Application of laser shock processing

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Laser Shock Processing (LSP), or strengthening the material surface by laser shock wave is very modern and progressive technique, which allows a significant increase in fatigue life of cyclically loaded parts. The compressive residual stresses are generated in the surface layer of material processed by laser beam, which can significantly improve the fatigue properties of the material and reduce the initiation and propagation of the surface cracks. This technique finds practical use of the most demanding applications like in the aerospace industry. For this reason, we are mapping the selected surface properties after the laser treatment for the better understaning of technology possibilities. After that another suitable applications can be found. It is also important to determine appropriate parameters for different types of material and requirements affecting the result.

Keywords: Laser shock processing, surface integrity, residual stress

1 Introduction

Machining of workpieces meets high surface requirements. The process is finished with specific surface finish and surface layer properties. The integrity of a surface is a combination of various characteristics that describe the functional properties of the surface. This means that surface integrity describes the topological aspects of the surface and their physical, chemical, mechanical and metallurgical properties.

The surface integrity is important especially in finishing operations, because it affects the properties of the product, such as its fatigue strength, corrosion resistance and service life. The properties of surface may be responsible for catastrophic defects.

Demand for finishing the surface with the inserted surface compressive stresses are required. Next to the conventional method laser shock processing can be used. This method can achieve wanted surface tensions. Moreover, conventional methods mostly reach different results, however laser the shock processing method has a great repeatability.

Devices of today allow to use the technique more efficiently than in the past. The operating frequency is up to 30 Hz when the laser spot size of about 1 mm and sufficient energy in the pulse is used. The surface of medium size components can be influenced in several hours. The laser sources, which have been developed in the Czech Republic up to 2015 have reached such intensity that the spot size can be increased up to several square centimeters while frequency is maintained, and the whole process can be speeded up. The higher production speed can significantly affect productivity and enable technique accessible to common applications for parts requiring high durability of the surface.

2 Laser shock processing

Laser Shock Processing (LSP) as a technique for surface processing has been in existence for over 25 years. The LSP being a new implementation of an old technique of creating surface compressive residual stresses, also has a unique advantages over conventional shot peening. While the extensive literature on shot peening helps to identify potential areas where LSP would be most beneficial, LSP generates a plasma that leads to the shock wave and creates deep compressive stresses. Hence, literature data from other similar techniques cannot be adopted categorically to LSP. Since LSP is new on an industrial scale, the details of optimising this process are not common in literature. [5]

In the LSP high energy laser pulses of very short durations are impacted on a material surface. The sample surface can be coated with an ablative absorbent layer that evaporates and creates a plasma. Plasma is confined by a laser-transparent outer layer, usually water (Figure 1). 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). The HEL is related to the dynamic yield strength (σy^{dyn}) at high strain rates and the Poisson’s ratio (ν). [4]

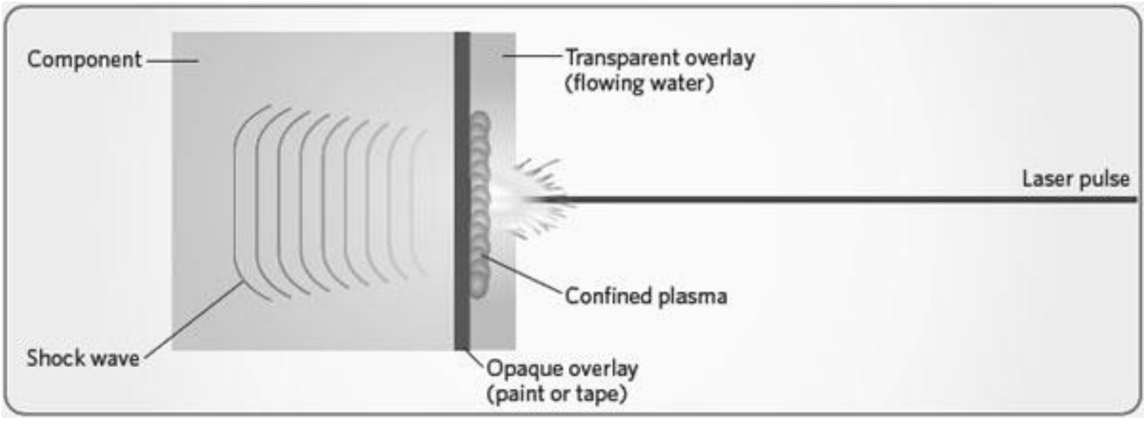

Fig. 1. *Principle of the LSP method[26]*

Along with plastic deformation, this process results in a deep compressive residual stress layer extending from the surface to depths up to 1 mm, depending on the energy density and material.[3] Typically a pulsed Nd:Glass laser (γ=1.07 μm) providing energy in the range of 1 to 100 J per pulse and pulse durations from 5-50 ns is used. [3, 5, 14]

Compared to other techniques such as shot peening (SP), ball-burnishing (BB) and ultrasonic shot peening (USP), the LSP is reported to produce lowest work hardening close to the surface. [6] With a protective environment and good surface strengthening, laser peening is suitable for fatigue life improvement of fastening holes. The LSP also has improved the crack growth resistance post foreign object damage (FOD) with delayed crack initiation [7] valuable for aircraft gas turbine engine compressor and fan blades. [8] It can also be used for rigid spinal implant Ti rods improve in flexibility by LSP for a given fatigue strength [9]. For Ti alloys suitable for high-speed motor rotors used in centrifugal compressors, the LSP decreases the fatigue crack growth rate [11]. Improvements in laser technique have enabled high throughput production [12] using new femtosecond lasers, though the extent of work hardening is similar for both femtosecond lasers and older nanosecond laser based peening [13].

A number of process variables, including laser shock intensity (energy/power density), spot size, multiple laser shots, overlapping of laser spots, etc., are available to control the depth of residual stress, surface roughness and distortion [14]. Intensity of LSP is mainly controlled by the power density (power per unit area) applied to the laser treated region and is proportional to the magnitude and depth of the compressive residual stress. The depth of compression can also be increased at the same energy by applying multiple impacts. Basic theory of deformation dynamics of shock compression has been investigated by several notable researchers starting from shear bands [15], constitutive behavior and thermally activated mechanism of dislocation motion [19], high-speed dislocations and modeling of shock front by dislocation movement [17] and constitutive modeling [18] of plastic deformation.

3 Surface characteristics and its measurement

For the file of the surface layer properties is uses the term "surface integrity" is. It is a group of characteristics describing the influence of the surface layer on the functional properties of the component. This file may be different with regard to the process used in production and also to the manner of loading components in operation, or with respect to the technical possibilities and economic aspects of quality control. [1, 2, 4]

The term can be understood as a free set of properties of surface layers that are created or influenced by production processes, which are expected to affect the functional properties of the investigated components. As the most important and most frequently analyzed factors which characterize the integrity of the surface after machining are the geometry of the machined surface and the rate and depth of hardening. Furthermore, the structural phase changes a sense, size and depth of residual stresses. [12, 26]

The geometry of the surface is divided by the size of disagreement with the perfect surface to macro-geometry and micro-geometry. The macro-geometry describes a shape deviations and the micro-geometry described which terms of surface roughness and its distribution. The service life of components is on dependent micro-geometry and it is measured by profilometers microscopes or roughness measurements. [3, 9]

The strength of a material is its ability to withstand an applied load without failure. All phenomena preventing movement of dislocations (grain boundaries, precipitates, other dislocations, etc.) increasing the strength. Almost all technique processes affect the mechanical properties of the newly created surface. These changes affect the final components quality especially the tribological and fatigue properties. These characteristics of the surface layer are the most often assessed by hardness changes. Hardness is measured mostly on oblique cut and with a sufficient number of repetitions.

An another factor of the surface integrity is a change of structure and phases. Every change in the structure of metals in the solid state is associated with a change in the arrangement of atoms. The movement of atoms in the crystal lattice is more easily carried out in the presence of failures of the crystal lattice and is related directly to temperature. The structural changes can be observed microscopically to scratch pattern.

One of the most important characteristics of the surface integrity is the residual stress in the surface. By external forces or moments on the set are tensions generated. These tensions are called intermediate stresses. However strains that are contained in the system without causing external loads are called internal stresses. Internal stresses which are caused by internal forces are in a closed system in equilibrium. However, if a system failure occurs, the internal stress is released and causes deformation of the system. There are many methods of residual stress measurements. The principles are operating at mechanical deformation measurement methods. Gradual stresses release always occurs with a simultaneous measurement of components deformations. [24]

4 Development of the measurement technique based on gradual electrolytic surface etching

The methode of gradual removing is based on measurement of sample deformation during etching. The samples were measured, weighed and clamped into the circlips of the measuring device. The surfaces of the samples that were not electrochemically dissolved, were covered with protective waxes. The part of the surface on which the course residual stresses were detected, was cleaned and degreased. The prepared sample was immersed in the bath and after the temperatures compensation of the sample and the bath was electrochemically dissolved. To ensure a uniform removal speed the bath was tempered and stirred, the supply current was stabilized and together with voltage continuously monitored. Deformation of the sample ε emerging by removing layers was monitored. The time course of distortion $\varepsilon(t)$ was converted to the dependence of deformation to the distance from the surface $\varepsilon(z)$. Provided uniform removal time ti is possible to determine the depth of the melted weight loss and its dependence on the time is considered to be linear. Calculation of residual stresses in the individual layers of sheet sample with rectangular cross section based on the mechanics of materials. The basis of calculation is the assumption that in the layer of thickness ΔH is the residual stress σ = constant. By removing layers ΔH at the flat sample the residual stress causes the same deformation as if it acted external force F. [19, 25]

$$F = \Delta H \cdot b \cdot \sigma., \tag{1}$$

The deflection of the sample (cantilever beam) is

$$y = \frac{1}{EI}\int_0^1 M.x.dx, \tag{2}$$

Where:
x... actual distance [mm],

$$I = \frac{bh^3}{12}, \tag{3}$$

I… moment of inertia [mm^4]

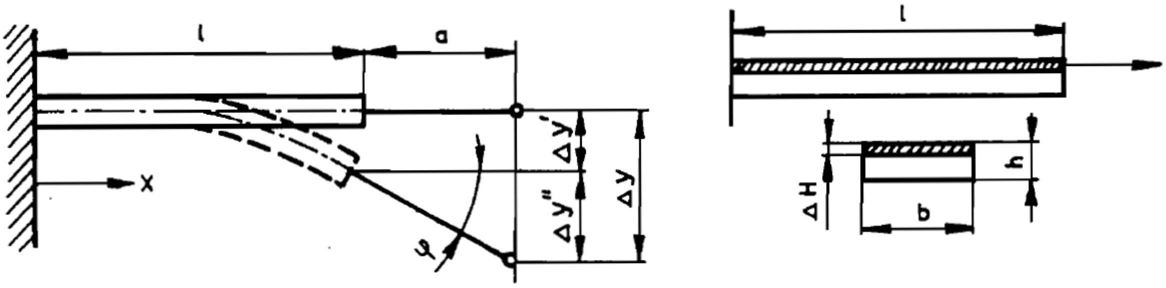

Fig. 3. *Depiction the measured values of the sample, wherein a - the length of the auxiliary caliper, φ - angle of rotation of the end cross section*

$$\Delta y = \Delta y' + \Delta y'', \tag{4}$$

Δy… measured value of the deformation [mm],
y' … deflection of the beam [mm],
y''… rotation of the measuring caliper in the measurement plane [mm],

$$\Delta y' = \frac{1}{EI}\int_0^1 M.x.dx = \frac{Ml^2}{2.EI}, \tag{5}$$

l… length of the etched part[mm],
E… modulus of elasticity [N.mm^{-2}],

$$\Delta y'' = a.\Delta\varphi = a.\frac{1}{EI}\int_0^1 M.dx = \frac{Mla}{EI}, \tag{6}$$

$$M = \sigma .b.\Delta H.\frac{h}{2} \ , \tag{7}$$

$$\Delta y = \frac{\sigma .b.\Delta H.h.l}{2.I.I}.\left(\frac{1}{2} + a\right) \ , \tag{8}$$

Stress is given by

$$\sigma_{vn} = \frac{\Delta y}{\Delta H}.\frac{E}{3.l(l + 2a).}.h^2 \ , \tag{9}$$

From the record of the registration devices the required values of the Δy and ΔH are found. These values are necessary to correct the scales in the x and y axes. The resulting tension calculated after dissolution of the first layer is

$$\sigma_{vn} = \frac{\Delta Y_n.L.M_y.E.h_0^2}{\Delta H_n.H.3.l.(l + 2a)} \cdot 10^{-2} \, , \tag{10}$$

H… total etching depth [mm],
ΔH_y… increase the thickness of the layer (dissolved) [mm],
h_0… original sample thickness [mm],
M_y… scale amplification - M = const. = 0.00045 [-],

If another layer ΔH is removed a calculation of tension must be corrected. The dissolution of the first layer causes the stress of the whole cross-section of the beam

$$\mathrm{F} = \sigma_1.b.\Delta H_1 , \tag{11}$$

Bending moment

$$\mathrm{M} = \sigma_1.b.\Delta H_1.\frac{h - \Delta H_1}{2} , \tag{12}$$

Correction has a tensile component (from F):

$$\sigma_1 = \frac{F}{S} = \frac{\sigma_1.\Delta H_1}{h - \Delta H_1} , \tag{14}$$

Bending component (from the moment M):

$$\sigma_0 = \frac{M.(h - \Delta H \ )}{2.W_o} = \frac{3.\sigma_1 \Delta h_1}{h - \Delta H_1} , \tag{15}$$

Total correction (action layer 1 to layer 2) is then:

$$\sigma_k = \sigma_t + \sigma_o = \sigma_1.\frac{4.\Delta H_1}{h - \Delta H_1} , \tag{16}$$

Stress in the layer is ΔH_2 given by:

$$\sigma_2 = \sigma_{v1} - \sigma_k = \frac{\Delta y_2}{\Delta H_2}.\frac{M_x.M_y}{3.l(l + 2.a)}.h^2 - \sigma_1.\frac{4.\Delta H_1}{h_1} , \tag{17}$$

$$h_1 = h - \Delta H_1 , \tag{18}$$

$$h_2 = h - (\Delta H_1 + \Delta H_2) , \tag{19}$$

The actual residual tension in the n-th layer under the surface is given by:

$$\sigma_n = \sigma_{vn} - \sum_{i=1}^{n-1} \sigma_1.\frac{4.\Delta H_1}{h_i} , \tag{20}$$

$$h_i = h_o - \sum_{i=1}^{n-1} \Delta H_i \ , \tag{21}$$

The following research was based on which were affected by laser with the wavelength of 1064 nm, the energy 2J / pulse with a relatively small area of the laser beam diameter 1.5 mm. A 2500 pulses per cm^2 was applied to the sample. Samples were made of Ti6Al4V material, which was normalized annealed. The surface of the sample was not covered with any covering material and water was jetted directly onto the surface.

For all samples affected by the LSP technique was found significantly compressed character of residual stress by etching measurement mothod. All samples show a pressure peak (from-325 to -514 MPa) at a depth of from 0.03 to 0.04 mm below the surface. Compressive residual stress is decreases with increasing depth. The transition to the compensatory tensile stress would occur at depths greater than 0.7 mm below the surface. The results of measurement have shown that the depth of strengthening is significantly larger than for other methods of mechanical strengthening (for the equivalent thickness of the sample). Also, microgeometry of the surface has not shown any signs of significant plastic deformation as mechanical methods (eg shotpeening). In therms of fatigue, this finishing technology can be described as the appropriate. Contribution for resistance to low-cycle fatigue would be considerable. Increase of the resistance to high-cycle fatigue would be relatively small, since the surface layer (0 to 0.03 mm) has a considerable residual stress gradient. In comparison with the measurement method of drilling, the measured values vary mainly on the surfaceand then deep below surface.

Both methods are not suitable for the measurement of residual stress directly on the surface, so it is appropriate to compare the measured results to a depth of 30 μm. In case of differences in big depth, these differences may be afeceted by different causes. The methods were not applied to the same sample, so each set of samples is affected different way. Another possible cause of the difference is that measurement samples were measured by the method of drilling immediately after treatment, whereas samples measured by etching were measured for several months after treatment. Due to such a long period the relaxation of the material may occur.

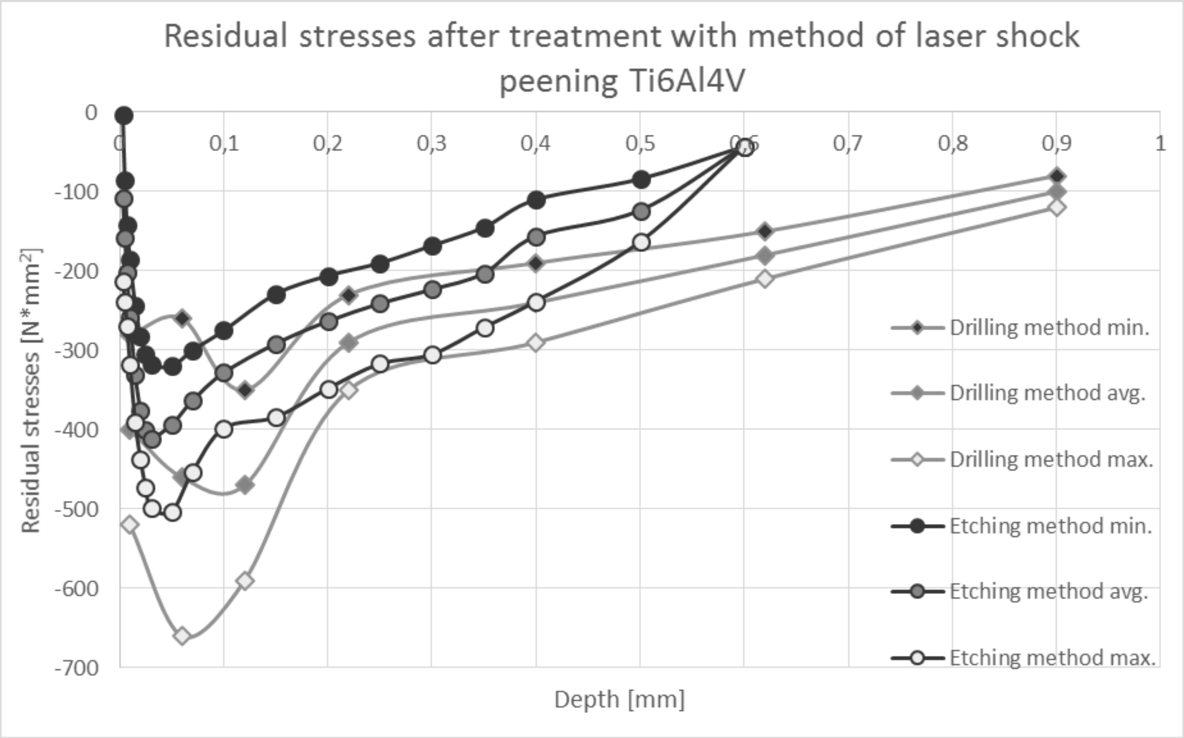

__Fig. 4.__ The course of residual stresses after laser shock peening processing applied on the Ti6Al4V alloy.

5 Improvement

In order to make the laser more attractive for surface treatment processes it is essential to reduce cost of laser power over the desirable focal spot dimensions. That request can be directly linked to greatly increased interest in the development of diode-pumped solid-state lasers (DPSSLs) with high pulse energy, high efficiency, and very good beam quality. The main reason is that semiconductor-laser bars have steadily grown in power and decreased in price per watt. In addition, novel beam conditioning techniques have been successfully applied to increase brightness and beam quality of diode-laser bars. As a consequence, several high-energy-class DPSSLs are being constructed worldwide (Fig. 1). These devices will have extremely large exploitation potential in various applications in new scientific and high-tech industrial processes. It can be assumed that these developments will also foster industrial application of laser large area materials processing and especially of laser shock processing which require lasers with a unique high power density and high repetition. [19, 20].

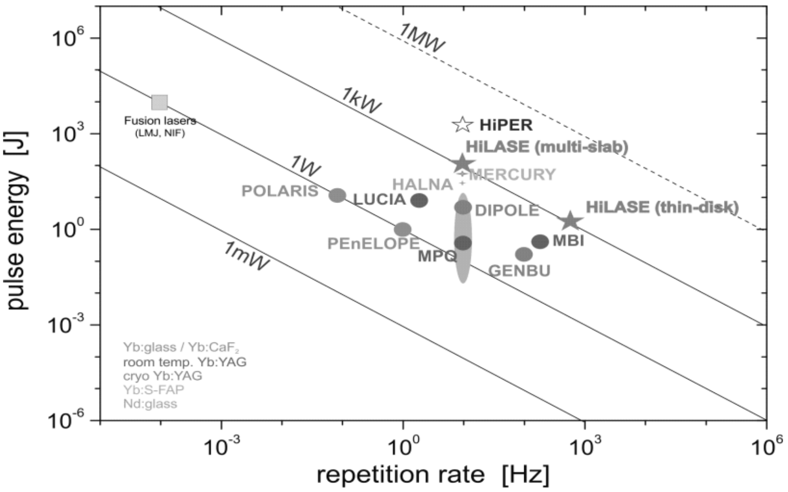

Fig. 5. *Comparison of existing and future high energy DPSSL facilities. [24]*

Efficient application of lasers in the surface treatment of metals requires lasers with high power density and repetition rate over a big spot size. A fully diode-pumped 100 J cryogenically cooled Yb:YAG multislab laser system with pulse duration of 2-10 ns, 10 Hz repetition rate and spot size of 51.51 mm^2 , developed as a part of the HiLASE project, is expected to start a new era in laser surface treatments. [16, 24]

6 Cooperation with other institutes

Device for the LSP in the Czech Republic is not finished yet. Therefore cooperation with the institutes which is involved in this technology was established. The strongest cooperation is with Spanish Polytechnic de Madrid, Italian Alma Mater University of Bologna and the Indian Raja Ramanna Centre for Advanced Technology.

Researchers at Spanish Polytechnic de Madrid, where is head of the laser department Prof. J. L. Ocaña, are engaged in the application of laser shock processing. For several years this technique affecting titanium alloys reaches valuable results. Residual stress level is in Madrid measured by drilling technique.

At Czech Technical University the samples affected on Spanish´s device have been measured. Some of sampels have been measured in Spain on local device. On both institutes different measurement methods were used.

AT CTU the samples were measured by gradual removing method electrochemical removing and compared with data measured by drilling method at Spanish institute. [21, 22]

7 Conclusions

In the first phase of measurement, the results have shown the usability of each applied methods. Comparison of residual stress measurement methods are very important not only for affecting the surface by Laser shock processing, but moreover for other finishing methods. Results can help with finding fields of application of measurement methods. The measured values by both methods of the surface tension were in the same range for the main area just below surface. But in the depths greater under surface the values of the each method were different. At present time the samples are measured by another method X-ray which can answer the reasons of these differences.

The most important compresive stresses were measured in the area, just under surface. Values of the compresive stress ranged from 300 to 600 MPa. The biggest value of the stress was measured identically on all samples and by both methods in depth from 30 to 50 μm. The transition from compressive to tensile stress occurs at greater depth than 0.7 mm below the surface. In comparison with another methods, the depth of reinforcement in general is relatively large. This depth may be up to one millimetre.

After completing LSP device at the Academy of Sciences of the Czech Republic the tests will start. One of the biggest advantages of this research is the experience due to cooperation with other institutes.

The laser shock peening is a progressive technique with many opportunities for applications with high requirements to surface characteristics. However this technology has been used just for special applications until present time. The next main objective is to find applications that are suitable for the LSP technique. Due to increasing average power and higher process speeds, the LSP will have much more possibilities in competition with other finishing technologies than ever before. [16, 24]

8 Acknowledgements

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