# LASER SHOCK PEENING OF A TITANIUM ALLOY: INFLUENCE OF PROCESS PARAMETERS

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## ABSTRACT

An investigation of the influence of laser shock peening parameters on a titanium alloy was undertaken. The samples were provided by SNECMA and are made of a material representative of the alloys used in the aeronautic field: Ti-5Al-2Sn-2Zr-4Cr-4Mo (Ti-17). In order to quantify the effect of each process parameter, an experimental design has been carried out (Sado, 2000). It is based on a full factorial design with 4 factors and 2 levels for each factor: thickness of the sample, laser fluence, pulse duration and number of impacts. In addition, 7 additional experiments were carried out: 3 to characterize the repeatability of the process and the order of the effects (linear or not) and 4 to evaluate the limits of the process. Altogether, 23 samples have been laser shocked. Only two parameters are kept constant: the sample material (Ti-17) and the covering rate (102-103%).
Six variables have been measured: the residual stress at the surface ($\sigma_{surf}$), $R_a$, $R_t$, the Vickers microhardness, the width of the diffraction peaks and the curvature of the sample.

Laser shock peening, aircraft, experimental design, titanium alloy

## 1. Introduction

While flying, a turbojet can swallow different foreign objects (birds, fragments, etc.). Damage induced by these objects is known as FOD (Foreign Object Damage), and can lead to the cracking of blades. In order to reduce maintenance costs, engine manufacturers try to find a way to increase the fatigue life of blades after FOD, by introducing compressive residual stresses. Various processes have been developed to induce a protective layer so as to increase the fatigue life. One of them, shot peening, is well established and routinely applied in aeronautics. However, this technology has a number of limitations: the depth of the compressive residual stresses is relatively small (about 0.2mm), the plastic strains are important and the material is work-hardened. This can lead to damage in the material microstructure and accelerate the relaxation of residual stresses.

The application of laser shock peening could overcome these drawbacks (Peyre, 2006). Developed in the beginning of the 70's, this treatment introduces, compared to shot peening, high compressive residual stresses deeper into the part with very small work hardening observed, leading to an appreciable increase of fatigue life. The objective of the present study is to point out and quantify the influence of the laser shock peening parameters.

## 2. Description of the experimental protocol

### 2.1. Laser shock peening

It is based on the use of a laser pulse, which duration is of the order of a few nanoseconds with a fluence range from 1 to 15 GW/cm², to generate a plasma by vaporizing a thin opaque layer (or coating layer). The expansion of the plasma generates shock waves that propagate into the material due to the confining medium. The shock waves, by penetrating into the material, plastically deform the body and introduce in depth compressive residual stresses.
The dimensions of the laser shocked samples are: 50 x 50 mm². They are treated on one face except on a thin band of 5 mm width all around.

### 2.2. Experimental design

To build the experimental design, all the parameters that could have a significant influence on the process were examined: laser fluence, pulse duration, nature of the pulse, wavelength of the laser, nature and thickness of the confining medium, nature and thickness of the coating layer, number of impacts, laser geometry, covering rate, angle of incidence and the trajectory of the laser. Those that were not relevant or that were fixed by the industrial partner were then dismissed. The significant parameters are summed up in Table 1. For each parameter, two intensity levels have been chosen: low and high so that the high level is 3 times the low level, except for the thickness for which the ratio is nine.
The responses that were relevant for the fatigue life of the specimen and to the industrial constraints were then determined. That is why it was decided to focus on the residual stress profile, the roughness, the deformations and the work hardening of the sample. The present work does not include the results concerning the residual stress profiles, which will be obtained soon. It was assumed that the uncertainty could be estimated from the interaction of order 4 since it is unusual to have a significant interaction of order 4. This uncertainty was compared to the value of standard deviation obtained by repeating some measurements and a similar order of magnitude was found. The Table 1 summarizes the significant responses and the associated uncertainties.

| Factor | Response | Uncertainty |
|---|---|---|
| Thickness | Stress at the surface ($\sigma_{surf}$) | 20 MPa |
| | Integral width of the diffraction peaks | 0.27°2 θ |
| Laser fluence | Ra | 0.2 µm |
| | Rt | 1.2 µm |
| Pulse duration | Vickers microhardness | 11 HV |
| Number of impacts | Curvature | 0.5 $m^{-1}$ |

**Table 1. Full factorial design $2^4$ experiments (left, list of studied factors and right, list of measured responses and associated uncertainties)**

### 2.3. Residual stress at the surface ($\sigma_{surf}$) and width of the diffraction peaks

X-Ray diffraction has been used to investigate on the residual stresses in a region near the surface of the sample. The method is based on the $\sin^2 \psi$ relation (Lu, 1998; Maeder, 1993), assuming that the stress component are zero on the surfaces parallel to the free surface of the sample. Here, the residual stress is averaged at 4 µm under the surface.

The experimental parameters used are the followings:

- Copper anode tube ($\lambda$ = 0,154 nm), 40 kV, 30 mA, $\chi$ setting with a PSPC
- Plane family {211} at 2θ=140°, 13 tilt values between -60° and +56°, 2 azim uth values 0 and 90°

The XEC are taken from the literature (Noyan, 1987):

- $S_1 = -2.64*10^{-6}$ MPa$^{-1}$
- $(1/2)S_2 = 11.90*10^{-6}$ MPa$^{-1}$

The measurement point is located at the center of the sample. The data processing is performed on Mathematica® (Mathematica®). The program is based on:

- Lorentz and polarisation correction
- Removal of the background noise, assumed to be linear
- Fitting of the diffraction patterns by a Pseudo-Voigt function
- Determination of the residual stress and the integral width

## 2.4. Curvature

The global shape of the specimens was determined with a coordinate measuring machine (CMM). The coordinates were acquired in the specimen reference system:

- Plane XY is defined from 3 points on the treated surface
- Direction X is determined by scanning two points on the front face
- Direction Y is determined by scanning the lateral face

The points were acquired along a square grid with 2.25 mm pitch, allowing a geometric data acquisition on the whole piece while avoiding possible sensor aberrations near the edges of the piece. A total of 441 points has been acquired for each sample. The processing of geometric data was also performed with Mathematica® (Mathematica®). The curvature of the samples has been calculated with five points, with a 2D polynomial interpolation. The degree of the polynomial function can vary from one line to another. Six lines have been fitted for each specimen, three longitudinally and three vertically, they are located at the center and at the extremities of the sample. The point of interest is located at the center of the specimen. Once the interpolation function was determined, the curvature was calculated with the following expression:

$$curvature = \frac{f''}{(1+f'^2)^{\frac{3}{2}}} \qquad (1)$$

where f is the interpolation function

## 2.5. $R_a$ and $R_t$

Among the variables that are representative of the roughness, it has been decided to concentrate on $R_a$ and $R_t$ as they are taken into account for the fatigue life of the specimen.  A Surtonic 3+ portable roughometer has been used. 10 lines of 25 mm long were scanned: 5 longitudinally and 5 transversally. 3 lines on 5 are located on the laser shocked zone and the 2 others on the untreated zone for reference. The lines are 25 mm long in order to take into account several laser spots. The data processing was performed by Talyprofile.

### 2.6. Vickers Microhardness

The microhardness measurements have been performed on a Mitutoyo AVK-C1 hardness tester equipped with a monitoring. A loading level of 49.05 N was applied without preload. Previously, the homogeneity of the hardness was tested. Four measurements were carried out at the center of the sample.

## 3. Results and discussion

In our experimental design processing, we have not calculated the interactions of order 3 and 4.

### 3.1. Residual stress at the surface ($\sigma_{surf}$) and width of the diffraction peaks

Figure 1 shows the effects of the factors on residual stress at the surface, in the longitudinal direction. The same trends are observed for the transversal direction. Moreover, it was observed that the residual stress field is not equibiaxial.

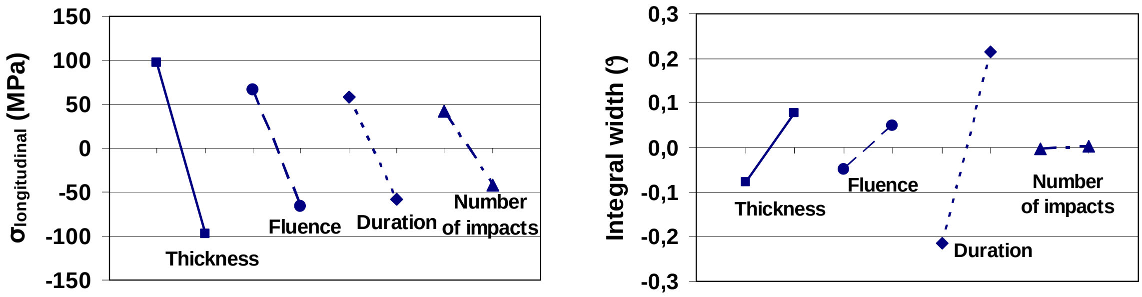


**Figure 1. Effects of the factors on the longitudinal residual stress (left) and the longitudinal integral width at the surface (right)**

For the residual stress, all the factors and all the interactions of order 2 have an influence since the measurement uncertainty is 20 MPa. The thickness and the laser fluence are the most influential.
So, if the value of the factors is increased, greater compressive residual stress will be introduced, which is a great asset since it will improve the fatigue life avoiding crack propagation. However, in the case of thickness, care should be taken because tensile residual stresses were found at the surface of the thin specimens.

Since there is a measurement uncertainty of 0.27°, it can be observed, for the integral width, that only the pulse duration has an effect which is moreover low. It increases the integral width which means that the specimen is slightly work hardened but much less than for shot peening. This is also an advantage for the fatigue life since it retains some ductility to the material. In transversal direction, the same trends can be observed.

### 3.2. Curvature

Concerning the curvature (in longitudinal and transversal directions), the effects of the factors are very different (Cf. Figure 2.) but all of them have an influence as the measurement uncertainty is 0.5 $m^{-1}$. All the interactions of order 2 have also an influence.
For the thick samples, the most curved specimen is got with the highest parameter levels. Moreover, it was noticed that the curvature radius in longitudinal and

transversal directions were different, which is consistent with the fact that the residual stress profile is not equibiaxial. This is to be related to the treatment path.
The curvature is an important response because it is representative of the industrial constraint (geometrical tolerance for the blade) and it will also enable to validate the relation between residual stresses and deformations.


**Figure 2. Effects of the factors on longitudinal curvature at the center of the specimen**

### 3.3. $R_a$, $R_t$ in surface and Vickers microhardness

For the roughness, Figure 3 shows the effects of the factors on $R_a$ in longitudinal direction. The measurement uncertainty is 0.2 µm, in this way none of the factors has a relevant effect. It was also observed that the roughness Ra is not affected by the fluctuation of the laser shock parameters. The average value of $R_a$ is 0.5µm on the treated areas; the untreated zone, a similar average value of $R_a$ has been observed.

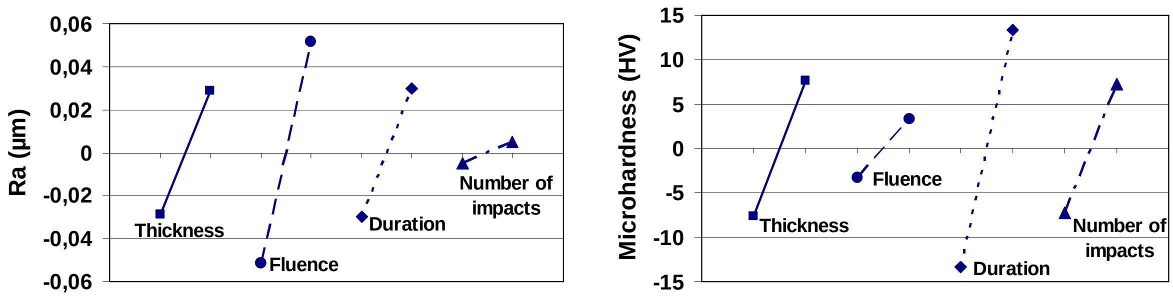


**Figure 3. Effects of the factors on Ra longitudinal (left) and Vickers microhardness (right)**

The same observation is made for $R_t$ referring to the measurement uncertainty of 1.2 µm. We have an average $R_t$ of approximately 6 µm. For the untreated zone, we have an average $R_t$ of 5.8 µm.
The small increase and the low values of Ra and Rt, compared to the untreated zone, are a great asset for the fatigue life since it will help avoiding crack propagation. This phenomenon can be explained by the fact that there is no mechanical contact on the material during the process.

Concerning the Vickers microhardness, with a measurement uncertainty of 11 HV, it can be noticed that the thickness, the duration, the fluence have an influence (Cf. Figure 3.). The interactions thickness/fluence and fluence/duration have also an influence.
Compared to the microhardness of the untreated zone, the increase due to laser shock peening is not very important. This observation is consistent with the results found for the integral width: the work hardening due to laser shock peening remains small.

## 4. Conclusions

This study presents the influence of laser shock peening parameters on a titanium alloy Ti-17. It has been shown that:

- All the selected parameters have an influence on the residual stress. For thin specimens, a tensile residual stress was found at the surface.
- Only the duration has an influence on the integral width. However a low work hardening was found, which is a great asset to retain some ductility to the material.
- All the parameters have an influence on the curvature.
- None of the parameters has an influence on the roughness. The treated and untreated zones have a similar roughness.
- The thickness, the duration, the fluence and the interactions thickness/fluence and fluence/duration have an effect on the microhardness. However, the increase is not very important and is consistent with the low work hardening found with the integral width.

The results show that laser shock peening can potentially increase the fatigue life of titanium components by generating low work hardening without modifying the roughness of the material. The microhardness and roughness results are consistent with those established by Peyre (Peyre, 1993).

A close perspective is the determination of the residual stress profile by the hole drilling method.

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