Application of laser shock peening

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Abstract

Laser Shock Peening (LSP), or hardening the material surface by laser shock wave is very modern and progressive technology, 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 technology finds practical use in the most demanding applications such as in the aerospace industry. For this reason, we are mapping all the surface properties after the laser *treatment for the better understanding technology possibilities. After that another suitable applications may be found. It is also important to determine appropriate parameters for different types of material and requirements then affect the result.*

Key words

Laser shock peening, surface integrity, residual stress

1. Introduction

Machining of workpieces meets high surface requirements. The process is finishing 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 the surface may be responsible for catastrophic defects.

A demand for finishing the surface with the inserted surface compressive stresses is required. Next to the conventional method, laser shock peening may be used. By this method, the required surface tensions may be achieved. Moreover, conventional methods mostly reach different results, however laser shock peening method has a great repeatability.

Devices that are using nowadays allow to use technology 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 are used. Medium components may be influenced in several hours. The laser sources, which are developing in Czech Republic to 2015, have reached such intensity that the spot size can increased up to several square centimeters while frequency is maintained, and the whole process can speed up. The higher production speed can significantly affect productivity and enable technology accessible to common applications for parts requiring high durability and resistance of the surface.

2. Laser shock peening

Laser Shock Peening (LSP), as a technique for surface processing, has been in existence for over 25 years. 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 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 optimizing this process are not common in literature. [5]

In the LSP high energy laser pulses of very short durations is impacted on a material surface. The sample surface is 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). HEL is related to the dynamic yield strength (σ_y^{dyn}) at high strain rates and the Poisson's ratio (ν). [4]

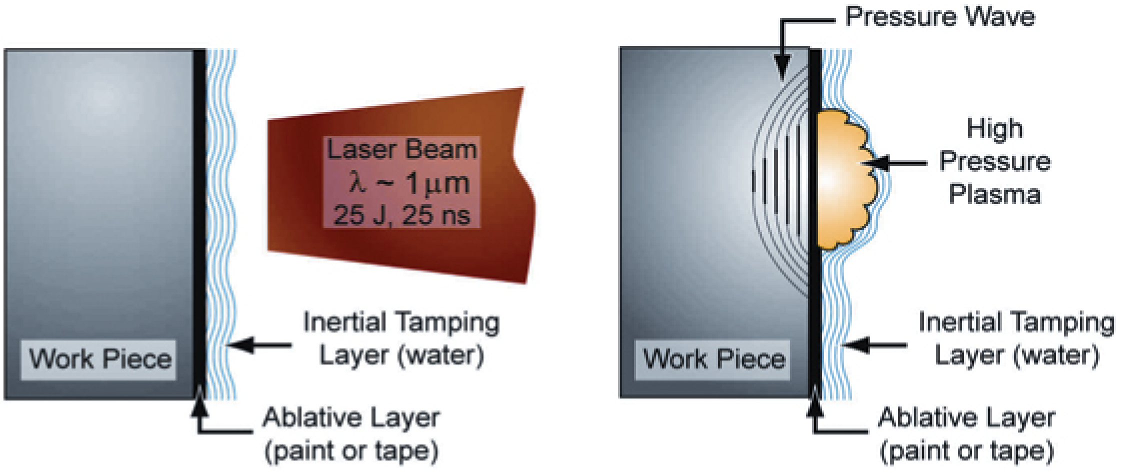

Fig. 1. *Principle of the LSP method*

Along with plastic deformation, this process results in a deep compressive residual stress layer extending from the surface to depths up to 1 mm, depend on the energy density and material. 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 [5].

Compared to other techniques like shot peening (SP), ball-burnishing (BB) and ultrasonic shot peening (USP), 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 has also 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, LSP decreases the fatigue crack growth rate [11]. Improvements in laser technology 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 [16], high-speed dislocations and modeling of shock front by dislocation movement [17] and constitutive modeling [18] of plastic deformation.

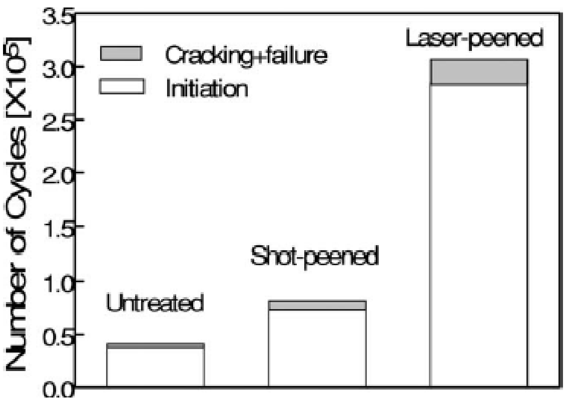

Fig. 2. *Comparison of initiation and later cracking stages at defined maximum stress for crack detection on 7075-T7351 aluminum alloy.* [3]

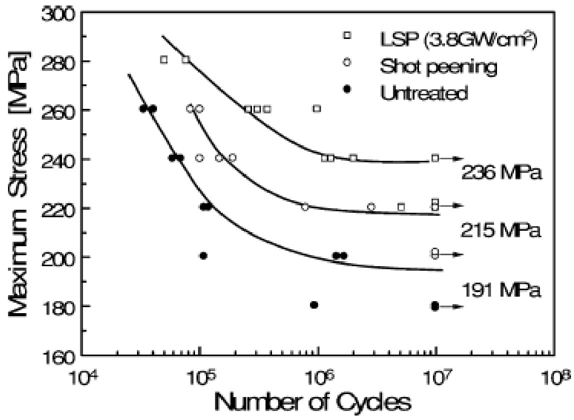

Fig. 3. *N curves for untreated, shock-peened and laser-peened 7075-T7351 alloy.* [3]

3. Surface characteristics and its measurement

For the file of the surface layer properties, the term "surface integrity" is used. This 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 technology 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 technological 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 and 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 in terms of surface roughness and its distribution. The service life of components is dependent micro-geometry and it is measured by profilometers, microscopes or roughness measurements. [3,9]

The surface harden is characterized as a high resistance crystal lattice of the metal mass against dislocation movements. All the phenomena that prevent movement of dislocations (grain boundaries, precipitates, other dislocations, etc.), increase the strength. Almost all technological 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.

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

One of the most important characteristics of surface integrity is the residual stress in the surface. By external forces or moments on the set, tensions are generated. These tensions are called an 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 measuring the residual stress. The principles are operating at mechanical deformation measurement methods. It always occurs that a gradual stress release with a simultaneous measurement of components deformations. The most common method is mechanical drilling and gradual removing. Other measurement methods include X-ray diffraction.

4. Cooperation with other institutes

Device for LSP in Czech Republic has not been finished yet. Therefore, a cooperation with the institutes that are 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 a head of the department Prof laser. J. L. Ocaña, are engaged in the application of laser peening. For several years, influencing of titanium alloys is conducted with valuable results. Residual stress level is measured by drilling technique. At our institute are samples affected on Spanish´s device, few of them are measured by their apparatus. Proposal cooperation is used by other measurement methods at CTU. Measurements of residual stresses by gradual removing method by acids and by x-ray diffraction are planned.

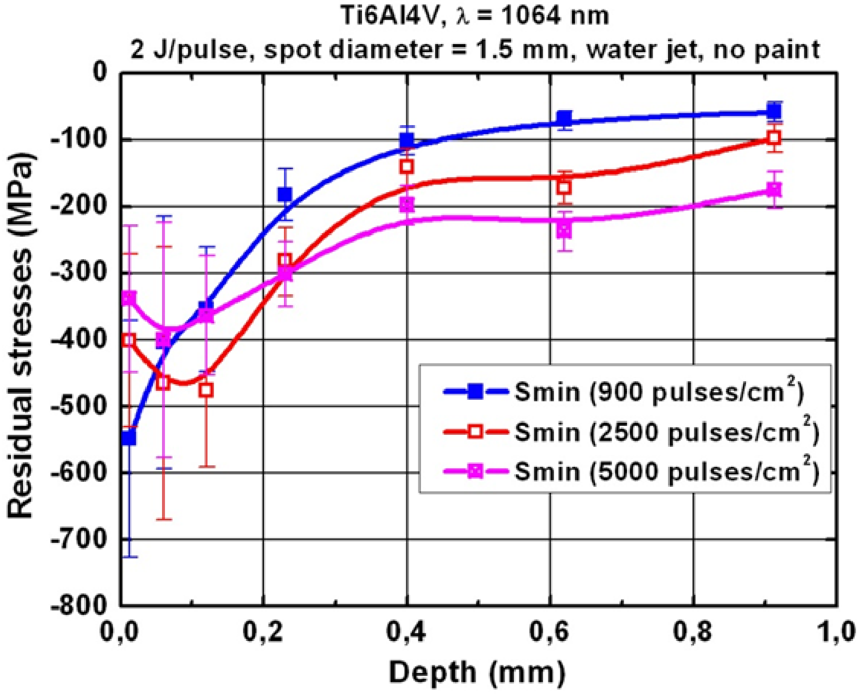

Fig. 4. *The course of residual stresses after laser shock peening processing applied on the Ti6Al4V alloy.*

At the University of Bologna, where is Dr. Alessandro Fortunato leader of the laser department, calculations and simulations of the LSP process are investigated. Therefore actual measurements can be compared with the theoretical calculation of the material properties after LSP.

The newly established cooperation with Indian Raja Ramanna Centre for Advanced Technology, through Dr. LM Kukreja, based on similar principles as the Spanish university. Nevertheless, the Indian device has different parameters and the technology is different and other details moreover. The Indian Institute results are measured by the X-ray diffraction method, for this reason, they are interested is compares with other methods of measurement.

5. Improvement

In order to make the laser more attractive for surface treatment processes, it is essential to reduce a 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. 5). These devices will have extremely large exploitation potential in various applications in new scientific and high-tech industrial technologies. It can be assumed that these developments will also foster industrial application of laser large area materials processing and especially of laser shock peening which requires lasers with a unique high power density and high repetition. [19, 20].

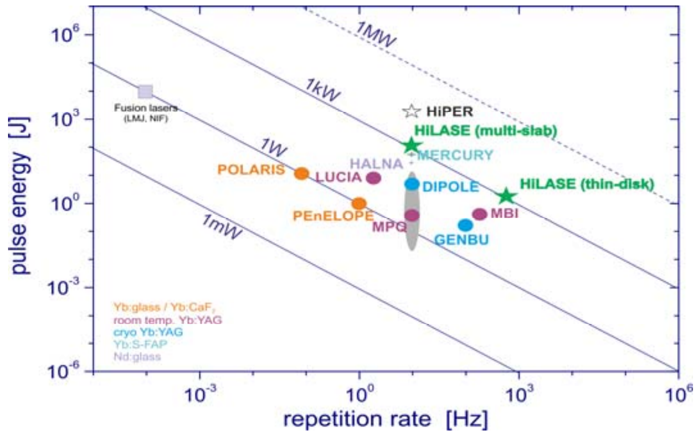

Fig. 5. *Comparison of existing and future high energy DPSSL facilities.*

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 the laser surface treatments. In this paper, we present the conceptual design of this laser system. Additionally, the beam delivery and further experimental stations, which will be established around the HiLASE lasers, are also discussed.

6. Conclusions

In the first phase of measurements, there is shown each of applied method. Comparison of residual stress measurement methods is very important, not only for influence by Laser shock peening, but moreover for other finishing method. Results can help with finding fields of application measurement methods.

After completion LSP device at Academy of Sciences of the Czech Republic, the first tests may begin. The biggest advantages are experience that we will have on the research begin due to cooperation with other institutes.

Laser shock peening is a progressive technology with many opportunities for applications with high requirements to surface characteristics. However this technology has been used just for special applications until present time.

Our next main objective is founding an applications what LSP is suitable for. Due to the increasing average power and higher process speeds technology the LSP will have much more possibilities in comparison with other finishing technologies than before.

Acknowledgements

This work was supported by the Grant Agency of the Czech Technical University in Prague, grant No. SGS13/188/OHK2/3T/12. And 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 DPSSLasers (CZ.1.07/2.3.00/20.0143) projects cofinanced from the European Regional Development Fund.

List of symbols

P	pressure	(GPa)
σ_y^{dyn}	dynamic yield strength	($N.mm^{-2}$)
X	number of cycles	(-)
σ_{max}	maximum stress	($N.mm^{-2}$)
ν	Poisson's ratio	(1)
γ	wavelength	(μm)
E	pulse energy	(J)
T	pulse duration	(ns)
n	spot size	(mm^2)
f	repetition rate	(Hz)

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