Experimental campaign on Laser Shock Peening treatment of thin alluminium open hole specimens

VISITING RESEARCH REPORT

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October 27, 2010

Abstract

This report is a result of a research visit at Centro Laser - Universidad Politécnica de Madrid, Spain. The activity was regarding aluminium alloy 7075-T73 and was carried out in two weeks: the research work was composed of treatment of 19 dog-bone specimens containing fastener holes with Laser Shock Peening and the characterization of the effect introduced in the specimens (residual stress measurement and roughness measurement).

The aim of this investigation is to evaluate the potentiality of the LSP process, by comparing the experimental results with the performances of the more conventional techniques for residual stress introduction around holes, such as cold-working and stress-wave methods.

1 Purpose of the visit

The purpose of this visit was a research programme at the Laser Centre of the Polytechnic University of Madrid (Centro Laser, Universidad Politecnica de Madrid) on the subject of Laser Shock Peening (LSP).

Laser Shock Peening is a very high intensity laser application used for insertion of compressive residual stresses in mechanical components, with a very wide range of possible applications. One of the applications is the use of LSP on aeronautical structural components, such as thin sheets of aluminium alloys. These sheets can suffer from fatigue damage starting from the fastener holes that are used to rivet together structural components and inserting compressive residual stresses using LSP is one of the possible problem solving approaches.

The aim of my visit was to ensure knowledge transfer on Laser Shock Peening technology, specially on optimal laser setup and usage, to my home institution, University of Bologna. The scientists at the Laser Centre of the Polytechnic University of Madrid have the necessary skills and knowledge and long experience in this kind of high intensity laser-matter interaction and their input was of crucial importance for implementation of LSP technology at my home institution, currently under way.

2 Introduction

The present research programme aims at evaluating the capability of the LSP to improve fatigue life in aeronautical structures by introducing compressive residual stresses around fastener holes in thin-walled structures representative of typical aircraft components.

The results of this experimental campaign will permit to compare LSP technology on 7075-T73 with cold working and stress wave technology on the same material [1].

Even though inferior results are expected, when comparing the residual stress distribution introduced by LSP with the ones deriving from cold working or stress wave treatment, the advantage of the laser shock peening technique is that it treats a larger portion of material influencing also the propagation of a crack, and this aspect could be very interesting from a widespread fatigue damage point of view.

3 Research programme

The specimens used for the present research were dog-bone specimens, obtained from 2.3 mm thick lamina of Al 7075-T73 (Figure 1).

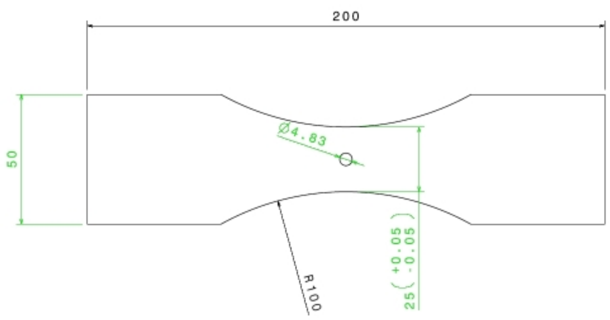


Figure 1: Geometry of the specimens

The specimens were divided for different purposes, as summarized in Table 1.

In addition, two more open hole specimens are dedicated to residual stress measurement (Table 2): the aim of treating two specimens of both of the materials in three different areas (base material treated LSP, open hole treated LSP and base material treated LSP and then drilled, Figure 2), is to obtain a comparison between the residual stress distributions in

Material	Specimen	N°	Treatments	RS Measurements	Tests
7075-T73	Open hole	13	LSP	Synchrotron	Fatigue
7075-T73	Open hole	3	LSP	X-ray	Propagation

Table 1: Research programme

these three areas. The reason for using these specimens in such a way is to reduce the number of specimens needed for residual stress measurement, without significantly affecting the number of remaining specimens dedicated to fatigue testing.

Material	Specimen	N°	Treatment	RS Measurements
7075-T73	Open hole	2	Figure 2	Synchrotron, x-ray, hole drilling

Table 2: Research programme-residual stress measurement on three areas specimens

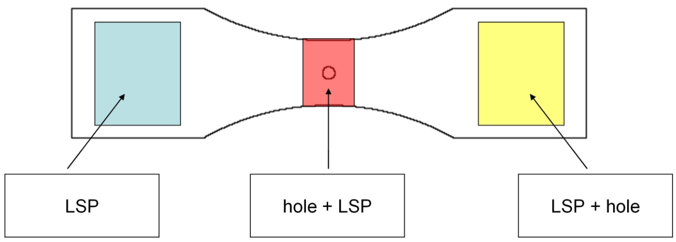


Figure 2: Specimen treated with LSP in three different areas

The measurement of the residual stress distributions will be carried out with Synchrotron, hole drilling method and X-ray.

4 Optimization of the LSP set-up

When it comes to LSP treatment of thin aluminium specimens, a very limited number of published works exists [2], [3]. This may be due to the fact that high energy lasers that are generally used for the LSP treatment (usually applied on titanium and steel) are not suitable for treatment of thin alumimium sheets without previous optimization of the process. Therefore, in order to avoid detrimental effects of the tretment on an Al specimen, it is important to chose carefully the setup of the process.

Fortunately, the laser used for LSP treatment for this experimental activity has a relatively low output energy, and it is particularly suitable for treatment of thin Al specimens. In addition, the experience of the researchers of Centro Laser in the application of this technology on thin Al sheets (2024 in particular) made it possible to identify quite easily the right parameters for this research activity.

4.1 Coating

There are two basic approaches in LSP technology: direct (without absorbent coating) and indirect ablation (with absorbent coating). The ablative layer has the function of protecting the surface of the treated specimen, since the direct exposition to the high temperature plasma can produce surface damage and increase surface roughness. The major difference between direct and indirect ablation lies in the fact that when no coating is used, the only way to avoid large surface damage is to use lower laser powers combined with very small impact size and high density of impacts, increasing the overlapping of the laser peen spots [4].

Given the fact that the laser available has a relatively small output energy, the best setup for the laser is the one with small peen diameter and consequently a high overlapping rate (as specified in the next paragraph). This fact lead to the decision to work in a direct ablation mode, since the great overlapping would increase both the costs and the time of the procedure if the protective painting needed to be applied after every shot.

4.2 Laser parameters

In LSP the laser parameters have the largest influence on the characteristics of the resulting residual stresses: it is important to define:

laser wavelength: different peak pressure are developed at different wavelengths (for t=25 ns: λ=1.064 μm:5 GPa, λ=0.532 μm:4.5 GPa, λ=0.355 μm:3.5 GPa).

laser power density: compressive stresses increase with the increase of laser power until certain value, when material damage occurs and no beneficial effects are present.

laser impulse duration time: reducing the pulse duration reduces the depth of the compressive residual stresses through the thickness.

laser impulse frequency: technological parameter - higher the frequency lower the necessary treatment times.

laser spot dimension: superficial residual stresses increase with the size of the impact and decrease with the plastically affected depth

laser spot overlapping: increasing the number of layers increases the value of compressive residual stresses until saturation

Table 3 shows the settings of the laser currently in use by Centro Laser for laser shock peening treatment. It was not possible to set these parameters so only the following were optimized:

The spot size chosen was 1.5 mm in diameter. There are two main reasons for using such a small spot:

Laser type	Wavelength [nm]	Output energy [J]	Pulse duration [ns]	Laser frequency [Hz]
Nd-YAG	1064	2.8 (10% loss)	9	10

Table 3: The settings of the used laser

- in order to obtain relatively high laser power densities (I_0 usually expressed in the terms of GW/cm^2) necessary for successful LSP treatment, small beam spot surface is required, given the relatively low laser energy.
- the absence of a protective layer (coating) doesn't permit the use of large spots because this could damage the surface of the treated specimen.

The spot was measured with a profile projector (Figure 3) and the results showed that it was not perfectly circular, having an elliptic shape with the two main dimensions of 1.5 mm and 1.2 mm. This inhomogeneity can be attributed to the laser source-specimen beam delivery optical system, and it is not considered to affect the quality of the treatment.

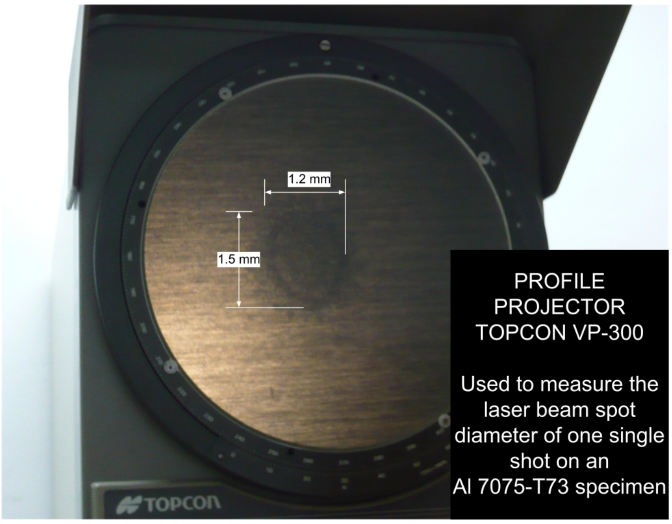


Figure 3: Measurement of the spot size

Given the relatively small peen diameter, the amount of residual stress is not as high as it would be with a larger one. Considering this fact it was necessary to set the appropriate density of laser peens (overlapping rate) in order to obtain significant residual stresses on the surface of the treated specimen. The overlapping rate was indeed optimized for this purpose and based on the results of other experimental activities on other Al alloys, it was decided to try two different settings:

- 625 spots per cm^2
- 900 spots per cm^2

Previous experimental activities on Al alloys performed at Centro Laser have shown that the optimum range lies between these two values: spot densities under 625 spots per cm^2 would not introduce significant residual stresses in the material, while increasing the spot density over 900 spots per cm^2 could cause excessive deformation of the specimen or even significant damage to the surface of the specimen. Both of the treatments were performed on the same specimen and on one side only, serving for purposes of residual stress measurement.

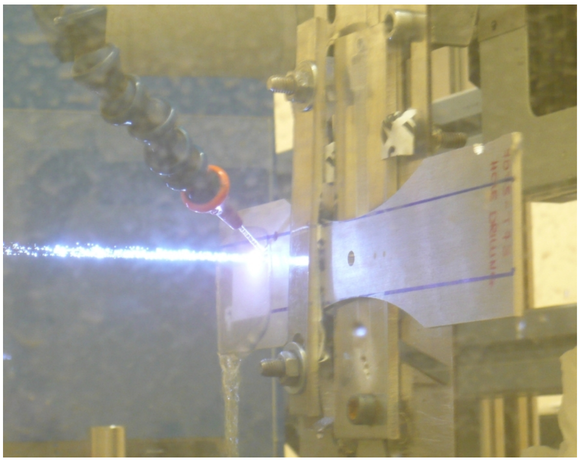


Figure 4: LSP treatment on optimization specimen

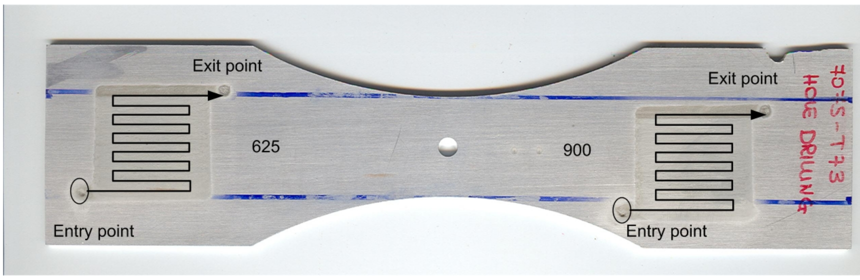
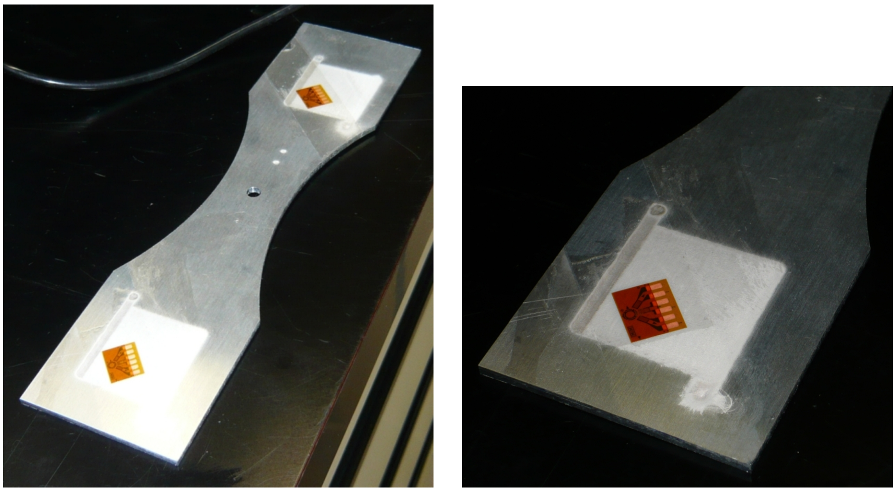


Figure 5: LSP treated specimen for optimization of the overlapping rate

Figure 4 shows the LSP process: the laser beam can be seen in spite the fact that the laser is operating in the invisible infrared regime; this is due to dispersed water particles of the overlay that interact with the laser beam causing dielectric breakdown of the water. In Figure 5, the specimen after the LSP treatment can be seen. It is interesting to observe in the figure the pattern of the laser beam together with the spot orientation (black lines and ellipsis), as well as the entering and exiting point of the beam. These points are a feature of the used laser and the inhomogeneity introduced is obviously undesirable for subsequent fatigue tests purposes. However, it can be easily avoided by starting and finishing the laser beam pattern outside the specimen.

This specimen was used for hole drilling measurement of residual stresses [5]. This is considered to be a semi-destructive technique of residual stress measurement, since the relaxation of stresses is performed by drilling a small hole (easily reparable) in the center of a strain gauge rosette (Figure 6). Based on the registered strain data, it is possible to reconstruct the residual stress profile in the depth of the specimen. The downside of this method is that its use on thin specimens is limited and after certain depths, correction formulas need to be applied in order to obtain an accurate estimation of residual stresses present in the material. The experimental set-up of the hole drilling measurement is shown in Figure 7.



(a) LSP treated specimen with attached strain gauges

(b) Detail: strain gauge rosette used

Figure 6: Specimen used for optimization of LSP parameters

The results of the residual stresses measurement can be seen in Figure 8. The hook-shaped profile of residual stresses could be explained by:

- The LSP treatment was realized in a direct ablation mode, where no thermal protective material is used. In this case, there is a thermal effect on the surface of the specimen and as a result, tensile stresses may occur after cooling of the material reducing the amount of compressive residual stresses.

- The spot dimension and its circular shape affect the distribution of

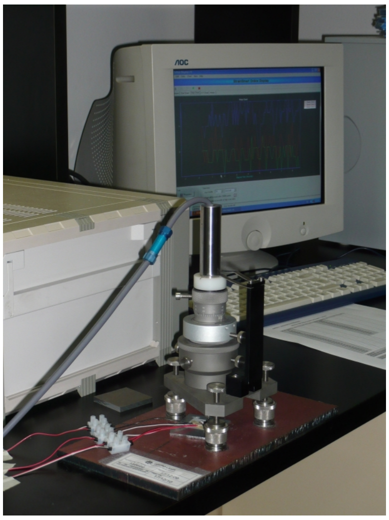


Figure 7: Hole drilling measurement

residual stresses. Such a small spot dimension creates a spherical shock wave (while a bigger one would create a planar one), with a complex shock wave interaction at the surface of the specimen that could affect the compressive residual stress in this area. This effect could be avoided or reduced by using a different spot shape (eg. square), unfortunately with the laser at our disposal this was not possible. Another way to look at the same phenomenon is that the stress distribution profile is very similar to the one obtained with shot peening treatment (even though much more deeper), where small diameter spheres are shot at the surface of the specimen. It can be assumed that a similar effect is produced by small circular laser spots.

- The accuracy of hole drilling method is limited when applied on thin specimens, therefore the measurement could be affected by this inaccuracy. Additional measurements using X-ray and synchrotron are to be performed in order to verify these preliminary results.

It can be noted that even though the setting with 625 spots per cm^2 causes deeper compressive residual stresses than the 900 spots per cm^2 setting (0.6 mm vs 0.45 mm), the maximum induced residual stresses are lower (229 MPa vs 332 MPa).

It is important to consider that the hole drilling method is accurate only near the surface, so the measured depth of compressive residual stresses might be not so accurate, considering the low thickness of the specimen. Therefore, it is deemed better to base the settings on the value of the residual stress (closer to the surface), more than on the reached depth of compressive residual stresses. Moreover the compressive residual stresses at the edge of

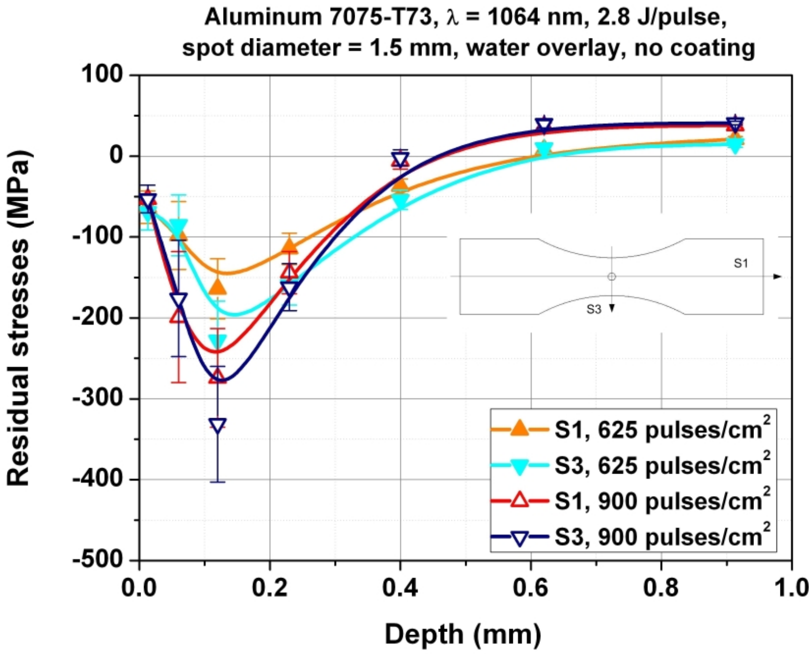


Figure 8: Hole drilling measurement results for the two different spot densities

the hole delay crack nucleation: the higher in amplitude are these residual stresses, the more pronounced this delay is.

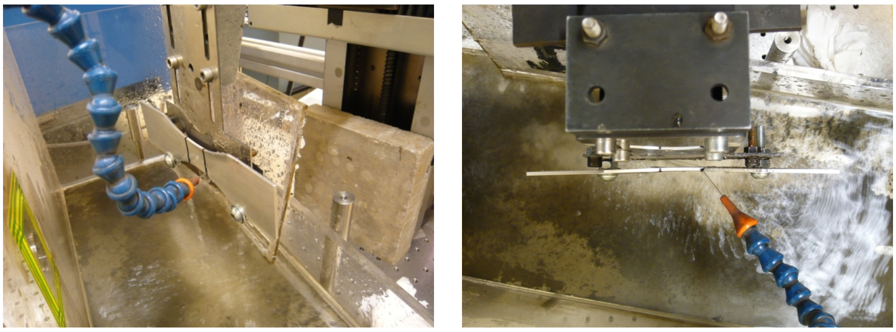
Given all these considerations, the set-up of 900 spots per cm^2 was the one chosen.

4.3 Specimen fixing

When a thin panel is laser peened, it is usually fixed to a immovable backing plate or a working table, often in combination of some kind of damping material, in order to prevent the unwanted wave reflection on the back side of the plate [6].

Anyway, for the in-service laser peening, having a back plate would increase the number of operations to perform for the treatment (therefore increasing costs and production time). Moreover, thin specimens are subjected to deformation in the peened zone, so they must be fixed very rigidly to the backing plate in order to avoid vibrations. This rigid fixing can cause undesirable local variation in residual stresses introduced in the specimen.

In order to avoid fixing problems without encountering undesired wave reflection, no backing plate was used (Figure 10) in combination with a short impulse times that in fact ensure less shock reflection.



(a) Front view (b) Top view

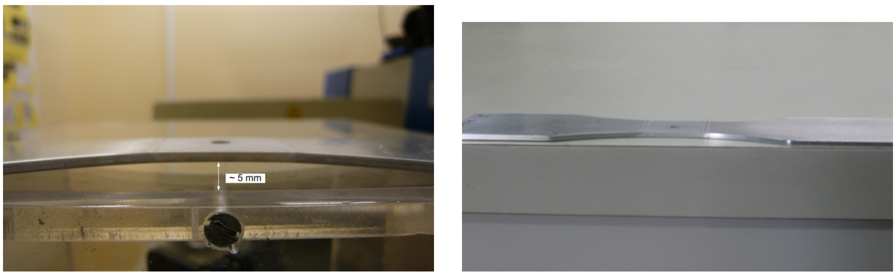
Figure 9: Fixing of the 7075-T73 specimen for the LSP treatment

5 Preliminary results

No fatigue tests or additional residual stress measurements have been done so far, anyway preliminary considerations can be made about the LSP procedure applied to the 7075-T73 specimen treated at Centro Laser.

5.1 Bending of the specimen

When shooting the specimen on one side only, its bending was very clearly visible (Figure 10(a)): this is obviously unacceptable. However, it is planned to treat the specimen on both sides in order to ensure the symmetry of the stress field. So, after shooting on both sides, the specimen re-established its original shape (Figure 10(b)).



(a) After LSP treatment on one side (b) After LSP treatment on both sides

Figure 10: Bending of the 7075-T73 specimen after the LSP treatment

5.2 Roughness

Since it was decided to perform LSP in direct ablation mode, it is important to control the state of the surface after the treatment.

(a) Confocal microscope with the examined specimen (b) Confocal microscope with the examined specimen - detail

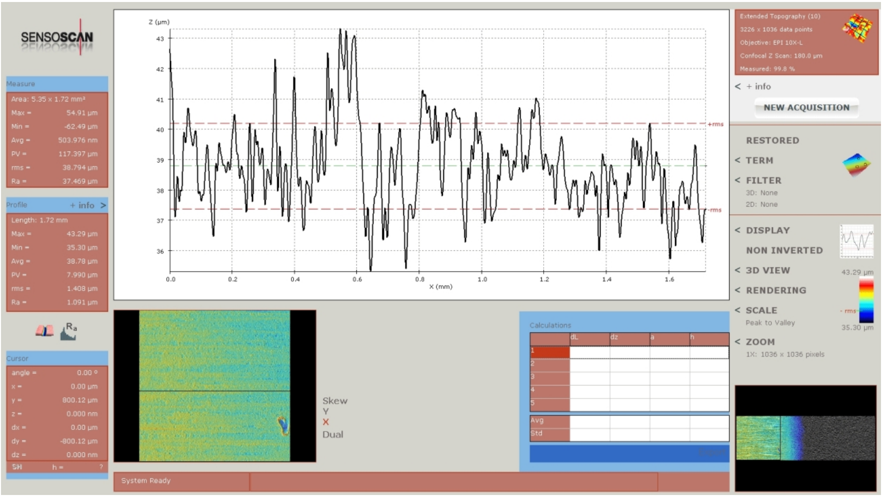
Figure 11: Roughness measurement

The thermal effect could indeed ruin the surface causing premature fatigue crack initiation and this effect is certainly to be avoided. Thanks to a confocal microscope (Figure 11), it was possible to obtain a three-dimesional map of the roughness of the specimen in the LSP treated zone and in the not treated one. Generally, a confocal microscope is composed of a "standard" optical microscope and a laser illumination system that allows point-to-point surface scanning, allowing higher both resolution and coverage when compared to a common optical microscope. The used microscope (Leica DCM 3D) is capable of a contact-free analysis of the micro- and nanogeometry of material surfaces to an accuracy of 0.1 nanometre.

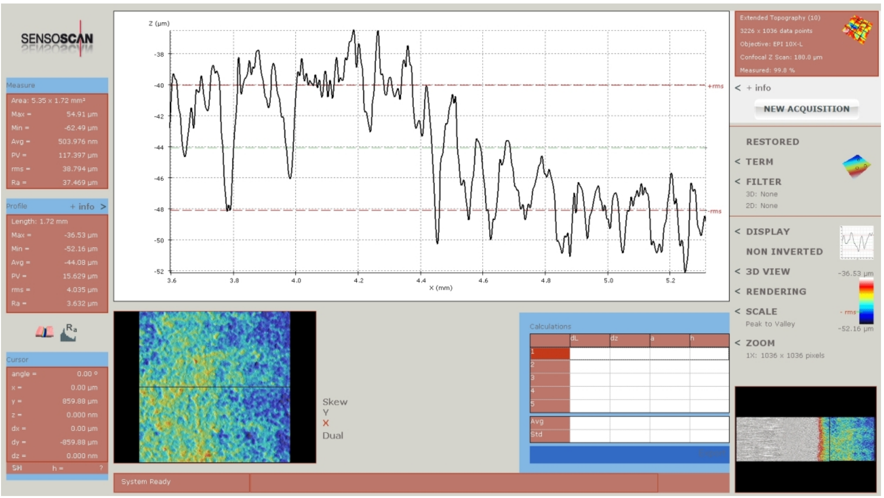
Figure 12 shows a 2D map of the surface roughness of the specimen. Comparing these 2-D maps, it can be noted that there is an 82 μm dislevel between the through-the-thickness coordinates of the base material (38 μm) and the LSP treated zone (-44 μm). This was expected since the plasma pressure on the treated area reaches very high values (order of several GPa) and the consequent plastic deformation is relevant. Nevertheless the increase in roughness is of limited extention: from 1.1 to 3.6 μm which is surely lower than the roughness increase of a shot peened surface. That is why the negative effect of the increased roughness due to LSP treatment is expected to be limited as well. These affermations are based on the observations reported in [7]:

> LSP generates a general depression of the material with no roughness changes; SP strongly affects the surface and creates potential initiation sites. Therefore much better fatigue performance is observed with laser-shocked 7075 than with conventional shotpeened specimens. This is attributed, through fatigue crack detection, to larger increases in the crack initiation stage for LSP than for SP specimens.

Table 4 gives a comparison between mean (R_a) and peak (R_t) roughness



(a) Roughness of the untreated surface of the specimen of Al 7075-T73



(b) Roughness of the treated surface of the specimen of Al 7075-T73

Figure 12: Roughness 2-D map

values: ones measured in this research activity and ones from [7]. The table shows that results relative to the roughness after LSP, obtained in this research, are comparable to the ones reported in the literature. The slightly higer values of the roughness measured in this research are probably due to different laser settings and shot overlay.

6 Future collaborations

The second experimental activity planned was the one regarding alluminium alloy 6082-T6, where the effect of treatment operations on residual stresses

Material condition	R_a [μm]	R_t [μm]	Reference
7075 as milled	0.6	5.2	
7075 LSP 3 shots	1.3	11	[7]
7075 SP 125%	5.7	42	
7075 as milled	1.1	7.9	Present experimental
7075 LSP 900 shots/cm^2	3.6	15.6	activity

Table 4: Comparions of roughness results

in open hole specimens with Laser Shock Peened holes will be investigated. For this activity, the specimens have alredy been prepared and the staff of the Centro Laser will conclude the LSP optimization and treatment of the specimens of Al 6082-T6, which will be subsequently sent in Italy for further testing. In additions, an agreement has been made to host a researcher from Madrid at the University of Bologna during the material characterizations tests (fatigue tests) of the treated specimens, in order to facilitate knowledge transfer in the opposite direction as well.

7 Projected publications

- Work relative to aluminium alloy 7075-T73: abstract submitted to International Committee on Aeronautical Fatigue "ICAF 2011" conference, to be held in May 2011 in Montreal, Canada
- Work relative to aluminium alloy 6082-T6: abstract to be submittd to "3rd International Conference on Laser Peening", to be held in October 2011 in Osaka, Japan

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