Induction of through-thickness compressive residual stress fields in thin A12024-T351 plates by laser shock processing

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Abstract

Purpose - With the aid of the calculational system developed by the authors, the analysis of the problem of laser shock processing (LSP) treatment for induction of residual stress (RS) fields for fatigue life enhancement in relatively thin sheets in a way compatible with reduced overall workpiece deformation due to spring back self equilibration has been envisaged. Numerical results directly tested against experimental results have been obtained confirming the critical influence of the laser energy and irradiation geometry parameters. The paper aims to discuss these issues.

Design/methodology/approach Plane rectangular specimens (160 mm x 100 mm x 2 mm) of Al cladded (-80um) Al2024 T351 were considered both for LSP experimental treatment and for corresponding numerical simulation. The test piece is fixed on a holder and is driven along *X* and *Y* directions by means of an anthropomorphic robot. The predefined pulse overlapping strategy is used for the irradiation of extended areas of material. From the geometrical point of view, a full 3D configuration for the real geometry and for the sequential overlapping strategy of pulses has been considered. The FEM elements used for the simulation are an eight node brick reduced integration with hourglass control in the treated area, namely C3D8RT, and a six node trainer prism in the rest of the geometry, where there is no applied load, namely C3D6T, that ease meshing complex partitions. The element size in the nearest of the treated surface is 100 x 100 x 25J4II, being the maximum element size which allows to maintain calculation convergence.

Findings Numerical results directly tested against experimental results have been obtained confirming: first, the critical influence of the laser energy and irradiation geometry parameters on the possible thin sheets deformation, both at local and global scales. Second, the possibility of finding LSP treatment parameter regimes that, maintaining the requirenents relative to in depth RSs fields, are able to reduce the relative importance of sheet deformation. Third, the possibility of finding LSP treatment parameter regimes able to provide through thickness compressive RSs fields at levels compatible with an effective fatigue life enhancement. Fourth, the possibility of improving this through thickness compressive RSs fields by double side treatments. Fifth, the capability of the experimental LSP treatment system at the authors site (CWPM) of practically achieve the referred through thickness compressive RSs fields in excellent agreement with the predictive assessment obtained by the used numerical code (SHOCKLAS)

Practical implications The referred results provide a firm basis for the design of LSP treatments able to confer a broad range of RSs fields to thin components aiming the extension of their fatigue life, an enormously relevant field in which the authors are currently working.

Originality/value The LSP treatment of relatively thin specimens brings, as an additional consequence, the possible bending in a process of laser shock forming. This effect poses a new class of problems regarding the attainment of specified RS's depth profiles in the mentioned type of sheets, and, what can be more critical, an overall deformation of the treated component. The analysis of the problem of LSP treatment for induction of tentatively through thickness RS's fields for fatigue life enhancement in relatively thin sheets in a way compatible with reduced overall workpiece

deformation due to spring back self equilibration is envisaged in this paper for the first time to the authors knowledge. The coupled theoretical experimental predictive approach developed by the authors has been applied to the specification of LSP treatments for achievement of RS's fields tentatively able to retard crack propagation on normalized specimens.
Keywords Laser shock processing, Residual stresses, Thin sheets, Through thickness RSs
Paper type Research paper

1. Introduction

The capability of laser shock processing (LSP) for the induction of residual stress (RS) fields in sub-surface layers of relatively thick specimens ($d > 6$ mm) in view of the improvement of their fatigue life has been widely demonstrated (Clauer, 1996; Peyre *et al.*, 1996; Rubio-González *et al.*, 2011; Sano *et al.*, 2012). However, the LSP treatment of relatively thin specimens (normally $d < 6$ mm, but also thicker ones depending on the treatment intensity) brings, as an additional consequence, the possible bending of the treated specimen, a feature that can otherwise be employed for forming procedures according to the laser shock forming process.

This effect poses a new class of problems regarding the attainment of specified RS depth profiles in the treated specimens, as their self-equilibration reaction after clamping removal can considerably alter the primary laser shock induced RS fields, thus possibly motivating undesired final RS field distributions, and, what can be more critical, an overall deformation of the treated component. A similar kind of problems has been analyzed for the case of Shot Peening by Guagliano (2001).

With the aid of the calculational system developed by the authors (SHOCKLAS®; see Ocaña *et al.*, 2004a, b), the analysis of the problem of LSP treatment for induction of RS fields for fatigue life enhancement in relatively thin sheets in a way compatible with reduced overall workpiece deformation due to spring-back self-equilibration has been envisaged. Numerical results directly tested against experimental results have been obtained confirming the critical influence of the laser energy and irradiation geometry parameters.

2. Problem definition and theoretical/experimental methodology

The fatigue life of a component depends upon the crack initiation and growth caused during usage. In many structural applications, cracks begin at the surface, leading to fatigue failure. The component fatigue life depends upon the surface and near-surface stress field generated by the loading conditions. The effects of surface and near-surface tensile stress can be mitigated by generating compressive RS fields at possible crack locations on the surface.z

LSP is based on the application of a high-intensity pulsed laser beam (instant peak power density, $I > 1\,\mathrm{GW/cm^2}$; laser pulse characteristic duration, $\tau < 50$ ns) at the interface between the metallic target and the surrounding medium (a transparent confining material, normally water) forcing a sudden vaporization of the metallic surface into a high-temperature and density plasma that immediately develops inducing a shock wave propagating into the material (Peyre *et al.*, 1996). This shock wave induces plastic deformation and a RS distribution in the target material (if its peak pressure is greater than the dynamic yield limit) able to protect the component by means of a compressive RSs field.

However, in view of the particular (not trivial) mode in which the stress distribution is altered inside the treated material by the LSP treatment and the possible associate problems due to component deformation, the way in which this effect must be achieved is not direct and is the object of the present investigation.

In this section, the main details of the LSP irradiation strategy, experimental procedure and numerical simulation tools used for the analysis are presented.

2.1 Laser irradiation geometry and pulse overlapping strategy

Plane rectangular specimens (160 mm × 100 mm × 2 mm) of Al-cladded (~80 μm) Al2024-T351 (Young Modulus, E ¼ 72 GPa; Yield Strength, YS ¼ 360 MPa; Poisson ratio, ν ¼ 0.33; Density, ρ ¼ 2,780 kg/m^3) were considered both for LSP experimental treatment and for corresponding numerical simulation. In Figure 1 the practical geometry considered for the LSP simulations is displayed showing the references used for the directions of evaluation of RSs. The figure also shows the pulse overlapping and specimen sweeping strategy used in the irradiation.

2.2 Experimental procedure

The practical irradiation system used for the LSP experiments is schematically and photographically shown in Figure 2.

The laser source is a Q-switched Nd:YAG pulsed laser working in fundamental mode (λ ¼ 1,064 nm) and at a repetition rate of 10 Hz. The FWHM (full width at half maximum) of the generated pulses is about 9 ns and the maximum pulse energy is 2.4 J/pulse. Using a flat mirror and a convergent lens, the laser pulse is focussed on the target. Both optical components are coated for 1,064 nm, what guarantees high transmittance efficiency. The convergent lens is used to control the transmitted laser

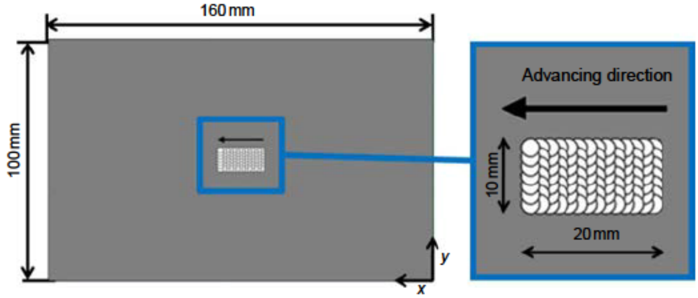


Figure 1. Practical geometry considered in the LSP simulations in which the residual stresses reference axes are attributed

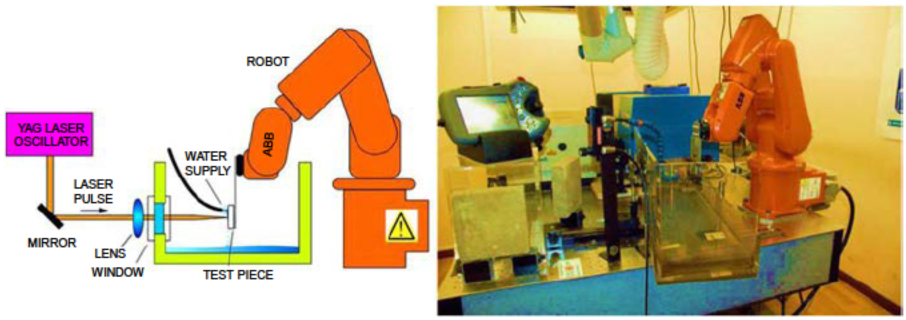


Figure 2. Schematic representation and photographic view of the LSP irradiation experimental setup used in experiments

energy. The laser interaction with the target is confined by a thin water layer and no protective coating is applied. Control of water purity is important in order to avoid the formation of water bubbles or the concentration of impurities coming from the material ablation due to laser treatment. The appearance of suspended elements can affect the LSP process by their interaction with the high-energy laser beam.

The test piece is fixed on a holder and is driven along X and Y directions by means of an anthropomorphic robot. The predefined pulse overlapping strategy is used for the irradiation of extended areas of material.

In Table I, the main laser irradiation parameters used for the analyses are shown for two characteristic values found by the authors to produce the sought through thickness residual stresses profiles in the considered plates (see Correa et al., 2015) defined in terms of pulse overlapping pitch and laser pulse diameter according to the definitions found in Ocaña et al. (2013). The equivalent overlapping density (EOD) indicates the number of individual pulses per unit surface, the equivalent energy density indicates the final energy that the unit surface has received along the treatment and the equivalent local overlapping factor (ELOF) indicates the average number of LSP pulses applied on a particular surface location.

2.3 Numerical modeling

In order to predictively assess the LSP treatment results, the numerical model SHOCKLAS® developed by the authors has been applied to the simulation of the selected treatments.

SHOCKLAS® is a complex calculational system analyzing the laser-material interaction at the used high laser intensity, including the associate plasma formation and solves the shock wave propagation problem into the solid material with specific consideration of its elastic-plastic behavior (Morales et al., 2011). The mechanical behavior analysis module (HARDSHOCK-3D) is based in the finite element model commercial code ABAQUS (Hibbitt, Karlsson, Sorensen Inc., 2014).

From the geometrical point of view, a full 3D configuration for the real geometry and for the sequential overlapping strategy of pulses has been considered. The FEM elements used for the simulation are an eight-node brick reduced integration with hourglass control in the treated area, namely C3D8RT, and a six-node trainer prism in the rest of the geometry, where there is no applied load, namely C3D6T. This makes more easy the meshing of the different scales in the complex partitions. The element size in the nearest of the treated surface is 100 × 100 × 25 μm, being the maximum element size which allows to maintain calculation convergence.

Table I. Summary of LSP parameters for two characteristic treatments applied to the defined specimens

Treatment condition	Laser pulse energy, E (J)	Laser pulse overlapping distance, d (mm)	Laser spot diameter, Ø (mm)	Equivalent overlapping density, EOD ($1/cm^2$)	Equivalent energy density, EED (J/cm^2)	Equivalent local overlapping factor, ELOF ( )
A	2.4	0.75	1.50	178	427	3.14
B	2.4	0.75	2.50	178	427	8.73

In LSP processes, the material is stressed and deformed in a dynamic way, with strain rates exceeding $10^6\,s^{-1}$, so the elasto-plastic behavior of Al2024-T351 is modeled using Johnson-Cook equation (Johnson and Cook, 1983) fitted with Kay parameters (Kay, 2003).

3. Results

In this section, results relative to the two most relevant aspects of the considered problem are presented, namely the analysis of the local/global deformation by LSP (predictive numerical simulation results) and the induction of through-thickness compressive RSs fields (numerical simulation results compared to experimental determinations).

3.1 Numerical analysis of local/global plates deformation

Although generally not considered in the LSP treatment of thick pieces, the deformation in thin plates is a relevant aspect to be taken into account in order not to negatively affect the pursued effect of induction of compressive RSs in the treated specimens.

In view of this relevance the SHOCKLAS® model has been applied to the determination of the deformation induced by the LSP treatment in the considered specimens. Both longitudinal (path x in Plate 1) and transverse (path y in Figure 3) deformations of the simulated plate have been evaluated for LSP treatment conditions showed in Table I.

In order to show the qualitative behavior of the considered deformation, in Plate 1 an augmented scale (50 ×) 3D simulation view is shown in which the described effect is clearly shown for the case of a long (100 mm) LSP treated stripe with parametric conditions A.

Quantitative deformation results for the two selected LSP parametric conditions are shown in Figure 4 (left and right), each of them corresponding to one of the selected paths (x and y). Results show substantial effects after LSP treatments both at the local

Plate 1.
Augmented scale (50 ×) 3D simulation view of the LSP induced deformation in a thin Al2024 T351 plate

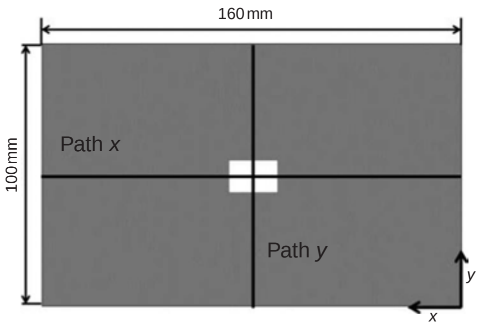


Figure 3.
Defined paths for analysis of LSP induced deformation

and global scales and it can be clearly observed that modification in the LSP parameters imply changes in the generated deformations.

Specifically, it can be observed how a larger ratio beween the laser beam diameter, Ø, and the pulse spacing (finally accounted by the ELOF parameter in Table I) leads to more favorable (lower level) deformations, both at the local and global scales, the effect being most pronounced at the local scale, which is the most critical from the point of view of induction of compressive RSs fields at points close to the plate surface. The additional fact that the global scale deformation for higher values of the ELOF parameter is generally lower (except possibly for the plate lateral edges, as shown in Figure 6) provides an important condition that can be used for the global scale overall deformation compensation by double-side plate treatment, a technologically relevant possibility as shown in the next section.

3.2 Residual stress fields

As a main objective envisaged by the LSP treatment, compressive RSs fields in a given depth below the treated surface are sought. In the case of thin plates, the induction of these fields must be compatible both with a given limit in deformation and with a given limit in the tensile RS induced at the surrounding zones of the treated zones.

According to the results of Section 3.1, a compromise between the EOD (assuring a minimum value of compressive RS) and ELOF (assuring a limited plate distortion) parameters must be found.

In Figure 5 (left and right), an analysis is provided based on numerical simulation results on the surface RSs along the defined x and y directions for different combined

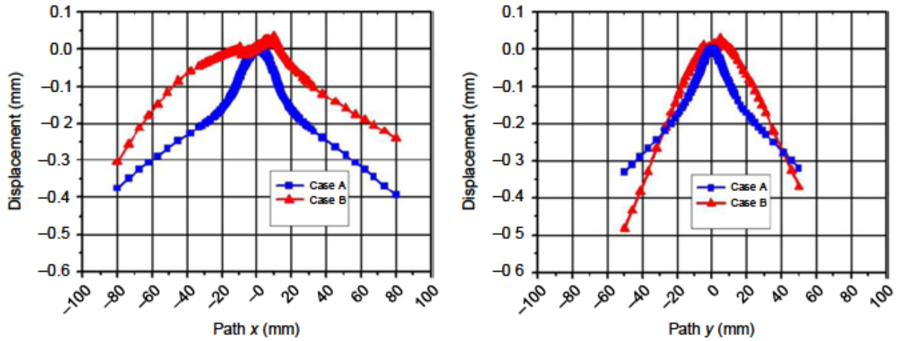


Figure 4.
Comparison between deformations along paths x (left) and y (right) for parametric conditions A and B

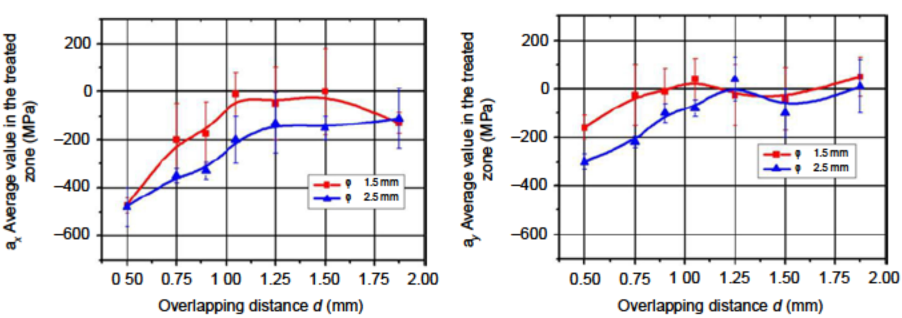


Figure 5.
Variation of surface average value of σ_x (left) and σ_y (right) RS's components in a transverse profile for different combinations values of Ø d (uncertainty bars indicate oscillations around average value)

values of the laser beam diameter, Ø, and the overlapping pitch, d, the main conclusion being that, for overlapping pitches in the range of d ¼ 0.75 mm (a practical value experimentally found providing at least a minimum level of compressive RSs), beam diameters around Ø ¼ 2.5 mm are preferable for induction of higher values of these stresses in both perpendicular directions.

With these data in mind, the final envisaged objective is the achievement of through-thickness compressive RSs profiles and this possibility has been both numerically and experimentally explored.

With the aid of the SHOCKLAS® simulation code, different parametric variations around the reference provided by the condition B in Table I and the corresponding results have been obtained. In Figure 6 (left and right) numerical simulation results are shown of the final RS state (in both perpendicular x and y directions) in a middle transverse cut (y direction) of the considered geometry. It is clearly observed how the plate front (direct laser beam incidence) is clearly in compressive RS and how the rear part of the plate is also under compressive RS (in both components), what in practice demonstrates the possibility of induction of the desired through-thickness compressive RS fields in selected treated areas that can be supported by adjacent areas concerning RS's global equilibrium.

This has been confirmed by the analysis of complete numerical through-thickness results. As a sample, in Figure 7, the variation along the normal to the plate surface in a given position of the treated zone is shown for the referred parametric conditions (case B in Table I) and a related case with the same laser beam diameter and an only sligthly changing displacement pitch d ¼ 0.9 mm (this choice of parameters has been chosen only to show the difference with the reference case B).

As a step forward for the practical demonstration of the capability for the induction of through-thickness compressive RS fields in the considered thin plates, the generation of these RS fields has been experimentally accomplished and the results obtained have been checked against the numerical results provided by the SHOCKLAS® model.
In Plate 2, a detail of the positioning of the RSs measurement gauges around the treated zone of the considered specimens is presented. In this case, the treated zone is 100 × 10 mm in order to provide room enough for the placement of RSs measurement gauges. Experimental RSs measurements is performed at the treated surface points

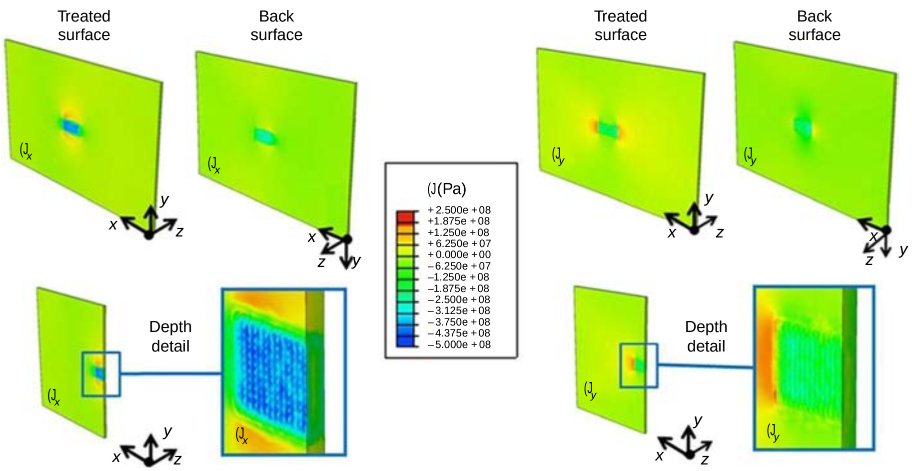


Figure 6. Representation of σx (left) and σy (right) components of the residual stresses fields in a treated specimen under the B set of parametric conditions

and surrounding areas obtaining in-depth profiles (only to a maximum of 1.0 mm depth in order no to exceed the applicability limitations of the method) by means of the hole drilling method (ASTM E837-08 Standard: ASTM International, 2008).

In Figure 8 (left and right), i.e., simulation results corresponding to RSs fields along the two defined perpendicular directions (x and y) are presented, respectively, for the defined LSP treatment conditions B in point 1 along with the corresponding experimental data obtained according to the referred ASTM standard. To be noticed

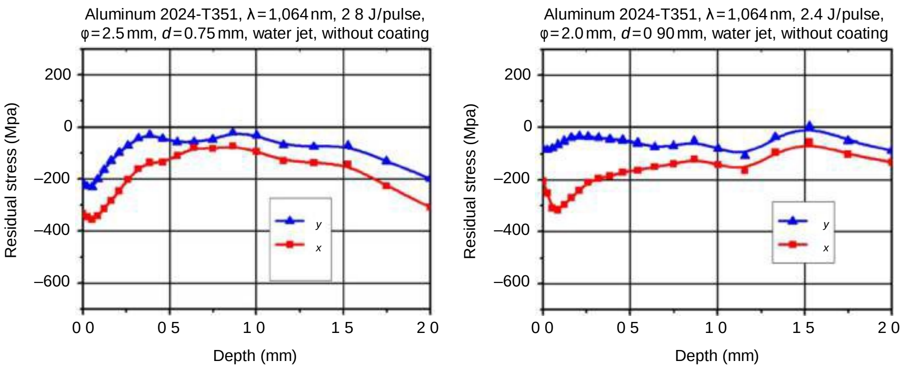


Figure 7.
In depth variation of residual stresses components in a representative point of a zone treated by LSP with parametric conditions B (left; Ø 2.5 mm, d 0.75 mm) and other close parameters (right; Ø 2.0 mm, d 0.9 mm)

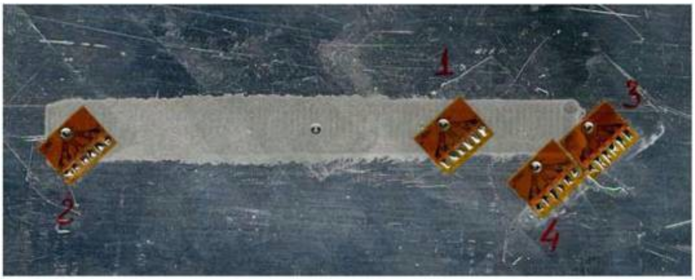


Plate 2.
Detailed view of the positioning of the strain gauges for the determination of in depth residual stresses fields according to ASTM E837 08 standard

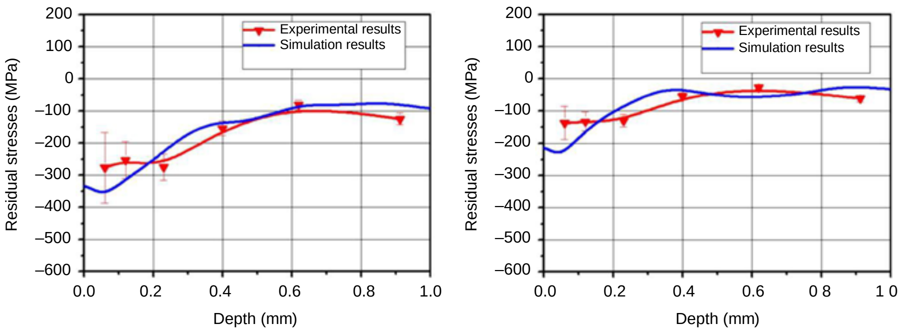


Figure 8.
In depth variation of numerically predicted and experimental values of σx (left) and σy (right) components of residual stresses fields induced by LSP treatment under parametric conditions B in point 1

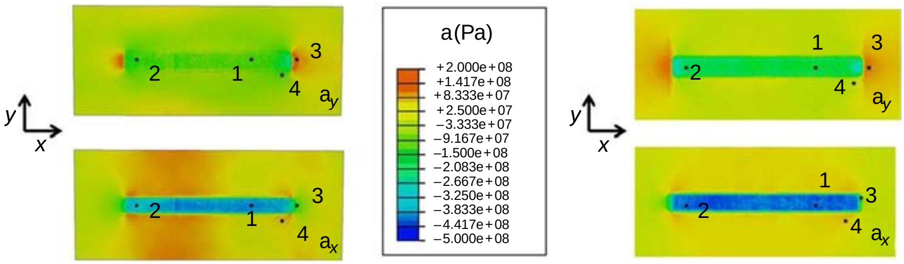
the effective induction of compressive RSs and the very good agreement of numerical predictions and experimental values.

Although in the selected case of parametric conditions B the achieved RS distribution field is quite satisfactory through the complete plate thickness for the concrete analysis point reported in previous figures, this is not unfortunately the case for other parametric combinations or for other points over the same treated surface, so that, in order to assure a minimum value of compressive RS across this thickness, the double-side treatment of the plates has also been investigated.

In Figure 9, the slight but positive effect of the double-side treatment can be appreciated in the simulation results corresponding to a sample with both single-side (left) and double-side (right) treatments.

From an analytical point of view, in Figure 10 numerical simulation results are presented showing the effect of the double-side treatment in both perpendicular components of RSs for a given point (point 1 in Figure 9) of a sample treated with the reference parametric conditions B.

Finally, in Figure 11, and as a complete verification of the capability of inducing through-thickness compressive RS in the considered kind of thin plates, the double-side



Note: Numbers indicate the position of the control points for measurement of in depth residual stresses and check against numerical simulation results

Figure 9. Representation of σ_x and σ_y components of calculated residual stresses in the front and rear sides of single side (left) and double side (right) LSP treated specimens

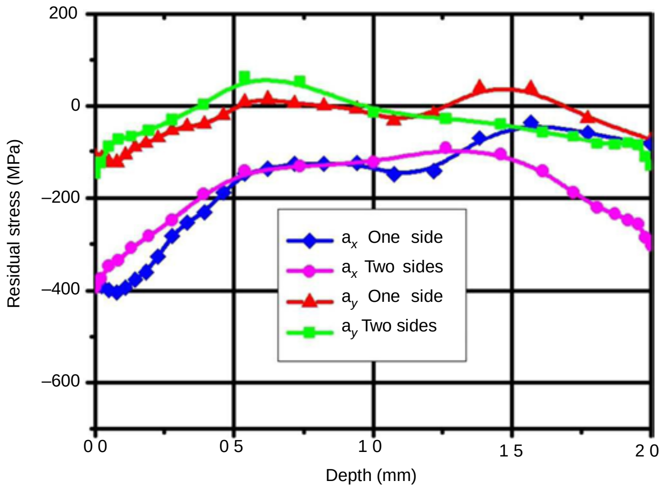


Figure 10. Numerical simulation results showing the effect of double side treatment on the σx and σy components of the residual stresses induced through the whole thickness in a point of a LSP treated plate (point 1 in Figure 9) with parametric conditions B

experimental RSs measurement results (needed in view of the maximum range of the ASTM E837-08 standard method) corresponding to one of the defined measurement points are displayed together with the numerical simulation results corresponding to the state of this point, the agreement being again really good.

Although the corresponding study is not included in the present paper (mostly addressed to the demonstration of the possibility of practically inducing through-tickness in the considered kind of specimens), a positive effect (i.e. an important correction of the local+global deformation induced by the one-side treatment) is achieved by means of the double-side treatment, a result that would be expected in view of the more symmetrical distribution of induced RSs around the plate mid plane achieved after the second face treatment compared to the first face treatment (as clearly shown in Figure 11).

4. Conclusions

The LSP treatment of relatively thin specimens (normally d O 6 mm, but also thicker ones depending on the treatment intensity) poses a new class of problems regarding the attainment of specified RS depth profiles in the treated specimens, as their self-equilibration reaction after clamping removal can considerably alter the primary laser shock induced RS fields, thus possibly motivating undesired final RS field distributions, and, what can be more critical, an overall deformation of the treated component.

With the aid of the calculational system developed by the authors, the analysis of the problem of LSP treatment for induction of RS fields for fatigue life enhancement in relatively thin sheets in a way compatible with reduced overall workpiece deformation due to spring-back self-equilibration has been envisaged.

Numerical results directly tested against experimental results have been obtained confirming:

(1) the critical influence of the laser energy and irradiation geometry parameters on the possible thin sheets deformation, both at local and global scales;

(2) the possibility of finding LSP treatment parameter regimes that, maintaining the requirements relative to in-depth RSs fields are able to reduce the relative importance of sheet deformation;

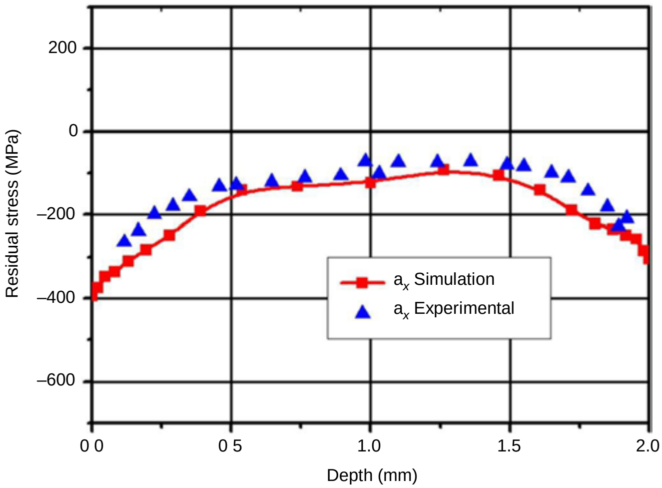


Figure 11.
Complete through thickness experimental residual stresses measurement results compared to corresponding numerical simulation results showing the effect of double side treatment in a point of a LSP treated plate with parametric conditions B

(3) the possibility of finding LSP treatment parameter regimes able to provide through-thickness compressive RSs fields in selected zones at levels compatible with an effective fatigue life enhancement due to critical stress concentration zones by using an appropriate RSs redistribution in the adjacent zones;

(4) the possibility of improving this through-thickness compressive RSs fields by double-side treatments that, in turn, are able to partly correct the possibly important local+global plate deformation induced by a one-side treatment; and

(5) the capability of the experimental LSP treatment system at the authors site (CLUPM) of practically achieve the referred through-thickness compressive RSs fields in excellent agreement with the predictive assessment obtained by the used numerical code (SHOCKLAS®).

The referred results provide a firm basis for the design of LSP treatments able to confer a broad range of RSs fields to thin components aiming the extension of their fatigue life, an enormously relevant field in which the authors are currently working.

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