Validation of post-process characterization methods for Laser Shock Peened Materials

J. Brajer[1, 2], J. Madl[2], J. Kaufman[1], D. Rostohar[1], Z. Pitrmuc[2] and T. Mocek[1]

[1] *HiLASE Centre, Institute of Physics ASCR, Za Radnici 828, 25241 Dolni Brezany, Czech Republic, Europe*

[2] *Department of Machining, Process Planning and Metrology, Czech Technical University in Prague, Technicka 4, 166 07 Prague 6 Dejvice, Czech Republic, Europe*
brajer@fzu.cz

Abstract

A parametric model which helping in determination of the most suitable characterization method for Laser Shock Peened materials has been developed. The model can be used for fast prediction of residual stress profile inside the treated material. The model will be also very useful in the case of new materials, helping to select in rough estimation the most appropriate laser or technological parameters.

***Keywords:** Laser shock processing, residual stress measurement, XRD, beam deflection, hole drilling*

I. INTRODUCTION

Laser Shock Peening (LSP) treatment nowadays is mainly characterized by residual stress measurements. Many used characterization techniques can be divided into three groups depending on the degree of destruction they inflict on the characterized sample. Another criteria concerns the material depth where the technique can be implemented. Direct comparison of techniques is often not possible as each of them can be more suitable for different depth. The most commonly used techniques are hole drilling and x-ray diffraction (XRD) (using table-top devices and synchrotron sources). Other techniques are based on measurement of deformation. All these techniques share relatively high investment cost and long characterization time delivering vastly differ results. Considering that the residual stress depth profile strongly depends on material properties, laser and technology parameters (spot size, overlap, coverage, water layer thickness, etc.), selection of right characterization techniques is essential.

II. MATHEMATICAL MODEL

During LSP high energy laser pulses of ns durations are used to create compressive residual stress in material surface. The treated sample is covered with an absorbent layer which evaporates under the laser pulse impact. The expanding plasma is confined by a laser-transparent outer layer, usually water (Figure 1.), and pressures up to 5 GPa are generated. That leads to plastic deformation to a depth at which the peak pressure no longer exceeds the metal's Hugoniot elastic limit (HEL) [1].

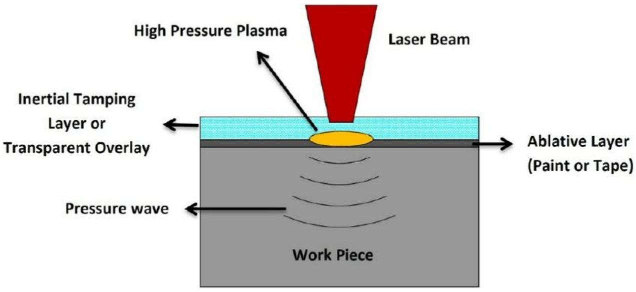


Figure 1. Schematic of Laser Shock Peening (LSP) Process. **Chyba! Nenalezen zdroj odkazů.**

The maximum pressure created by the expanding plasma can be calculated using the following formula **Chyba! Nenalezen zdroj odkazů.**:

$$P\,(GPa) = 0.01\sqrt{\frac{\alpha}{\alpha+3}}\,\sqrt{Z}\,\sqrt{I} \qquad (1)$$

where I is the laser intensity in GW/cm^2, α is the ratio of thermal to internal energy and Z is the reduced shock impedance of the target material and confinement medium.

In the next step, according to the linear theory the wave propagation trough undisturbed, homogeneous isotropic elastic half-space under uniform surface pressure p(t) can be estimated. The resultant pressure (1) is then used as a spatially homogeneous border condition for calculation of pressure wave propagation through the material.

Defining the half-space by $x \geq 0$ (with the initial condition $\tau(0,t) = -p(t)$), the stress is given by [3]:

$$\tau(x,t) = (\lambda + 2\mu)\frac{\partial u}{\partial x} \qquad (2)$$

where τ is stress in the material , λ and μ are Lamé constants, and $\frac{\partial u}{\partial x}$ is the single strain component ε_x.

Using inverse Fourier transformation on a material displacement u in equation (2) and applying initial conditions the stress can be express as

$$\tau(x,t) = D\frac{p\left(t-\frac{x}{c}\right)}{x^{\frac{3}{2}}} \tag{3}$$

where c is a speed of wavefront separating the disturbed and undisturbed medium, while D is a constant related to material properties.

Substituting pressure and time gives in linear approximation relation between the pressure wave magnitude and the distance from material surface as shown in Figure 2. While the residual stress corresponds to the pressure derivation, using equation (3) we get for the residual stress

$$\tau_R(x,t) = -pD\frac{\frac{x}{c}+\frac{2}{3}\left(t-\frac{x}{c}\right)}{x^{\frac{5}{2}}} \tag{4}$$

However, equation (4) does not apply across the whole depth. When the plasticity limit is reached, the residual pressure cannot exceed its theoretical maximum. The critical distance up to which the maximum residual stress is reached is given by [1]

$$L = \frac{C_{el}C_{pl}\tau}{C_{el}-C_{pl}}\left[\frac{P-(\sigma_Y-\sigma_0)(1+\lambda/2\mu)}{2\sigma_Y(1+\lambda/2\mu)}\right] \tag{5}$$

where C_{el} and C_{pl} denote elastic and plastic speed of deformation in base material, respectively, while σ_Y is a material yield strength and σ_0 is a homogeneous initial stress. The magnitude of maximum residual stress is [1]

$$\sigma_{res} = \sigma_0 + \mu\varepsilon^P\left(\frac{1+v}{1-v}\right)\left[1-\frac{4(2)^{1/2}}{\pi}(1+v)\frac{L}{a}\right] \tag{7}$$

where v is the Poisson's ratio of the material and a is the size of a square-shaped area under impact.

The magnitude of maximum residual stress as a respond to the initial pressure of 5GPa is also shown in Figure 2.

In general, residual stress inside material can be divided into three categories. The residual stress further from the surface (pressure wave derivation), the constant part where the maximum residual stress is reached and the residual stress close to and on the surface. The last category is influenced by relaxation processes where the residual stress goes back to equilibrium. This effect is not included in this simplified mathematical model.

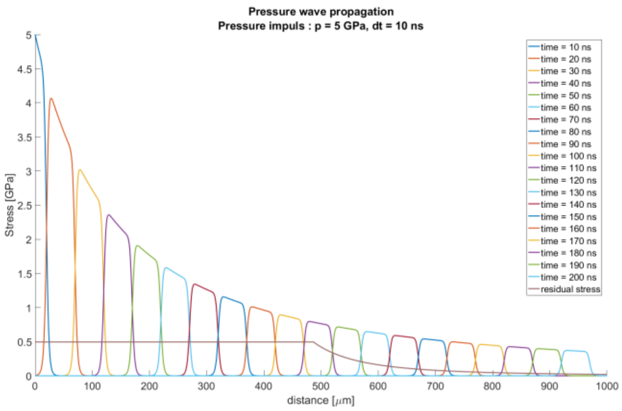
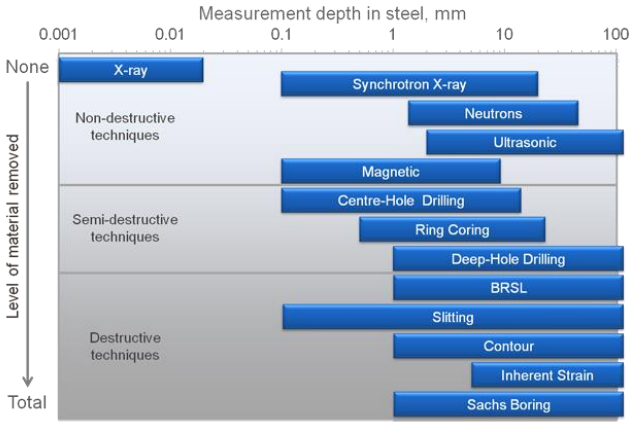


Fig. 2. Pressure wave propagating through material and resultant residual stress (brown line) as a function of distance from material surface. The initial pressure on surface is 5 GPa and its duration 10 ns.



III. COMPARISON OF MEASUREMENTS WITH THE MATEMATICAL MODEL

Fig. 3: Classification of residual stress measurement techniques **Chyba! Nenalezen zdroj odkazů.**

The residual stress measurement was performed on a Ti6Al4V sample which was exposed to LSP treatment at the laser centre of Universidad Politécnica de Madrid. The laser used was Nd:YAG (1064 nm) with pulse duration of 10 ns, energy 2.5 J and repetition rate 10 Hz.

In this case, three distinct residual stress measurement methods were used. First, it was beam deflection method which is based on deviation of laser beam deflection due to sample bending as parts of its surface are gradually removed and new stress equilibrium is achieved (Figure 4. left).

The second method was XRD which uses diffraction of x-rays to determine changes in distance of neighbouring atomic planes in a crystal lattice. In case of surface measurement (units of microns) this method is non-destructive. In order to measure the stress deeper in the material, layers of the material are removed by electrolytic etching (Figure 4. middle). The last method was hole drilling. In this case, relaxation of residual stresses is caused by material being drilled away. The subsequent deformations are then measured using strain gauges (Figure 4, right). A brief summary of other methods is shown in Figure 3.

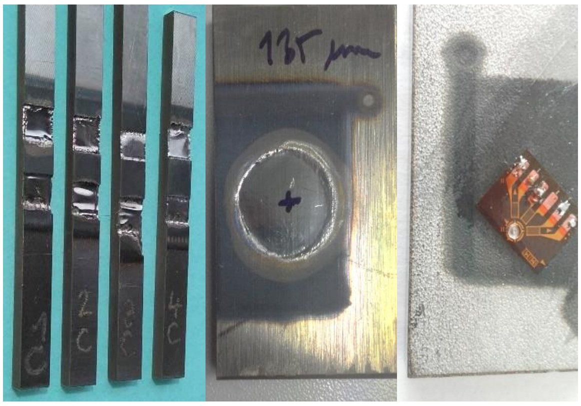


Fig. 4. Samples after residual stress measurement: beam deflection method (left), X-ray diffraction (middle) and hole drilling (right)

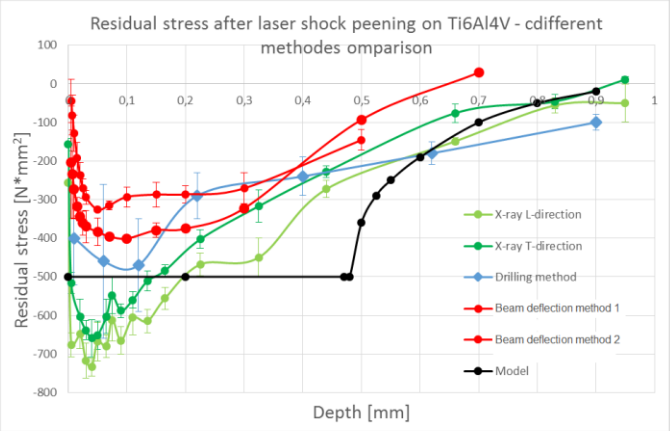


Fig. 5. Residual stress profile of titanium alloy Ti6Al4V treated by LSP. Measurements by 3 different techniques and a mathematical model are compared

Cleary, each characterization technique provides different results. Comparison of mathematical model with XRD shows that the model does not work close to the surface (Figure 5). The average measured residual stress magnitude corresponds with the model at depth of 0.2 mm and 0.7-0.9 mm where the stress falls to zero.

The hole drilling method overlaps with the model approximately at 0.6 mm under the surface. Beam deflection shows large discrepancy with the model everywhere. However, the difference between this technique and the model is roughly constant across the whole measured depth.

The relevance to the real stress profile may be estimated by comparison with the mathematical model. The whole decision making process of which process to use when is summarized in Figure 6.

IV. CONCLUSION

Three characterization techniques (beam deflection, hole drilling and XRD) were used in order to obtain residual stress profile for an LSP treated sample up to 1 mm deep under the surface.

The results were then compared with a mathematical model. The largest discrepancies between the measurements and the model were 250 MPa, 260 MPa and 350 MPa, respectively. In order to achieve better agreement with the model, correction coefficients for each characterization technique can be used in order to bring the discripance down to 40%, 24% and 23 % of its original value

From the model it was found out that the most suitable characterization method for material Ti6Al4V is XRD due to good agreement both close to the surface and at larger depth. It is also worth mentioning that the residual stress profile shape obtained with beam deflection method copies the shape of mathematical model although both profiles are vertically shifted. The method is therefore promising for revealing trends in the profile shape.

ACKNOWLEDGMENT

This work benefitted from the support of the Czech Republic's Ministry of Education, Youth and Sports to the HiLASE (CZ.1.05/2.1.00/01.0027) and DPSS Lasers (CZ.1.07/2.3.00/20.0143) projects co-financed from the European Regional Development Fund.

Prof. J. L. Ocaña and his team from the UPM Laser Centre Madrid are gratefully acknowledged for demonstrating laser surface treatment on Ti6Al4V samples and measurement of the residual stress by the hole drilling method.

REFERENCES

[1] Peyre P., Fabbro, R., Brethe L., Dubouchet C. laser shock processing of materials, physical processes involved and examples of applications, Journal of laser applications, 1996, 8, 135-141 ISSN 1042-346X

[2] Gujba, A.K.; Medraj, M. Laser Peening Process and Its Impact on Materials Properties in Comparison with Shot Peening and Ultrasonic Impact Peening. Materials 2014, 7, 7925-7974.

[3] Achenbach, J. D. Wave propagation in elastic solids. New York: American Elsevier Pub. Co., 1973. ISBN 0444104658.

[4] OVERVIEW residual stress measurements. (10.10.2016). Retrieved from http://www.veqter.co.uk/residual-stress-measurement/overview ISSN 1042-346X

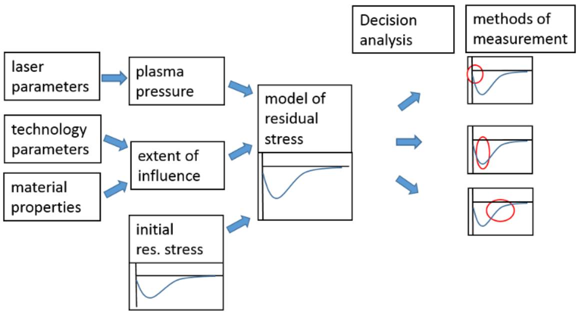


Fig. 6. A simple model to determine an appropriate residual stress characterization method