

# Residual stress measurements in laser shock processed materials

P. Muñoz<sup>1</sup>, J. Ruiz-Hervias<sup>1</sup>, J.A. Porro<sup>2</sup> and J.L. Ocaña<sup>2</sup>

1 Departamento de Ciencia de Materiales, UPM, Madrid, Spain

2 Centro Láser UPM. Universidad Politécnica de Madrid, Spain

## Abstract

Laser Shock Processing (LSP) is employed to produce compressive residual stresses in the subsurface region of the material by using high-intensity laser impulses to increase the durability of machinery or structural components subjected to fatigue or stress corrosion cracking. By using this technique it is intended to increase the maximum depth at which compressive residual stresses are present in the material with respect to the values obtained with traditional shot peening. In addition, as the supplied energy can be accurately controlled, it is expected that the repeatability of the residual stress field would be improved. However, sometimes tensile residual stresses have been found at the surface of LSP samples. Consequently, it is important to understand the generation of residual stresses during LSP in order to explain this behavior. In this work, residual stresses were measured by X-ray diffraction both at the surface and at the subsurface region (using electro-polishing up to 400 micron depth) of several metallic materials subjected to LSP. The effect of the pulse density on the residual stress field is discussed for all tested materials.

**Keywords :** Residual stresses, X-ray diffraction, Laser Shock Processing

## Introduction

Laser shock processing (LSP) is a surface treatment technique intended to create compressive residual stresses at the surface region of the material. This way the durability in fatigue or stress corrosion cracking would be improved [1]. Residual stress fields from laser shock processing are usually larger in magnitude and deeper than those created by traditional shot peening. The process parameters are easier to control and it is possible to apply LSP to selected regions of a component. LSP basically consists on the application of a high intensity pulsed laser beam ( $I > 1 \text{ GW/cm}^2$ ;  $t < 50 \text{ ns}$ ) at the surface of a metal. It immediately vaporizes a thin surface layer of the material. Due to the absorption of the laser beam energy, the vaporization produces a rapidly expanding plasma. If the sample surface is submerged in a transparent media, such as water, the plasma is trapped between the specimen surface and the transparent overlay. The overlay layer confines the vapor and enhances the amplitude and duration of the pressure pulse acting on the surface. During further expansion, by absorbing heat from the laser beam, the pressure increases to extremely high levels. This causes a pressure pulse that reacts against the specimen surface and then travels through the metal in the form of a shock wave. If the shock pressure is larger than the dynamic yield stress of the material, it produces plastic deformation at the surface region. As a consequence, compressive residual stresses will be generated to restore the equilibrium with the rest of the material [2]. The different LSP parameters, namely pulse density and duration, spot size and the degree of overlap, will have an influence on the resulting residual stresses field [3]. In this work, LSP specimens were prepared by using different pulse densities and residual stresses were measured by X-ray diffraction. Four different materials were used, namely AISI 1045 steel, AISI 316L stainless steel, 2024 aluminium alloy and Ti6Al4V titanium alloy.

## Experimental

The LSP experiments were performed in Centro Laser of UPM, by using a Q-switched Nd:YAG laser, operating at 10 Hz with a wave length of 1064 nm and providing 2.8 J/pulse. The FWHM of the pulses was 10 ns. A convergent lens was used to deliver the laser energy over a 1.5 mm spot diameter and purified water was used as a confining medium. Different pulse densities were used: 5000, 2500, 1600 pulses/cm<sup>2</sup> on titanium alloys and 900 and 1600 pulses/cm<sup>2</sup>

on steels and aluminium alloys. The irradiation system used for the experiments is shown in Fig. 1.

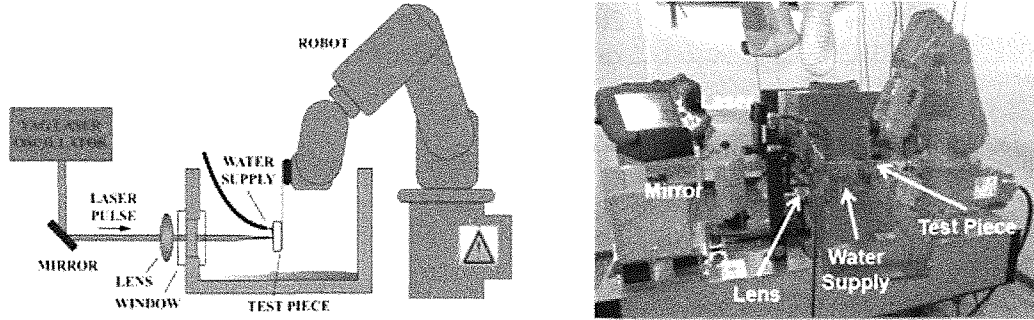


Figure 1. Schematic representation of the LSP irradiation setup

Residual stress measurement was performed by X-ray diffraction based on Bragg's Law [4].

$$2d_{hkl} \sin \theta_{hkl} = \lambda \quad (1)$$

The wavelength of the radiation  $\lambda$  is known (X-rays are produced by the metallic target of an X-ray tube) and  $\theta_{hkl}$  is diffraction angle. Consequently, it is possible to calculate the lattice plane spacing of a family of crystallographic planes (hkl)  $d_{hkl}$  using Bragg's law.

The change in the lattice spacing can be used to calculate the elastic strain through the following expression:

$$\varepsilon_{\psi\phi} = \Delta d / d \quad (2)$$

The calculated strain is normal to the diffracting plane, (the angle  $\psi$  is the angle between the normal to that plane and the normal to the surface) and it can be transformed to the sample coordinate system using tensor transformation [4].

$$\varepsilon_{\phi\psi} = \varepsilon_{11} \cos^2 \phi \sin^2 \psi + \varepsilon_{22} \sin^2 \phi \sin^2 \psi + \varepsilon_{33} \cos^2 \psi + \varepsilon_{12} \sin 2\phi \sin^2 \psi + \varepsilon_{13} \cos \phi \sin 2\psi + \varepsilon_{23} \sin \phi \sin 2\psi \quad (3)$$

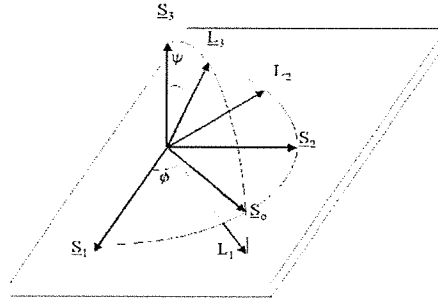


Fig. 2  $S_1, S_2, S_3$  sample coordinate system;  $L_1, L_2, L_3$  laboratory coordinate system

The stress is obtained from the strain with the formulae usually derived from linear elasticity theory [4].

$$\varepsilon = \frac{1+\nu}{E} \sigma - \frac{\nu}{E} Tr(\sigma) \quad (4)$$

$$\varepsilon_{\phi\psi} = \frac{d_{\phi\psi} - d_0}{d_0} = \frac{1+\nu}{E} (\sigma_{11} \cos^2 \phi + \sigma_{22} \sin^2 \phi + \sigma_{33} \cos^2 \psi - \sigma_{33}) \sin^2 \psi + \frac{1+\nu}{E} (\tau_{13} \cos \phi + \tau_{23} \sin \phi) \sin 2\psi + \frac{1+\nu}{E} \sigma_{33} - \frac{\nu}{E} Tr \quad (5)$$

In order to investigate the residual stress state, XRD analysis of the surface layer in the as-treated specimens was performed using a PROTO iXRD X-ray diffractometer and its commercial software XRDWin. The X-ray parameters are shown below.

Material	Plane (hkl)	Radiation	2θ (degrees)	Exposure time (sec)	Collimator	β oscillation	N° beta angles
AISI 1045 steel	(BCC,211)	Cr_K-α	156.4	1/10	1 mm	±3°	7
AISI 316L stainless steel	(FCC,311)	Mn_K-α	152.8	1/10	1 mm	±3°	7
2024 T351 aluminium alloy	(FCC,331)	Co_K-α	148.9	2/20	2 mm	±7°	11
Ti6Al4V	(HCP,213)	Cu_K-α	139.7	5/20	4 mm	±5°	7

Table1. X-Ray parameters for the different materials

Measurements were carried out on each of the test specimens up to a depth of 400 microns in two directions. The longitudinal one corresponds to the direction of the laser treatment and the transverse one is perpendicular to the longitudinal. In order to carry out in-depth measurements, electropolishing was used to remove successive layers of material. After each step, a depth profile was measured with a dial gage (0.001 mm resolution). The correction proposed by Moore and Evans was employed to correct the stress relaxation associated to electropolishing [5].

## Results

The residual stress profiles (measured as a function of depth) are shown in Figures 3-6. The results indicate compression near the surface of titanium specimens, almost zero stress for aluminium-alloy specimens and tensile stress at the surface in the case of steel and stainless steel. Immediately below the surface, the stresses become compressive, the minimum being reached at 50-100 micron depth. It can be seen that the residual stresses remain negative up to the maximum measured depth (400 micron).

### AISI 1045 Steel

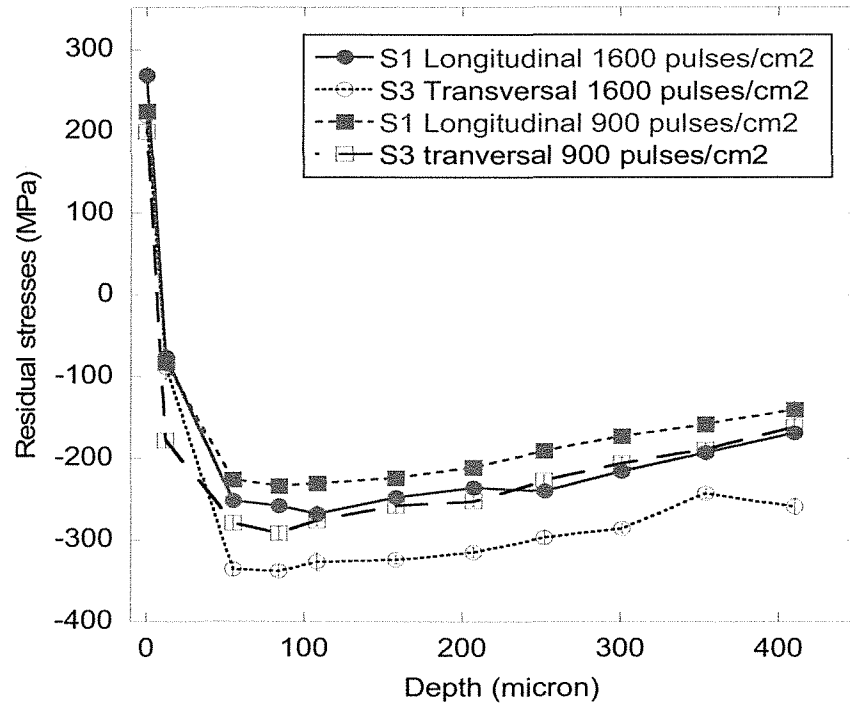


Fig.3. AISI 1045 steel residual stress profiles

### AISI 316L stainless steel

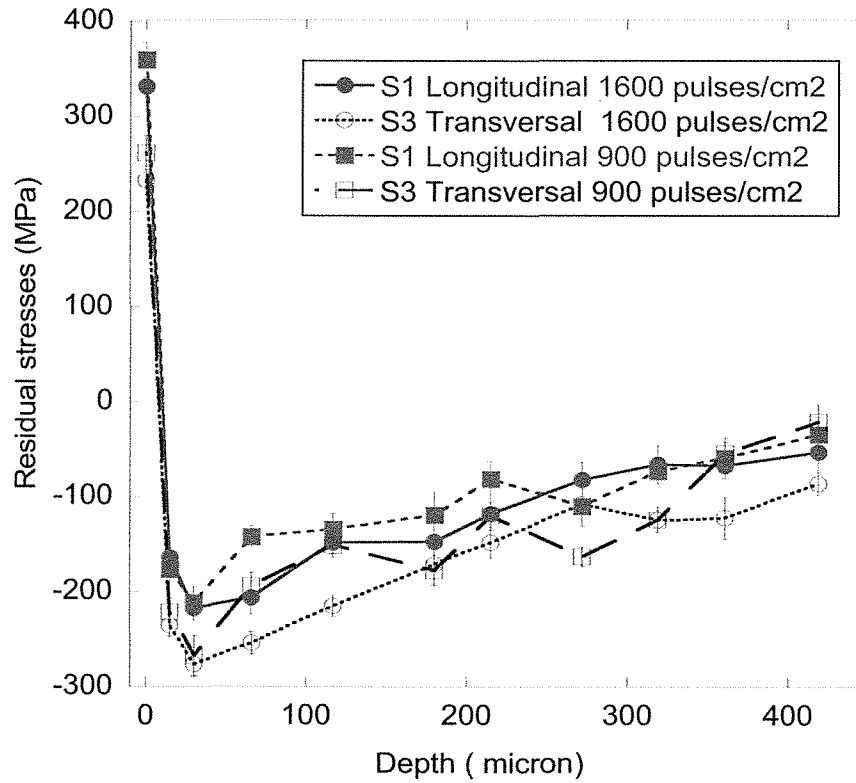


Fig.4. AISI 316L stainless steel residual stress profiles

### 2024 aluminium alloy

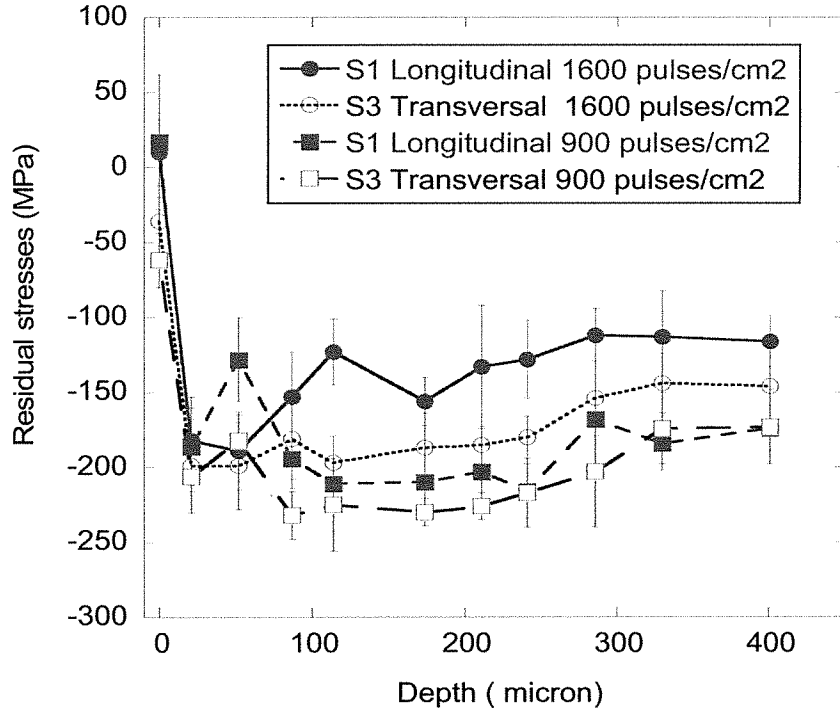


Fig.5. 2024 T351 Aluminium alloy residual stress profiles

### Ti6Al4V

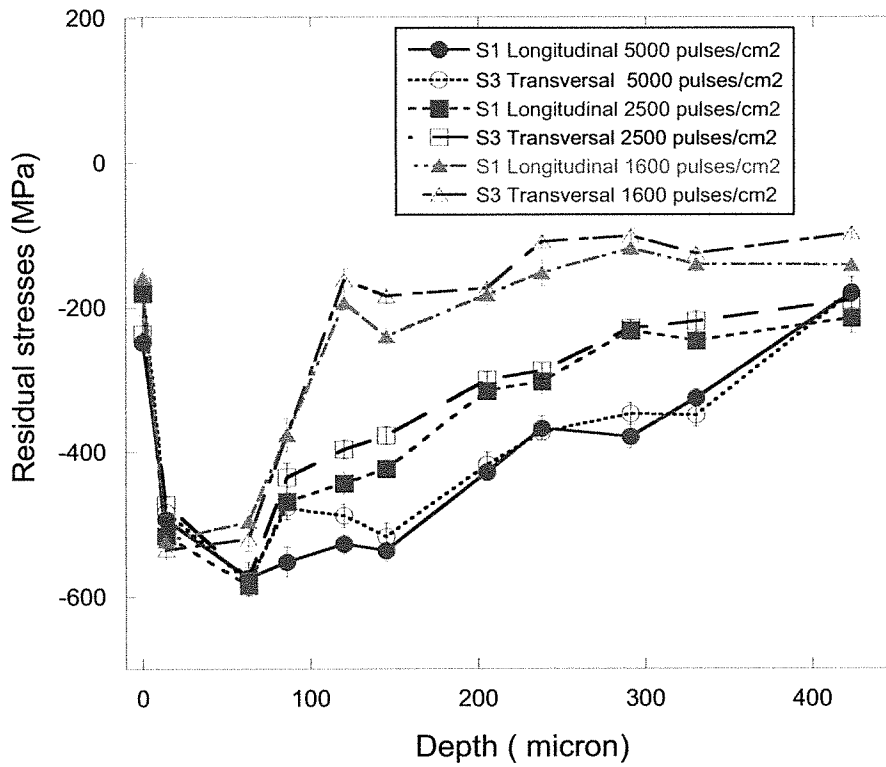


Fig.6. Ti6Al4V alloy residual stresses profile

## Discussion and conclusions

The X-ray diffraction technique allows the estimation of microstresses from the peak broadening. It is known that the peak width is affected by the heterogeneity of the plastic deformation in the measurement region and by the number of coherently diffracting domains contributing to the diffraction peak. From an analysis of the FWHM values (full width at half maximum) it has been found that the peaks are broader at the surface region than inside the material, especially in the case of the steel and aluminium test specimens. This might be due to the considerable plastic deformation that takes place right at the first microns from the surface due to the LSP treatment. In addition, the transient shock waves can also induce microstructure changes near the surface which might contribute to the peak broadening.

It can be concluded that LSP is an effective method of inducing compressive stresses in metallic materials. Nevertheless, tensile residual stresses have been measured at the surface of the steel and aluminium samples. The explanation of this phenomenon is that the shockwaves that are necessary to produce compressive residual stresses require a high pressure and high temperature plasma. Consequently, in the area close to the surface the temperature has the dominant effect. The induced temperature leads to an immediate reduction in the residual compressive stress on the surface. On the other hand, inside the material the pressure effect is greater than the thermal one and, therefore, higher compressive residual stresses are obtained. It has been demonstrated that the laser parameters have to be adjusted to maximize the residual stress values for each type of material. In materials with low yield stress and hardness, such as the case of aluminium alloy, better results are obtained with the smallest pulse density (900 pulses/cm<sup>2</sup>). However, in the case of titanium alloy Ti6Al4V (higher yield stress), the highest pulse density (5000 pulses/cm<sup>2</sup>) will produce the largest compressive stresses. The same trend can be observed for the steel samples.

## Acknowledgements

The authors are grateful to the financing provided by the Ministry of Science and Innovation of Spain through the project BIA2011-26486.

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