New possibilities for efficient laser surface treatment by diode-pumped kW-class lasers

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Abstract: The newly developed so call multy-slab laser at premise of the research centre HiLASE is already recognized as a potential new source for efficient laser surface treatments. Once the system is in full operation the pulses of up to 100J with pulse duration of 2-10 ns will be delivered with repetition rate of 10 Hz. In this paper the status of this new laser system is presented. Additionally the design of a new experimental station for laser surface treatments is also discussed. According to preliminary plans the station will be ready for first experiments in 2016.

INTRODUCTION

Metal fatigue is normally the limiting factor in long term safe usage of any machine or its part as well as in usage of constrictions such as bridges or tall buildings. Fatigue occurs as a result of applying cyclic load and unload. As the result in the material are develop cracks leading to complete damage. Interestingly each material perform differently under same cycling load. Many parameters influence the fatigue life such as impurities, how the metal parts were heat-treated, the operation condition (temperature for example) as well as the material's hardness and especially its surface conditions. The way to increase fatigue life is to perform surface enhancement processes which will increase the depth of the compressive residual stress. A laser as a tool in surface treatment of metals offers many advantages such as reproducibility, a high throughput and product quality. For the direct application, the laser surface treatment in comparison with traditional methods is also favour by its flexibility with respect to the processed geometries as well as for a simple integration into existing production lines.

Despite obvious improvement, the laser surface treatments are present only in limited number of cases in industry. One of the main reason for this limitation is directly connected with the high cost of laser sources, related to an investing as well as to a running cost. Recent trend in steady grown in power of semiconductor-laser bars accompanied by decreased in price per watt, open a gate for development of new class of diode-pumped solid-state lasers (DPSSLs). In addition, novel beam conditioning techniques which allowed to increase brightness and beam quality of diode-laser bars ensure also high pulse energy and very good beam quality of DPSSLs.

Relaying on these new trends, the HiLASE project (High average power pulsed LASErs) [1] team is developing several laser systems. In the Table 1 are given parameters of a fully diode-pumped 100 J cryogenically cooled Yb:YAG multislab laser system. This system according to its properties will be suitable source for many applications, among all of them the laser surface treatments was selected for further development.

The 100 J/10 Hz laser is under construction now and it will be commissioned by August 2015. Additionally, the development of compact thin-disk based kW-class laser systems for science and novel applications such as e.g. picosecond peening is also in the progress. There are three separate thin-disk beamlines under construction with different output parameters: beamline A (750 mJ, 1 kHz, 3 ps), beamline B (500 mJ, 1 kHz, 2 ps), and beamline C (5 mJ, 100 kHz, 1 ps). More details about thin disk lasers are presented in [2].

The laser state of the art and the HiLASE preparations of application laboratory for surface treatments

Following the concept already presented in our previous publications [3, 4, 5], the HiLase team in close cooperation with Central Laser Facility at STFC Rutherford Appleton Laboratory (CLF) is developing the laser system [6]. On the Fig 1. the laser setup in the CLF is shown . Recently stable operation at over 10J at 1030 nm after the firs amplifier was achieved [7].

Furthermore, long term shot-to-shot energy stability of 0.85% rms at 7 J output was demonstrated during extended operation over 48 hours [8] corresponding to almost 2 million shots. The first 100J pulses are expected during June 2015.

At mean time the HiLASE building was prepared (a clean room of ISO standard 7) to accommodate the laser system after commission in August 2015.

In the design of the HiLASE building, the laboratory for surface treatments is localized on one floor above the laser hall. As a consequence, the laser beam delivery system required to be development. For the laser beam delivering system, which should preserve laser pulse energy and beam quality, two concepts are under investigations. The first concept is based on usage of mirrors which are mounted in the system of tubes under vacuum. In the second concept, the beam delivery system, based on fibres, is under consideration. The second concept, although is already used for beam delivery of lasers with mJ energy level [9] is more challenging and calling for deep studies and investigations. Nevertheless, we should mention that the concept of fibre laser delivery is of great importance also for out of lab applications.

Beside the laser beam delivery system, the station for surface treatments is also under design. In order to be one step closer to

Table 1 Output parameters of 100 J/10 Hz laser.

Parameter	Specification
Pulse energy	>100 J
Av. Output power	>1 kW
Pulse length (FWHM)	2-10 ns
Pulse shape	Programmable(150 ps steps)
Repetition Rate	1 – 10 Hz
Output beam size	75 mm * 75 mm(SG order > 8)
RMS modulation	<1%
Wavefront quality	lambda/10
E-o efficiency	>12 %

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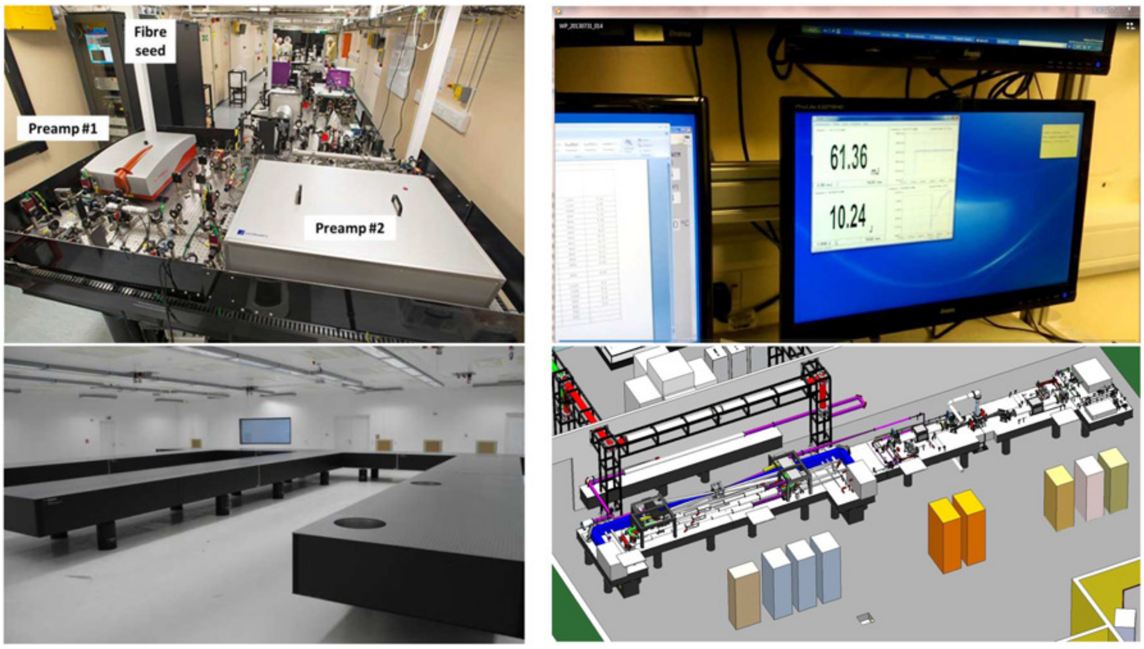

Fig. 1 *100J system under development in the in the CLF (up left) with recent demonstration of amplification to 10J (up right). The HiLASE clean room ISO 7 standard already prepared for housing laser systems (down left) with visualization of installation of 100 J laser system in HiLASE with laser beam delivery system.*

treatments required by industry, an industrial type of a position table equipped with a robot is already installed at the future station. In the proposed design the water jet and the laser processing head will be mounted on the robotic arm while the treated sample will be mount on the position table (Fig. 2). The special advantage of the proposed concept is acceptance and treatments in 3-D space of big samples which weight can go up to 300 kg. Additionally while on the table will be a water tank, there is an option to apply under water treatment. Important part of the station is a unique processing head which was designed especially for laser surface treatments. The main feature of the processing head, containing system of movable lenses, is the ability to set various laser beam sizes in the focus. Another advantage is integration of laser pointers allowing to show the exact position of focused laser beam. In order to efficiently protect the output lens of the focusing element, in the processing head will be integrated 4 nozzles system for constant air deflating. (Fig. 2)

Development of the characterization technique based on gradual electrolytic surface etching

In close cooperation with the Department of Machining, Process Planning and Metrology of Czech Technical University, the new characterization technique for measurement of residual stress is under development. Samples made of Ti6Al4V were treated by 1064 nm laser pulses of 2J by covering cm^2 with 2500 pulses. The surface of the sample was not covered with any additional material and water was jetted directly onto the surface.

The method of gradual removing is based on measurement of sample deflection during etching. The samples were measured, weighed and clamped into the vice of the measuring device. In the first step the surfaces of the samples were covered with protective waxes. In the second step the part of the surface on which the course residual stresses profiles were measured, was cleaned and degreased. After the described preparation the sample was immersed in an electrolyte bath. The electrolyte consists of hydrofluoric and hydrochloric acid diluted by ethanol in a ratio 1:10:100. To ensure a uniform removal speed the bath was temperature stabilized (in particular case temperature was between 25 and 30 degrees of Celsius) and stirred, the supply current was stabilized and together with voltage continuously monitored. In a particular case voltage in a range 10 to 15 V was applied. DC current, which can differ due to depletion of electrolyte, was kept constant during individual sample measurement.

Deformation of the sample ε emerging by removing layers was monitored. The time course of distortion ε (t) was converted to the dependence of deformation to the distance from the surface

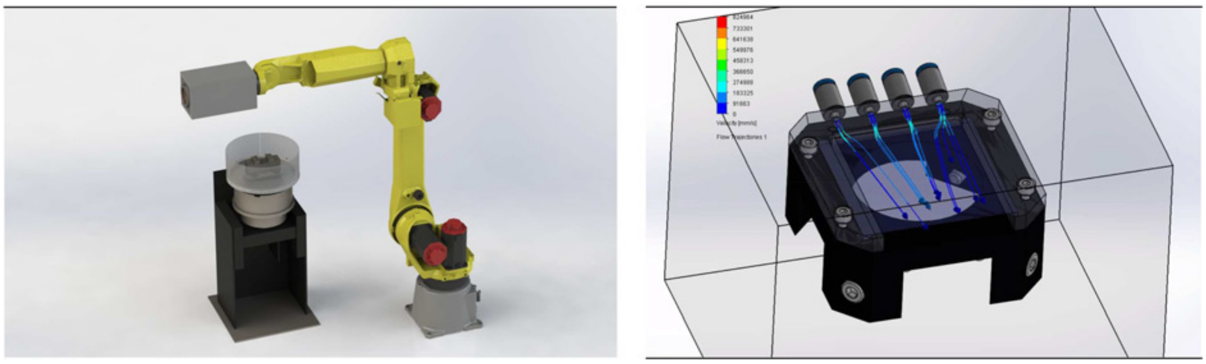

Fig. 2 *Simulation of future laser processing station (left) and nozzle system for efficient protection of the output focusing lens against splashing water.*

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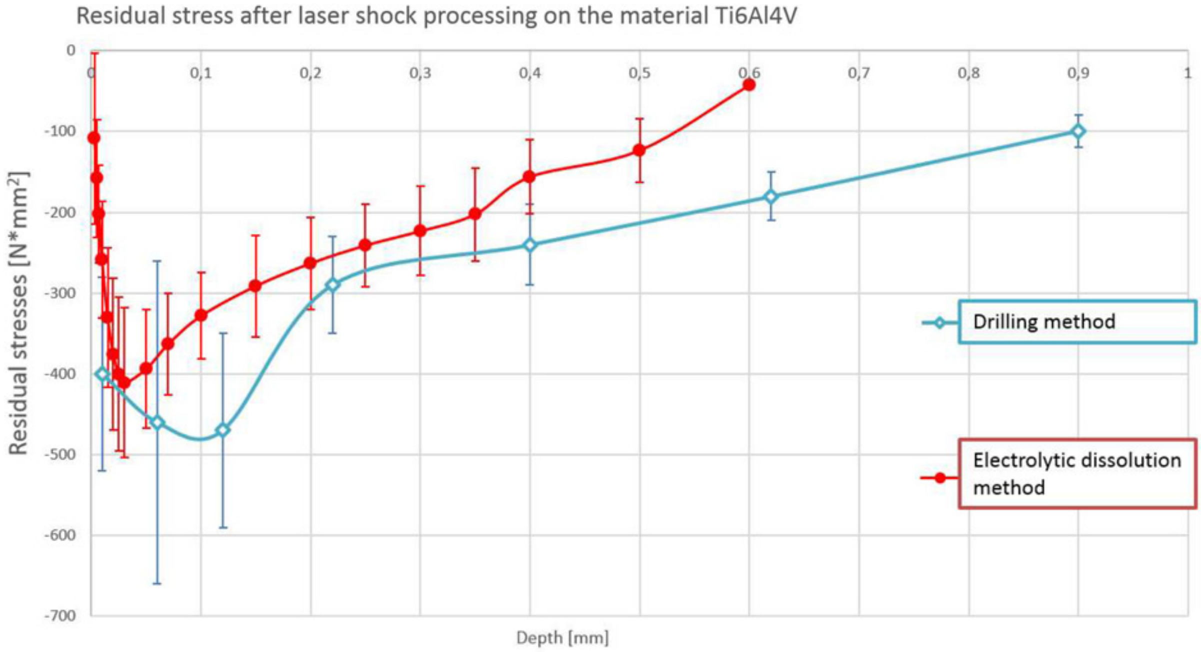

Fig. 3 *Residual stress measurement after laser shock processing on material Ti6Al4V*

$\varepsilon(z)$. On the basis of weight loss and linear removal rate it is possible to determine etched depth and to calculate residual stress profile. Calculation of residual stresses in the individual layers of sheet sample with rectangular cross section is based on the mechanics of materials. The basis of calculation is the assumption that in the incremental layer of thickness ΔH the residual stress σ = constant. By removing layers ΔH at the flat sample the residual stress causes the same deflection as if it acted external force F. [10]

For all treated samples was found significantly compressed character of residual stress by etching measurement method. All samples show a pressure peak (from-325 to -514 MPa) at a depth of 0.03 to 0.04 mm below the surface (Fig. 3). As it is expected compressive residual stress is decreasing 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. shot peening). In terms 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 surface and then deep below surface.

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 designing and construction. In this paper, the summary of state of the art of both laser development and laboratory construction is given. Our preliminary results on residual stress measurement by the technique based on gradual electrolytic surface etching is also presented. Once is filly operation, the HiLASE application laboratory for surface treatments will be available for scientific community or for industrial applications.

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