ^B, and the change of stresses to force the deformed surface back to its original flat after the cut, σ^C:

$$\sigma^A = \sigma^B + \sigma^C \quad (1)$$

where σ is the stress tensor including both normal and shear stresses in the *x*, *y* and *z*-directions.

The shear stresses and their influence on the final normal stress results for the contour method have been investigated previously [9, 19]. It was concluded that averaging the contour measurements of the two cut surfaces before the data analysis will minimize any contribution of shear stress relaxation to the calculation of the normal stresses. In addition to shear stress effects, averaging the contour data of the two cut surfaces is also useful to minimize any anti-symmetric artefacts arising from the cutting or contour measurements [6]. Therefore, only normal stresses are considered by the contour method and any contribution of shear stresses are assumed to be minimized after averaging the two cut surface contour profiles. Hence, Eq. 1 can be rewritten as:

$$\sigma^A(x,y,0) = \sigma^B(x,y,0) + \sigma^C(x,y,0) \quad (2)$$

where $\sigma(x,y,0)$ is the normal residual stress components at the cut surface in the *x*, *y* and *z*-directions.

For the normal stresses at the cut surface in the *z*-direction, Eq. 2 can be written as:

$$\sigma_z^A(x,y,0) = \sigma_z^C(x,y,0) \qquad (3)$$

where $\sigma_z^B(x,y,0)=0$, due to elastic stress relaxation in the *z*-direction [11]. However, for the other normal stress components, $\sigma_x^A(x,y,0)$ and $\sigma_y^A(x,y,0)$, Eq. 2 becomes;

$$\sigma_x^A(x,y,0) = \sigma_x^B(x,y,0) + \sigma_x^C(x,y,0) \qquad (4)$$

$$\sigma_y^A(x,y,0) = \sigma_y^B(x,y,0) + \sigma_y^C(x,y,0) \qquad (5)$$

Thus, $\sigma_x{}^B(x,y,0)$ and $\sigma_y{}^B(x,y,0)$ are required for the original residual stresses, $\sigma_x{}^A(x,y,0)$ and $\sigma_y{}^A(x,y,0)$, in addition to the components of $\sigma_x{}^C(x,y,0)$ and $\sigma_y{}^C(x,y,0)$.

By employing the same contour method routine for $\sigma_z{}^C(x,y,0)$ (as given in detail in [11, 17]), $\sigma_x{}^C(x,y,0)$ and $\sigma_y{}^C(x,y,0)$ can be obtained. Then, to obtain the original residual stresses, the remaining in-plane stresses after cutting in the *x* and *y*-directions, $\sigma_x{}^B(x,y,0)$ and $\sigma_y{}^B(x,y,0)$, should be measured. The cutting step does not induce significant stresses that could cause a change in the measured surface contour. However, when the stresses are measured directly on the cut surface, effects of residual stress owing to the cutting can be observed [9]. Therefore, before residual stress measurements to be performed at the cut surface, the cutting-affected layer has to be removed by techniques such as electro-polishing. It is assumed that the in-plane residual stresses do not vary significantly through the removed layer. This can be expressed as:

$$\sigma^A(x,y,0) \approx \sigma^A(x,y,0-\delta-t) \qquad (6)$$

where δ is the thickness of the layer removed, and *t,* introduced by the authors here in Eq. 6, is the average penetration depth of the incident beam like X-rays into the sample. *t* would also be the average depth of the sampling volume for a destructive residual stress measurement method like incremental hole drilling, if the stresses were to be measured by such a technique instead of diffraction methods.

Results

A 2D residual stress contour map and a line profile of stresses in the *z*-direction, $\sigma_z{}^A$, are shown in Figs. 2 and 3, respectively. Since the stress relaxation is complete in this direction, the contour method results are the total residual stresses (Eq. 3). The results were obtained from the contour method by applying a new cubic spline data smoothing routine optimized for the near-surface stresses [11]. The line profile of residual stress shown in Fig. 3 was obtained from the centre of the sample (x=0) and is plotted from the laser peened surface into the depth, i.e. along the –*y* direction. The surface stresses are around −300 MPa, and the depth of the compressive region is about 3.0 mm. Deep compression and improved surface finish are characteristic of laser peening, leading to higher fatigue resistance compared to conventional shot peening [12]. The round corners of the sample were also peened, as shown in Fig. 1b, and are in compression but of a lower magnitude than the flat region owing to lower constraint. The compressive stresses at the peened surface are balanced by internal tensile stresses, as expected.

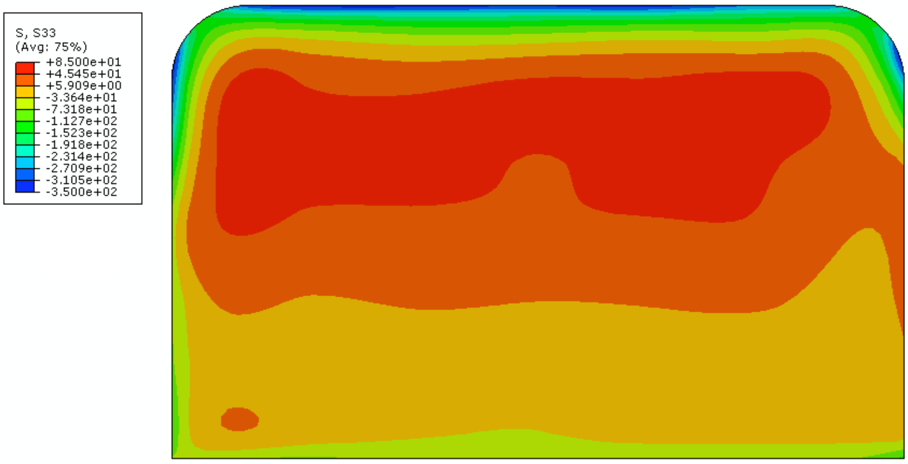

Figure 2: 2D stress map of $\sigma_z{}^A$ determined by the contour method [13]

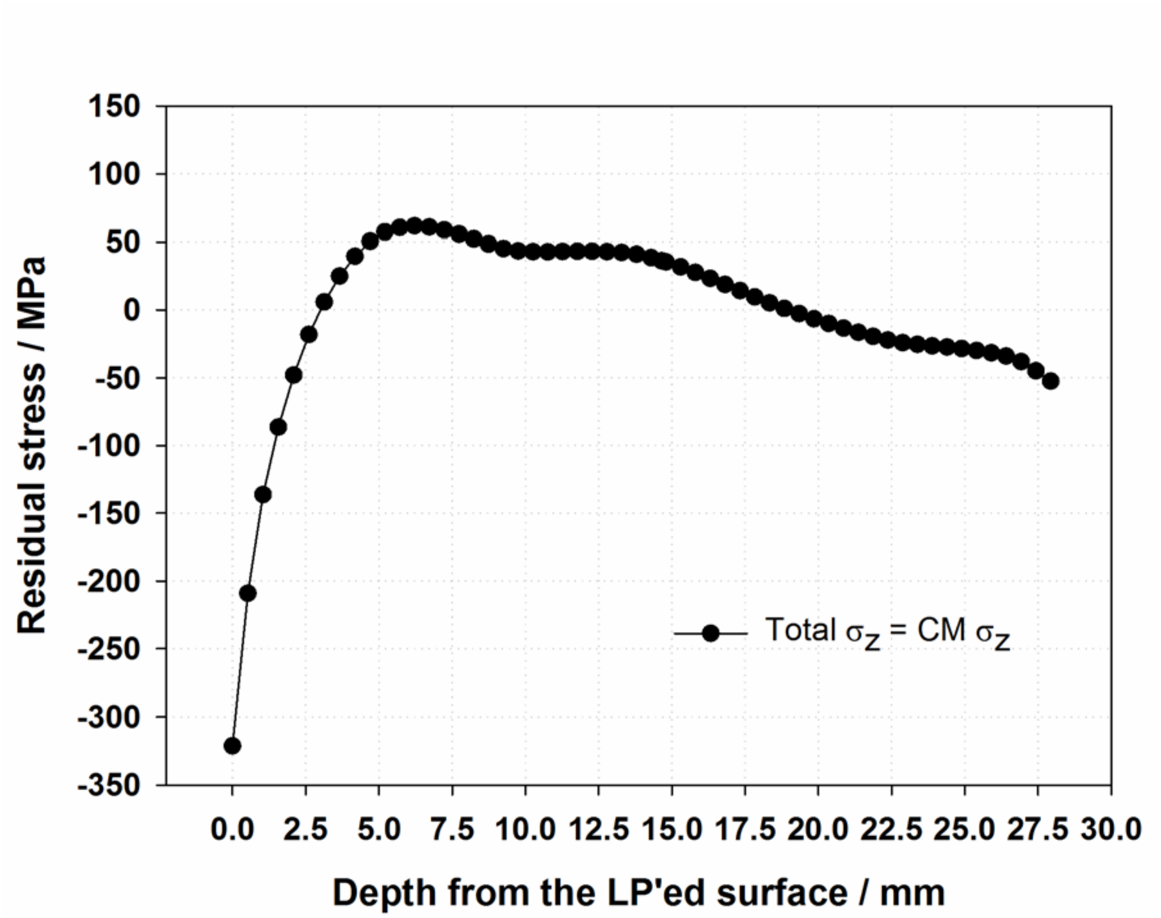

Figure 3: Line profile of residual stress at the centre of the sample, i.e. x = 0, from the laser peened (LP'ed) surface in the minus *y*-direction from the contour method (CM) for σ_z.

After the stresses σ_z^A were obtained, the in-plane stresses in the *x* and *y*-directions, σ_x^A and σ_y^A, were determined by the superposition principle with additional data obtained using X-ray diffraction. The residual stress profiles for the *x* and *y*-directions, which were obtained at the centre of the sample (x=0) along the –*y* direction, are shown in Figs. 4 and 5. The total stresses are the original residual stresses introduced after laser peening (σ^A), the X-ray diffraction results are the stresses at the cut surface after cutting and partial stress relaxation (σ^B), and the contour method results represent the required stresses for deformed surface to flat surface (σ^C). The total stresses were calculated according to Eqs. 4 and 5, where the X-ray diffraction experiments were carried out.

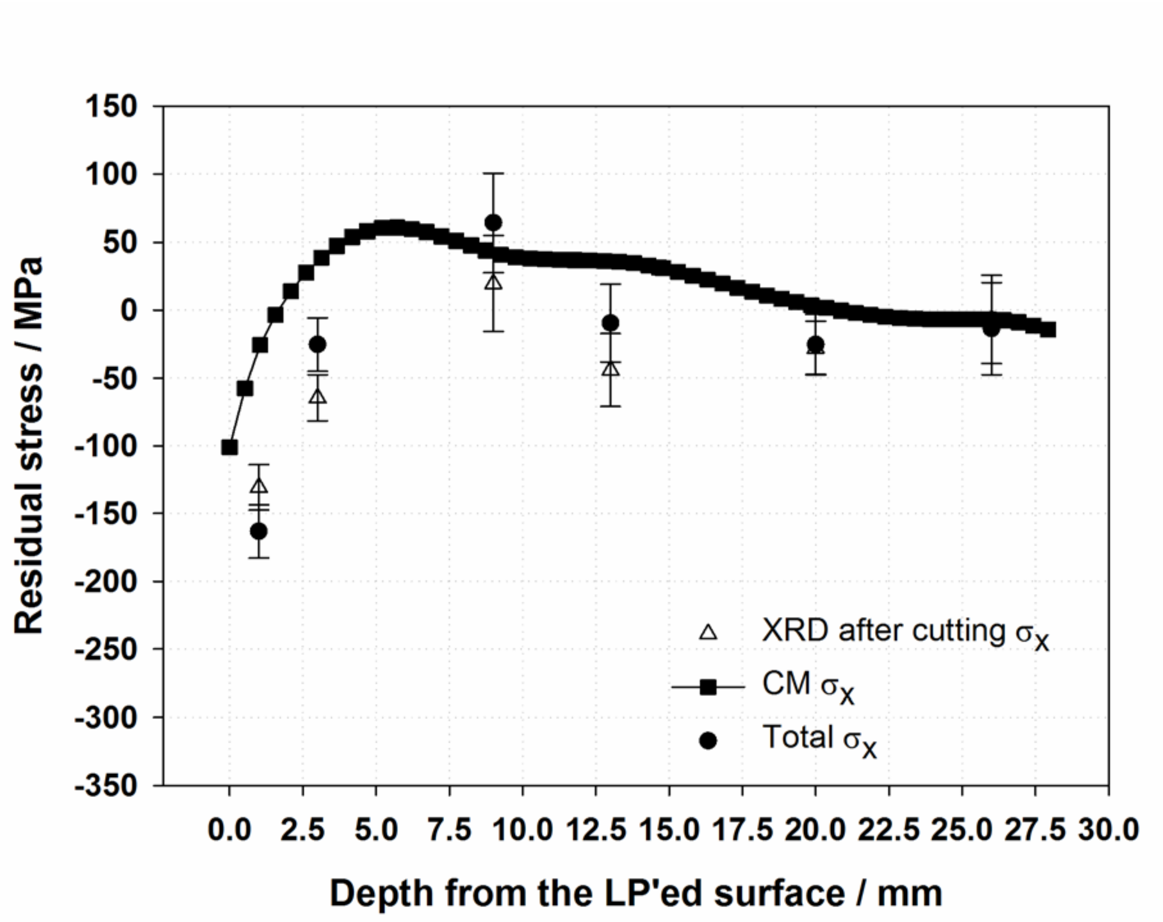

Figure 4: Line profile of the σ_x component of residual stress as determined by the contour method at the centre of the sample, i.e. x = 0, from the laser peened (LP'ed) surface in the –*y* direction. Total stresses (σ^A), X-ray diffraction (XRD) results after cutting for the contour method at the cut surface (σ^B) and the contour method (CM) results (σ^C) for σ_x.

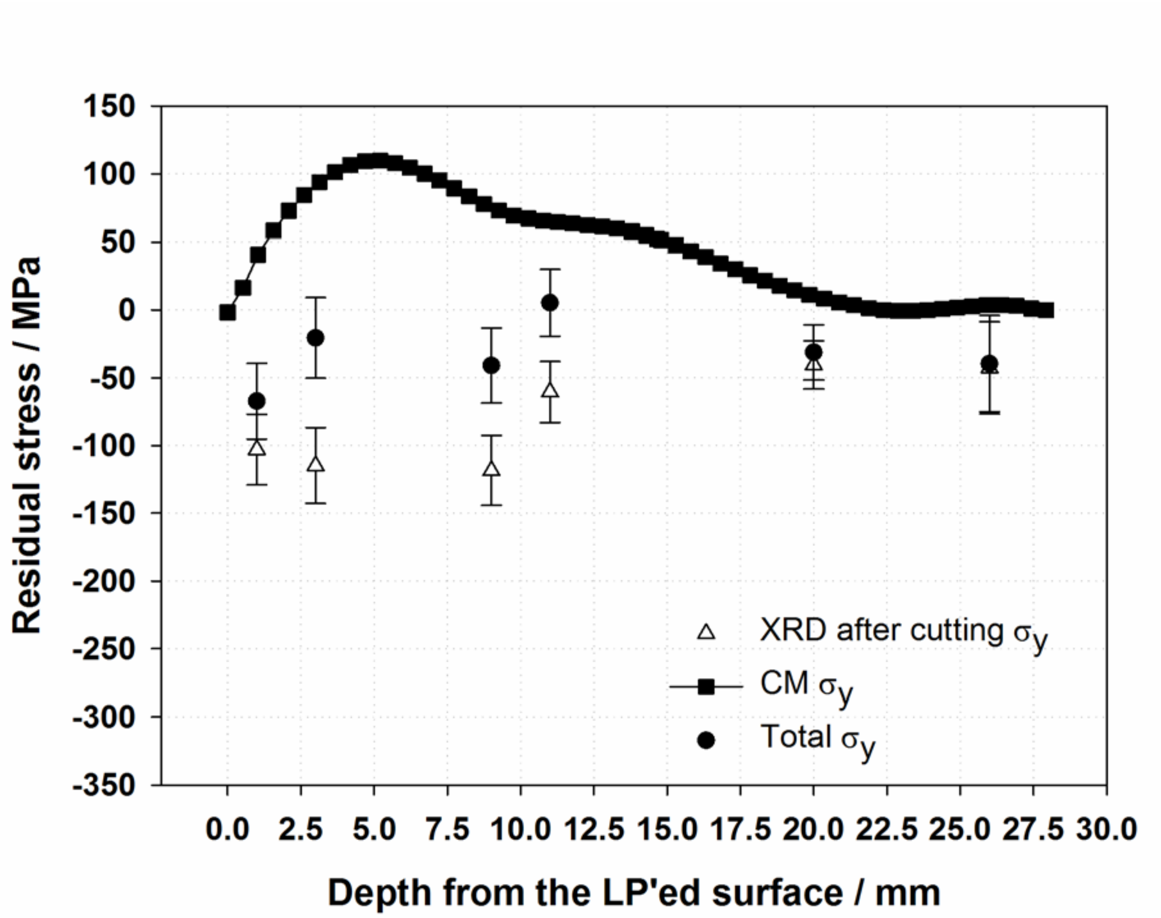

Figure 5: Line profile of the σ_y component of residual stress as determined by the contour method at the centre of the sample, i.e. x = 0, from the laser peened (LP'ed) surface in the –*y* direction. Total stresses (σ^A), X-ray diffraction (XRD) results after cutting for the contour method at the cut surface (σ^B) and the contour method (CM) results (σ^C) for σ_y.

The number of X-ray diffraction measurements on the cut face near the peened surface is limited as the technique requires a sampling area, which is of 2.0 mm diameter in this study. The X-ray diffraction results were conducted on one of the cut surfaces after removing approximately δ =130 μm by electropolishing. The results were obtained at a layer about 150 μm from the cut surface, as 17 μm is the average penetration depth of X-rays into the sample, *t*, and the rest is the thickness of the removed layer by electro-polishing, δ (Eq. 6). Owing to the peen spot overlapping, the stresses in the *z*-direction, $\sigma_z{}^A$, are expected to be reasonably uniform.

The total residual stresses in the *x*-direction, $\sigma_x{}^A$, were also compressive near the peened surface, balanced by internal tensile stresses, very similar to the stresses in the

z-direction, $\sigma_z{}^A$. The laser shots used in a laser peening process will induce direction-independent plastic deformation, as long as the laser intensity is uniform over the spot area. Therefore, an isotropic biaxial residual stress field in the x and z-directions can be expected. In the study by Heckenberger *et al.* [12], the residual stress field in a similar sample was investigated by X-ray diffraction and incremental hole drilling. The incremental hole drilling residual stress results show that the stresses in the x and z-directions are very similar to each other. The only difference between the stepped sample studied in this work and that of Heckenberger *et al.* is the overlapping pattern to obtain 300% coverage, which should not lead to any significant difference to residual stress distribution, as also shown in detail in [12]. The total stresses obtained from the contour method in the z-direction, $\sigma_z{}^A$, and the stresses in the x-direction, $\sigma_x{}^A$, from the combined contour method and X-ray diffraction employing superposition principle can be seen in Fig. 6. The stress field in the z-direction, $\sigma_z{}^A$, has previously been validated (Fig. 7). The stresses in the x and z-directions are very close to each other, mostly within the error bars, which increases confidence in the results obtained by employing the superposition principle. The total residual stresses, $\sigma_y{}^A$, shown in Fig. 5 are very low compared to $\sigma_x{}^A$ and $\sigma_z{}^A$.

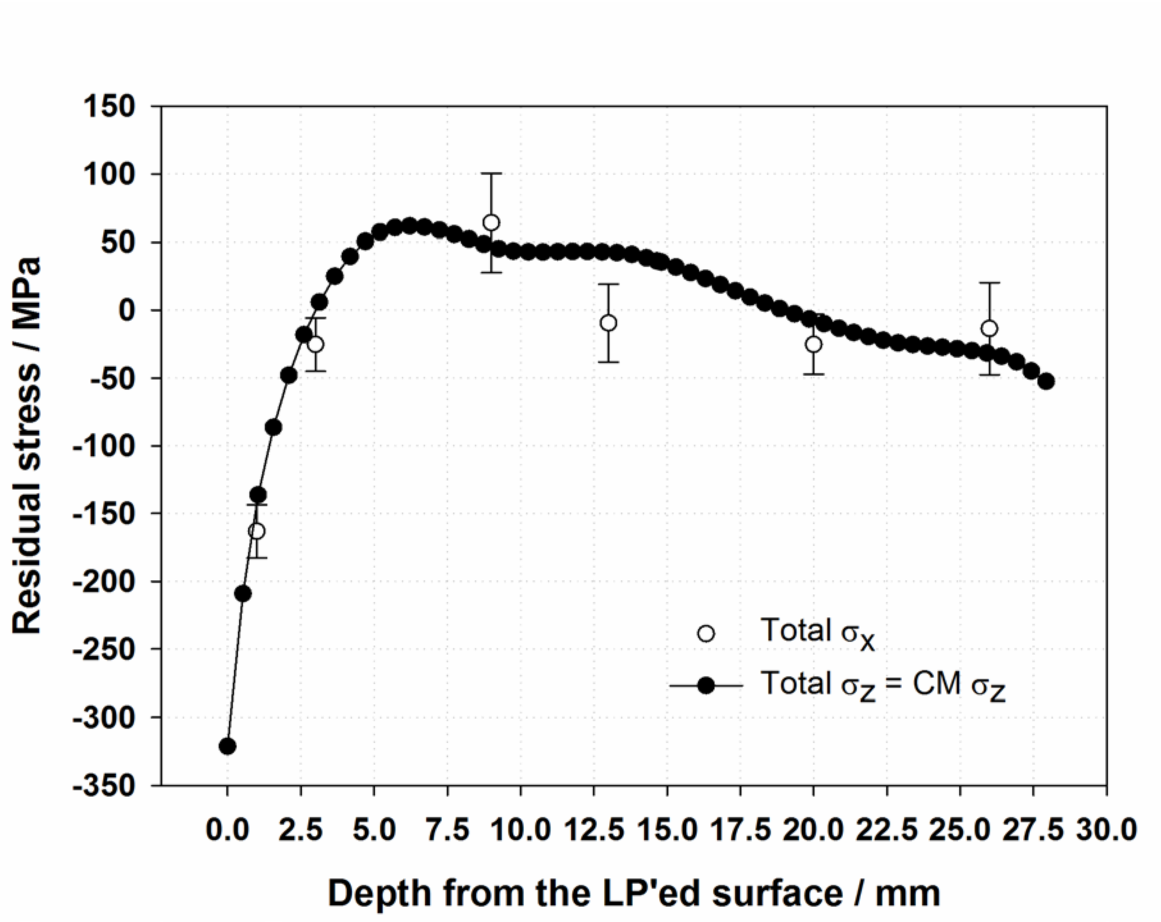

Figure 6: Comparison of the σ_x^A, total stresses from the superposition principle and the total σ_z^A stresses from the contour method results.

The residual stress results in the *z*-direction, σ_z^A, up to 1.1 mm from the laser peened surface are shown in Fig. 7 [11]. The residual stresses in the *x*-direction, σ_x^A, from the same region up to 3.5 mm depth are shown in Fig. 8. The residual stresses obtained using the superposition principle obtained in this work are compared to incremental hole drilling results, as well as the X-ray diffraction and incremental hole drilling results from Heckenberger *et al.* [12]. As noted previously, there are only two data points from the X-ray diffraction method. When the results of the contour method employing the superposition principle are extrapolated up to the surface and compared to the other results, the agreement is very good in trends and magnitudes, except the incremental hole drilling results of Heckenberger *et al.* [12] which are slightly more compressive. However, considering the four different results from three different techniques and two different research groups, as well as the inherent uncertainty in the results, the comparison is promising in terms of applying the contour method with superposition to obtain multiple near-surface residual stress components.

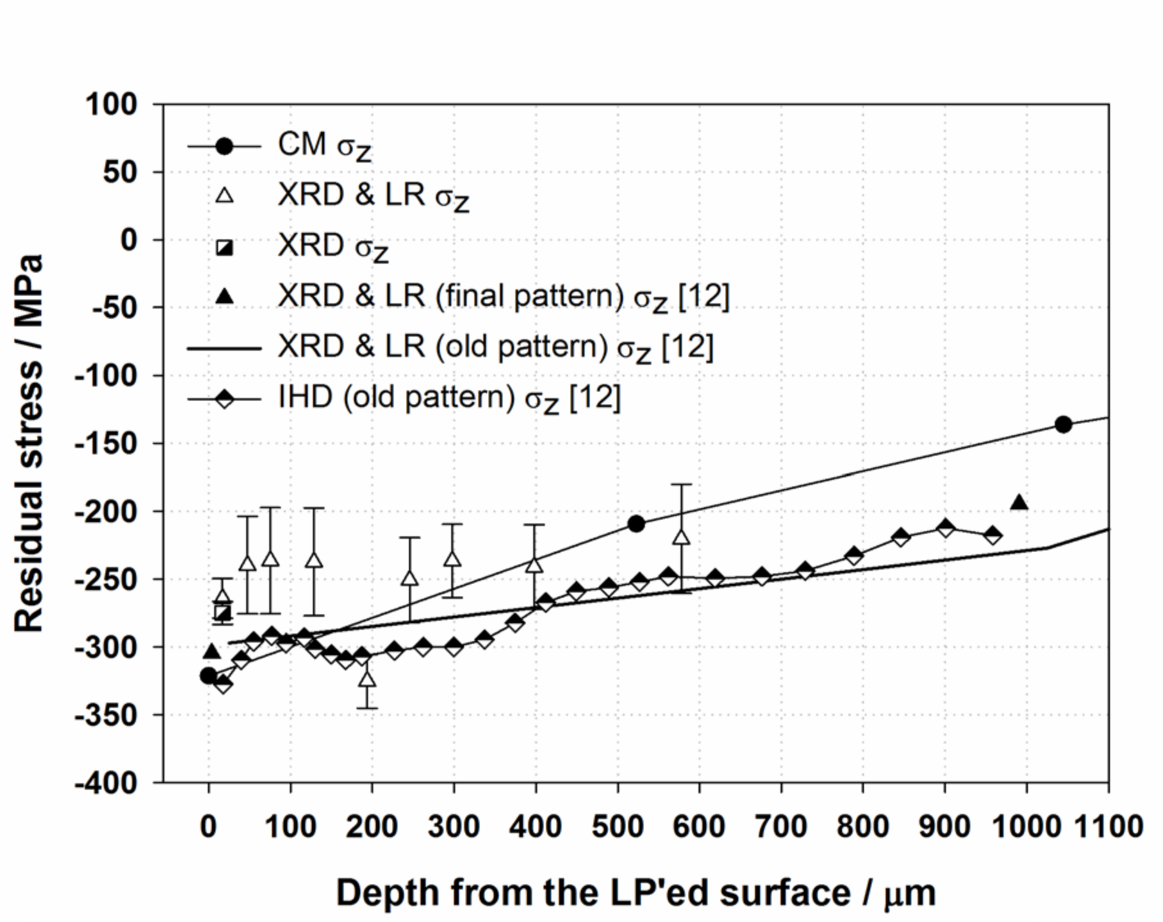

Figure 7: Comparison of contour method (CM), X-ray diffraction (XRD), incremental hole drilling (IHD) and X-ray diffraction and layer removal (XRD & LR) of σ_z up to 1100 μm from the laser peened (LP'ed) surface. There are two sets of X-ray diffraction and layer removal results labelled in the original publication [12] as "final pattern" and "old pattern". The only difference in these two samples is the overlapping pattern of spots used to obtain 300% coverage. The stepped sample was peened according to the "final pattern". (After, [11])

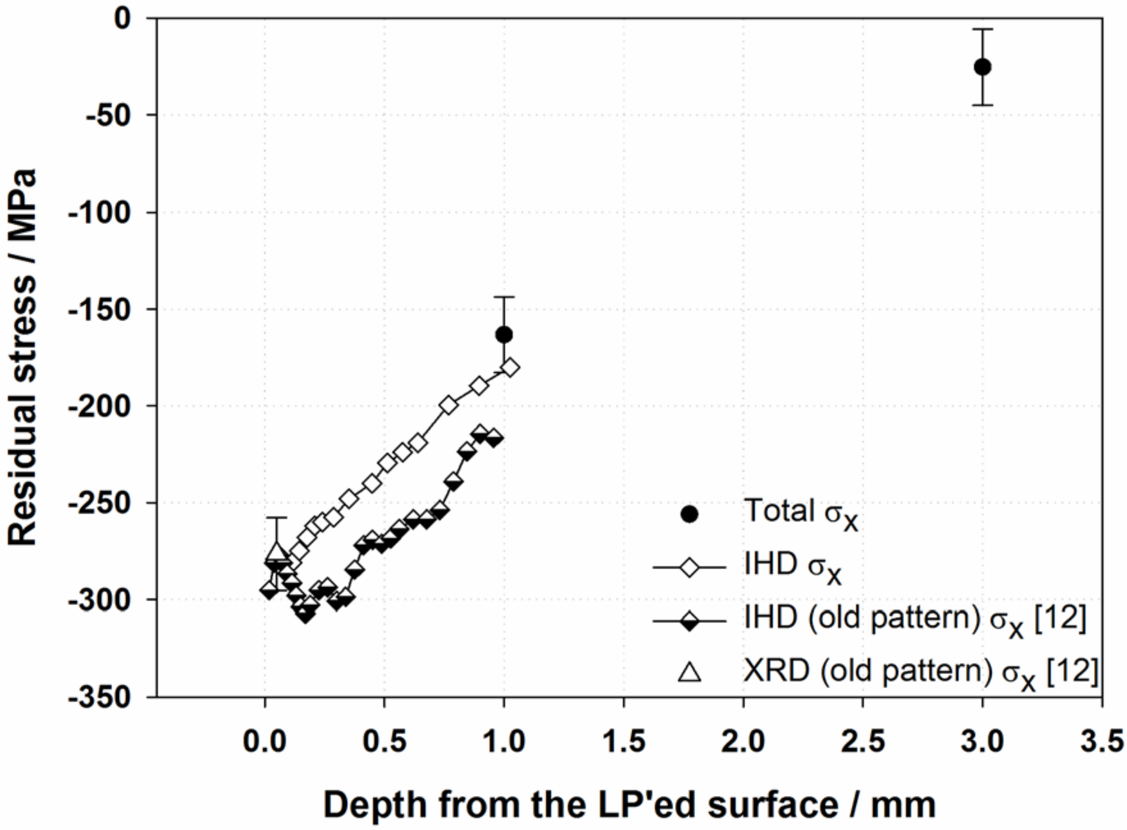

Figure 8: Comparison of the total stresses, X-ray diffraction (XRD) and incremental hole drilling (IHD) of σ_x up to 3.5 mm from the laser peened (LP'ed) surface. There are two sets of results labelled in the original publication [12] as "final pattern" and "old pattern". The only difference in these two samples is the overlapping pattern of spots used to obtain 300% coverage. The stepped sample was peened according to the "final pattern".

Discussion

In this work, multiple-near surface residual stress fields were obtained by the contour method and the X-ray diffraction employing the superposition principle, introduced by [9]. The results were compared to those obtained by the incremental hole drilling and X-ray diffraction techniques. The stresses in the *z*-direction, σ_z^A, were obtained by the contour method by the authors previously [11]. The near-surface results were compared to the results from different techniques, and were very similar in terms of both magnitudes and trends (Fig. 3). These verified results were compared to the stresses obtained in the *x*-direction, σ_x^A, by employing the superposition principles including the near-surface region. Comparison of stresses in the *x* and *z*-directions with the data in the literature for the same material shows good correlation (Fig. 6). Further comparison for the near-surface region in the *x*-direction shown in Fig. 8 increases the reliability of the near-surface residual stresses obtained by the superposition principle. Therefore, the normal stresses including the near-surface region for the stepped sample in the *x* and *z*-directions, $\sigma_x{}^A$ and $\sigma_z{}^A$, were obtained and compared by the contour method.

Total stresses in the *y*-direction, $\sigma_y{}^A$, were also found by employing the superposition principle as shown in Fig. 5. However, it was not possible to obtain stresses in this direction by incremental hole drilling from the peened surface, since only in-plane stresses (*x* and *z*-directions) can be obtained. Methods including neutron and synchrotron X-ray diffraction could be used to obtained stresses in the *y*-direction. Considering the residual stress generation mechanism by laser peening [20], the residual stresses in this direction would be only due to the Poisson effect, which can be expected to be very small, compared to the stresses in the *x* and *z*-directions, as shown in Fig. 5.

The X-ray diffraction method was used for the remaining stresses at the cut surface, *i.e.* σ^B for the stress in the *x* and *y*-direction, $\sigma_x{}^B$ and $\sigma_y{}^B$. However, owing to the collimator tip diameter, the closest measurement to the peened surface was averaging the circular area of 2.0 mm diameter for the stresses in the *x*-direction. If incremental hole drilling was performed instead of X-ray diffraction, the closest measurement would be similar owing to the volume of removed material, depending on the diameter of the drilled hole. For instance, the diameter of the hole is 2.0 mm for the incremental hole drilling experiments presented in Figs. 7 and 8. Hence, no matter which technique is preferred, the residual stresses from any experimental method are the averaged stresses over a volume. However, the definition of the volume or gauge volume (term representing the volume of the material over which the stresses are averaged used mostly in diffraction techniques) depends on the technique, which could be tailored for some methods for the near-surface stresses.

The capability of the contour method for the determination of near-surface residual stress fields was investigated by the authors previously. It was shown that the accuracy of near-surface residual stresses determined by the contour method depends on the quality of the cut and displacement measurement of the cut surface as well as the applied data analysis against cutting and measurement artefacts, which was improved for the near-surface results by the authors. It was concluded that the residual stresses at the surface can be obtained by the contour method under the conditions stated. Therefore, the closest measurement to the surface is limited by the techniques for the superposition principle used in conjunction with the contour method. Hence, when the area of interest is very close to the surface, such as the near-surface residual stresses after shot peening, residual stress measurement methods having higher resolution for the near-surface stresses should be preferred along with the contour method. The synchrotron X-ray diffraction method would be one of the few methods satisfying the required conditions. The elongated nature of the gauge volume due to technique itself would enable obtaining stresses very near to the surface. However, different issues including the partially filled gauge volume and resulting "pseudo-strains" [21] would have to be considered for the near-surface stresses by the synchrotron X-ray and neutron diffraction.

The average uncertainty of the contour method was found as about 10 MPa by using the model error approach, as discussed in [22]. The uncertainty of the X-ray diffraction results were calculated based on the deviation from linearity of the *d* vs.

$\sin^2\psi$ plot that is used to calculate residual stresses in the $\sin^2\psi$ method. The total uncertainties reported for the "total stresses" from the superposition principle were obtained by employing a quadrature approach, as used by [9]. The uncertainty of the incremental hole drilling results depends on both practical and theoretical issues. If the practical issues including surface preparation, attachment of the strain gauge to the surface, finding the datum before the experiment etc., are done properly, the expected uncertainty would be small. The strain gauges used have a measurement accuracy of 1 με, and a stress accuracy of better than 10 MPa can be expected.

Conclusions

1. The contour method and surface X-ray diffraction were used in combination, by application of the superposition principle, to determine the three orthogonal residual stress components in a laser peened aluminium alloy sample. This combination of experimental techniques is unique in providing a detailed map of one stress component and point measurements of the remaining two. Measurements were validated by incremental hole drilling and surface X-ray diffraction measurements.
2. The laser peening induces high (−300 MPa), deep (~3.0 mm) and equi-biaxial in-plane compressive residual stresses into the sample. The combined contour and X-ray results indicate that the biaxial stress state observed at the surface is maintained into the depth. As expected, the surface normal stresses are low and reasonably constant into the depth.
3. The accuracy in determining the near-surface residual stress depends on the resolution of both the contour method and the other method required for the superposition principle. The contour method results are dependent on the spline

fitting routine used on the measured contour data; the X-ray diffraction data are limited by the sampling area applied.

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