HiLASE center: Development of Laser Shock Processing facility and validation of post-processing characterization methods

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Abstract
New generation of diode pump solid state laser can deliver significantly higher average power. One of such sources called Bivoj is located in HiLASE research center in the Czech Republic. The laser delivers 10 J and 100 J energy pulses with 10 Hz repetition frequency at 1030 nm. Bivoj's square laser spot with homogeneous intensity distribution has tuneable size ranging up to several square centimeters [1]. A prominent increase in the material treatment speed using the LSP technology in combination with Bivoj laser can therefore be expected.

The paper will be divided in two parts. In the first part of the paper will be given report on the status and further plans for developing LSP station at the HiLASE center. The second part of the paper will be focused on a parametric model which has been developed to determine the most suitable measurement method for validation of the treated surface characteristics. The experimental part then revolves around comparison of various methods for residual stress measurements. The reliability and applicability of each method at different treatment conditions is evaluated.

Keywords : Bivoj, Laser shock processing, residual stress, HiLASE,

Introduction

HiLASE center of the Institute of Physics under Academy of Sciences in Czech Republic,is engaged in the development of pulsed diode-pumped solid-state lasers with high energy per pulse and their applications. Thanks to current technology achievements development of picosecond and nanosecond lasers enters unexplored mode of high average power level of 1 kW (see Fig. 2). Lasers with these parameters are not currently available, but they have significant application potential. The technological goals of HiLASE center is to answer to this long-term global demand. On Figure 1 are shown by a green star lasers which are in the process of development at the HiLASE center as well as other laser systems developed by different world institutions. In addition to the development of laser sources, the HiLASE center also investigate application potential of such laser system. Both laser development and their potential applications will also strengthen the strategic position of the Czech Republic in this highly promising field.

Laser Shock Processing (LSP) technology at HiLASE centre is using Bivoj laser source [7].Optimized opto-mechanical assembly and improved cryogenic cooling technology of laser crystals permitted achievements of energy of 100 J level at a repetition rate of 10 Hz and pulse duration of a few nanoseconds [5]. It is also possible in principle, scale up the laser energy further to the level of 1 kJ or more. A laser with such parameters is currently is not present at any laser facility.[1]

1. Status of LSP technology

In the LSP treatment high energy laser pulses of short, ns durations is impacted on a material surface. The surface of the sample is covered with an ablative absorbent layer that can be evaporates by laser and creates a plasma. In case of usage of uncovered sample the plasma is created directly from the surface of the sample, but the pressure can be lower and some damage of the sample surface can occurs. Plasma is confined by a laser-transparent outer layer, usually water (Figure X). This confinement generates pressures up to 10 GPa and leads to plastic deformation to a depth at which the peak pressure no longer exceeds the metal's Hugoniot elastic limit (HEL). HEL is related to the dynamic yield strength (σ_Y^{dyn}) at high strain rates and the Poisson's ratio (v). [4]

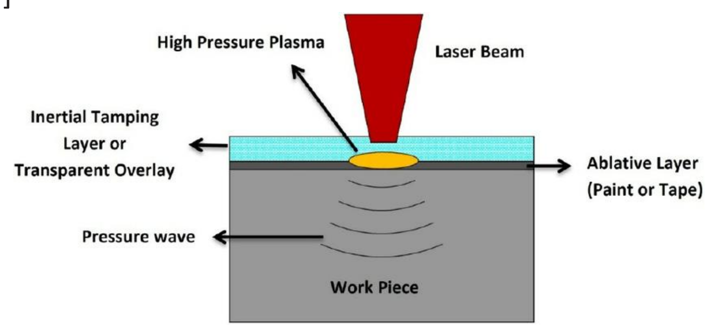

Figure 1. Schematic of Laser Shock Peening (LSP) Process. [9]

For the treatment is usually used energy in pulse in range 1-20 J. This energy level for suitable impact to metals allows usage of laser beam of 1-4 mm in the diameter. Workpieces requiring treatment by LSP technology tends to be large (Aircraft Turbine Engine Blades)[6] . Taking in the account relatively small laser spot size and low repetition rate of LSP used lasers of only few tenths of Hz, just parts of workpieces like leading edges or stressed joints are treated. Bivoj laser design permits energy level of up to 100 J in 2-10 ns pulse with repetition rate of 10 Hz. Combination of these parameters is promising much faster LSP treatment of the workpiece than was possible in the past (maybe here you should write spot size for 10J and for 100 J which are corresponding to 5GW/cm2, this will immediately demonstrate increase of processing speed). Moreover due to Bivoj laser energy and pointing stability we are able to reach uniform square beam.

After the operation demonstration at STFC [8] in December 2015 Bivoj laser was transferred to HiLASE center. At the moment of writing (August 2016) stable operation at 10J (with standard deviation of 0.4%) energy level is already demonstrated while scaling up to 100 J level [7] is expected in coming months (see Figure bellow)

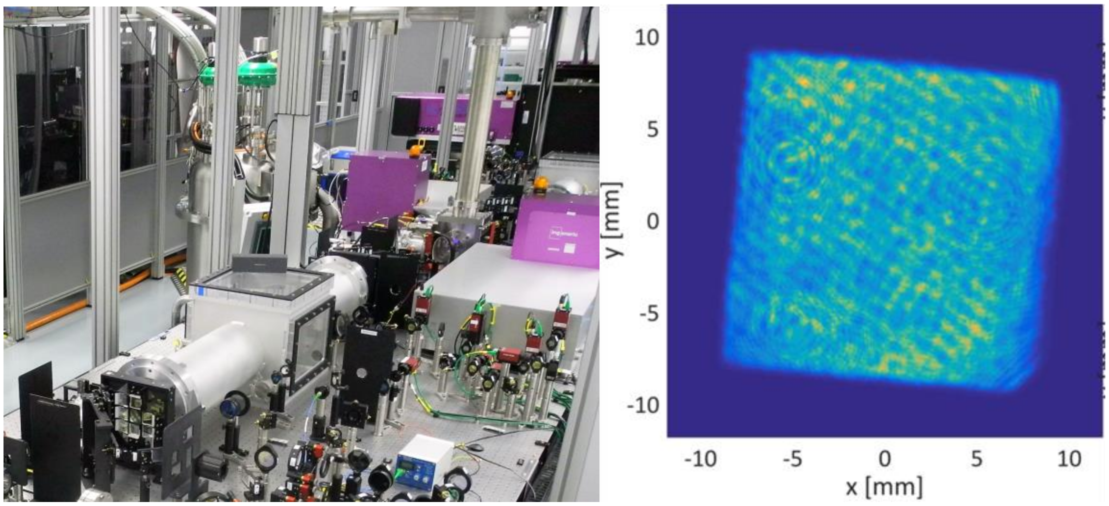

Figure 2. Bivoj laser system at HiLASE center (left). The uniform laser beam of 20mm x 20 mm (right) with excellent energy stability at 1 to 10J (1-10 ns pulses with 10 Hz repetition) is ready for further applications including LSP.

2. LSP setup

Around Bivoj laser system an experimental setup for LSP is in the process of installation. The experimental setup is developed on the way to permit in parallel, for each laser pulse, LSP as well as monitoring laser parameters (see figure 5). A f = 200 mm lens will allow changing of spot size from 2.8 mm x 2.8 mm to 4.5 mm x 4.5 mm at the sample surface. Combining the energy level (1 to 10 J) and spot size it is possible to deliver from GW/cm2 up to GW/cm2 at the surface of treated sample. Additional fine energy tuning is possible by Bivoj laser attenuator. Using a small leak of one of mirrors the energy stability and laser beam profile will be monitored by the laser diagnostic system (see figure 5) based on two cameras.

LSP setup also contains an alignment laser which will be used for setting a sample in correct position and testing robotic arm movement. While Bivoj laser is delivering laser beam at 1030 nm, a targeting He-Ne laser will be used for demonstration and education purpose (see figure 3).

In the future around the LSP optical setup will be enclosed in order to protect optical elements from dust contamination. Front side of covering is designed with window for laser protected by an air knife.

Figure 3: Schematic presentation of the LSP setup (left) and corresponding 3D model (right up). The image of LSP setup on the optical table (right down).

3. Water delivery system

Water flow is divided in two separately controlled branches. In each branch is possible to measure flow rate and temperature of the water. One outfall is closely tied with robotic arm and second with positioner, due to this placement the water system is capable to follow any shape of specimen or any laser-robot mutual movement. Ends of pipes are solved by changeable jets, which can be optimize for sample complexity and size of laser spot.

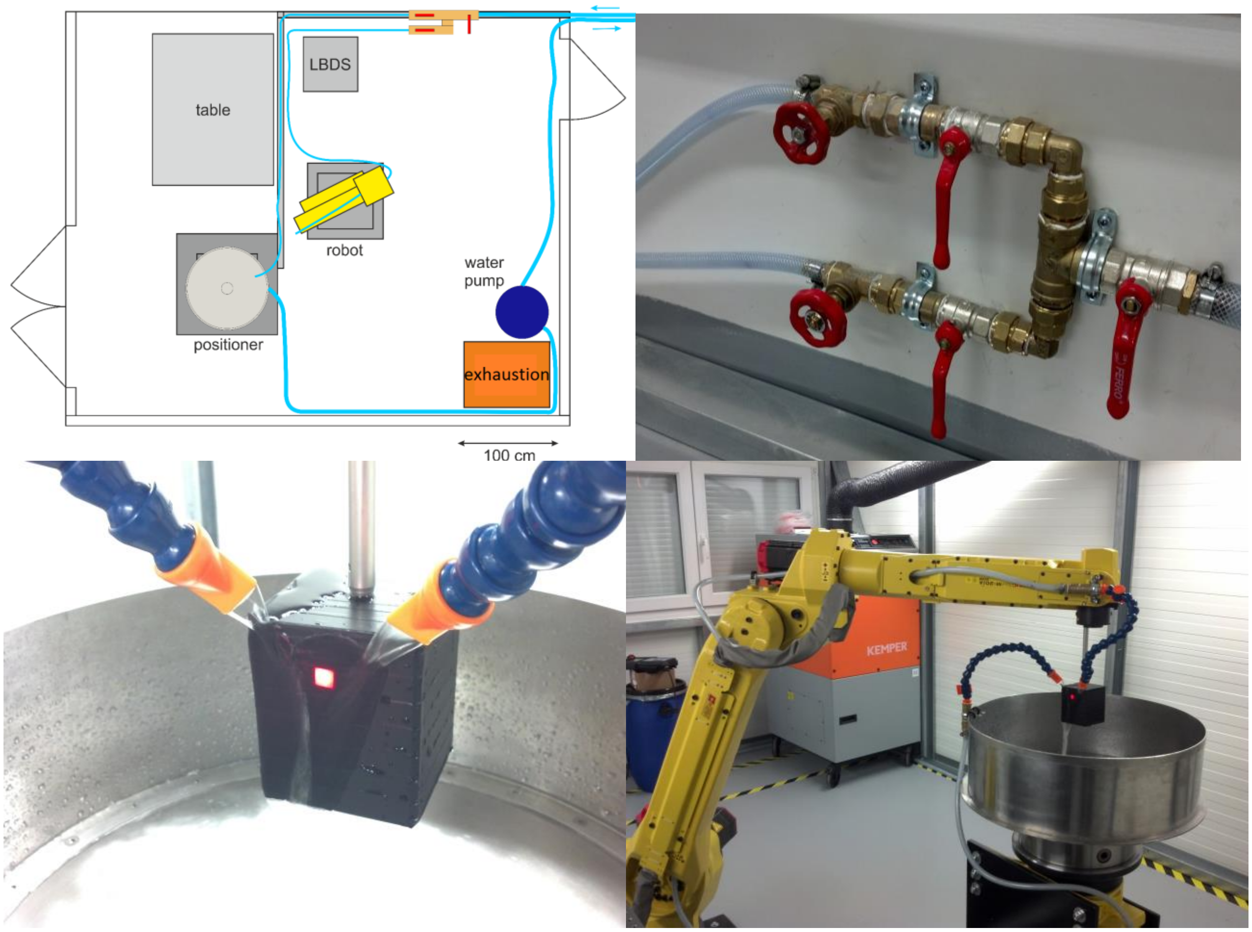

Figure 4. The equipment layout in LSP cell (left up), Water delivery system with option of adjustment flow rate for each branch separately (right up), Detail of water jets (left down), LSP setup with robotic arm and aquarium (right down)

An inseparable part of the LPS technology are components allows the fixture and movement of the sample. And last but not least safety, measurement and communication features.
For holding samples ware proposed holders which allows mounting various shapes and sizes of the samples. Holder and another features are carried on the robot Fanuc M-20iA/20M. This robot is capable operate with load of 20 kg with 0.08 mm repeatability. With robot is connected positioner with maximal load 300 kg.

Operation of the laser is realized by robot interface. To interface of the robot are connected two independent shutters, safety system and process monitoring system too. Moreover the system of interlocks is connected in the whole building and it can work independently.

4. Validation of post-processing characterization methods

For the validation of the results was developed decision analysis model. This model is based on characterization of residual stress identified by the parameters entering into the process. The

model is able to detect main characteristics of the waveform of the residual stress in the surface of the material.
For measurement after LSP are still used various methods. Most used measurement technique is hole drilling method and x-ray method, but it can be used another methods based on deformation or radiance in synchrotron.

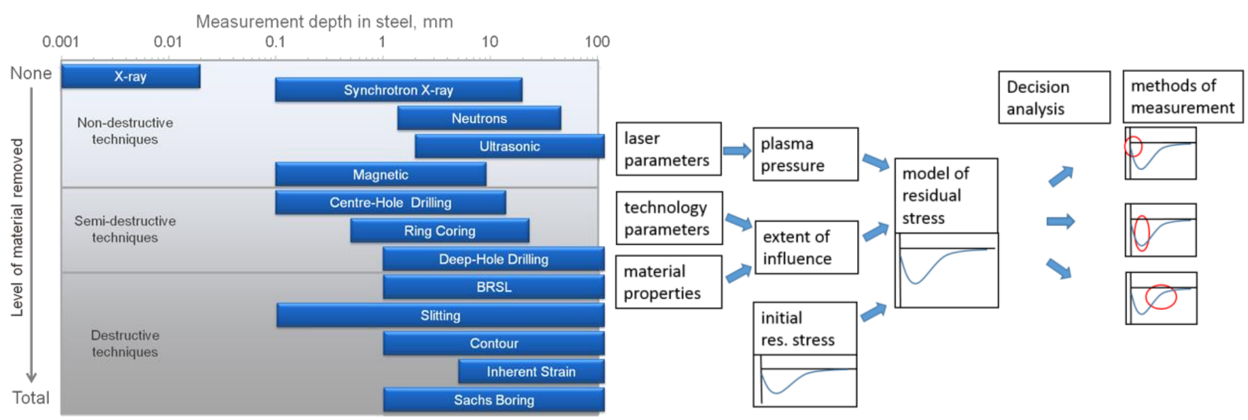

Figure 5. Classification of residual stress measurement techniques (left) [13] model to determine the appropriate method (right)

This model can be used for very fast prediction of maximum value and maximum depth of residual stress in the surface. By comparison of results from measurements can be decided, which method of measurement is more suitable for shallow and deep treatment by LSP. In case of new material, laser or technological parameters can be choose most appropriate method by usage of calculation.
To determine the appropriate method of measuremet of residual stress the preasure in plasma is calculated. Plasma preasure is based on defined formulas [10],[11],[12]
Power density is a function of frequency, pulse time, power and spot area (1). The laser fluence is expressed as a function of laser pulse energy and focal spot area (2). Load or pressure P which must exceed the dynamic yield strength for plastic deformation (3). Equation (4) shows the reduced shock impedance Z for the target material Z_{target} and confining medium Z_{water} which is related to the density and speed of sound in the material.

(1) $$I\,\left(\frac{GW}{cm^2}\right) = \frac{P_{avg}}{f\,(pt)\,a}$$

(2) $$Fluence\left(\frac{J}{cm^2}\right) = \frac{Laser\ pulse\ energy\ (J)}{focal\ spot\ area\ (cm^2)}$$

(3) $$P(GPa) = 0{,}01\sqrt{\frac{\alpha}{\alpha+3}}\sqrt{Z}\sqrt{I_0}$$

(4) $$\frac{2}{Z} = \frac{1}{Z_{water}} + \frac{1}{Z_{target}}$$

Calculation of presure in plasma was used for calculation of residual stress. The stress was calculated with Half-space subjected to uniform surface tractions model. Model is based on transient wave propagation according to the linear theory. The wave motion is generated in an initially undisturbed, homogenous, isotropic elastic half-space sample. Application of spatially uniform surface pressure p(t). Suppose the half-space is defined by x≥0 denoting the normal stress in the direction x by $\tau(x, t)$, at boundary is x=0. Residual stress τ_z is derivation of normal stress τ in same direction.

(5) $$\tau(x,t) = \frac{p(t-\frac{x}{c})}{x^{\frac{3}{2}}}$$ (6) $$\tau_z = \tau'$$ (7) $$\tau_{z\,(x,t)} = -pC\frac{\frac{x}{c}+\frac{2}{3}(t-\frac{x}{c})}{x^{\frac{5}{2}}}$$

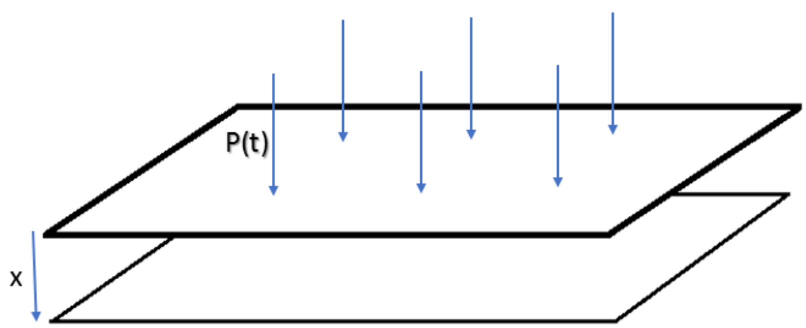

Figure 6. Model for callulation residual stress based on surface presure, time and xistance prom the surface.

Calculated residual stress was composed with initial residual stress before treatment. Based on the final result was chosen right method of measurement.

5. Conclusion

The HiLASE project team in cooperation with the CLF is in the process of finalizing development of 100 J laser system based on cryogenically cooled multi-slab laser amplifiers. In the parallel time the application laboratory for surface treatments is under construction. In this paper, the summary of state of the art of laser development and laboratory construction is given. Our preliminary results on residual stress measurement and calculation is also presented. Once is fully operation, the HiLASE application laboratory for surface treatments will be available for scientific community or for industrial applications.

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