

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

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## Abstract

The aim of the HiLASE project is to serve as a platform for development of new lasers based on thin-disk laser amplifiers and cryogenically cooled multi-slab laser amplifiers as well as to build state of the art application laboratory. In this paper, applications related to surface treatments will be highlighted. Once is fully equipped the application laboratory will be open for any other advance investigations selected by scientific community or by industrial applications. Efficient application of lasers in the surface treatment of metals requires lasers with high power density and repetition rate over a big spot size [1]. 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, developed as a part of the HiLASE project, is expected to start a new era in the laser surface treatments. In this paper, we will shortly present the conceptual design of this laser system. Additionally, the beam delivery and a further experimental station for material processing, established around this laser, are also discussed. Beside equipment, the surface treatments also required knowledge related to establishment of laboratory experimental setup and procedures for the process quality characterization. While laser system for surface treatment in the Czech Republic is not finished yet, the cooperation with the institutes which are involved in this technology was established. Our strongest cooperation is with Centro Láser de la Universidad Politécnica de Madrid and Alma Mater University of Bologna. Regarding the process characterization close link is established with the Czech Technical University in Prague [2].

## 1 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. 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.

The HiLASE project (High average power pulsed LASERs) [1] following this trend developing a fully diode-pumped 100 J cryogenically cooled Yb:YAG multislab laser system with pulse duration of 2-10 ns

and 10 Hz repetition rate. According to the laser predefined output parameters (see Table 1) this laser will be an ideal tool for laser surface treatments of very large areas. The 100 J / 10 Hz laser is now under construction and 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 are 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].

**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	51 mm * 51 mm (SG order > 8)
RMS modulation	<1%
Wavefront quality	$\lambda/10$
E-o efficiency	>12 %

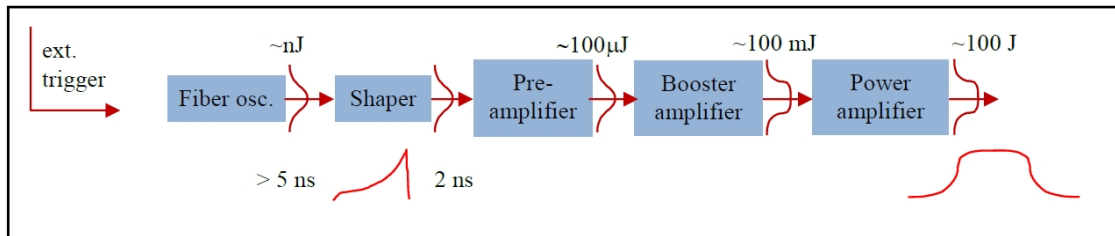
Once installed in the HiLASE center, DPSSL systems will be available to external users for testing and prototyping of various laser technologies.

## 2 The conceptual design of the HiLASE multi-slab laser

The conceptual design of a 100 J class multi-slab laser system based on Yb<sup>3+</sup>:YAG. Yb<sup>3+</sup> was chosen because of the long lifetime of its upper laser level (1 ms), simple energy level structure, and low Stokes defect (< 9 %). However, the Yb<sup>3+</sup>:YAG is a quasi-three level system which requires high pump intensity for laser operation thus increasing the amount and cost of the pumping diodes. By cooling the crystal to low temperatures, the energy scheme changes to four levels, thus decreasing the threshold intensity by several orders of magnitude [3,4]. Cooling the slabs down to low temperatures around 160 K has the additional advantage of reducing the mechanical stresses and the thermally-induced wavefront distortions [5]. The HiLASE laser system consists of ~100 mJ front-end that is followed by 4-pass power amplifier consisting of two identical multi-slab laser heads [6].

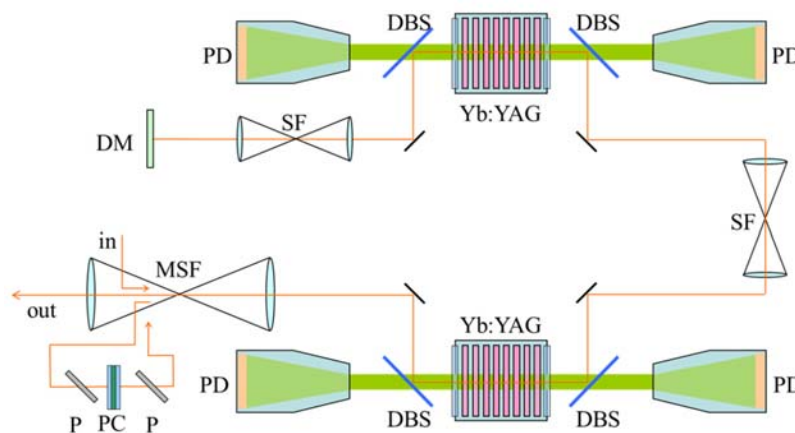
The laser system starts with an externally triggered Yb<sup>3+</sup>:glass fiber oscillator generating narrowband ns pulses with central wavelength of 1030 nm at high repetition rate of several MHz. The precise triggering, pulse picking, and arbitrary pulse shaping is achieved in fiber based pulse shaper, where pulses with arbitrary shape and duration of 2 ns are created. The fiber oscillator was chosen because of its robustness and pulse shaping capability [7]. Shaped pulses with nJ energy are further amplified [8] to ~100 μJ energy required by the booster amplifier [9] that will further amplify the pulse to 100 mJ. The booster amplifiers

will be pumped by flat-top beam with square aperture, which will create square flat-top beam that will be then injected into the power amplifier with square aperture of the active medium. The detailed layout is shown in Fig. 1.



**Fig. 1** Schematic layout of 100 J laser system. The system consists of a fiber oscillator, a pulse shaper, pre-amplifier, a multi-pass booster amplifier, and a power amplifier.

The conceptual design consists of a single power amplifier with two identical 50 J amplifier heads. Each amplifier head contains 8 slabs with 4 doping levels of  $\text{Yb}^{3+}$  (0.4 at.%, 0.55 at.%, 0.86 at.%, and 1.5 at.%). The active volume of each slab is around 55 mm x 55 mm x 7 mm, and the super-Gaussian pump beam is 45 mm x 45 mm. The  $\text{Yb}^{3+}:\text{YAG}$  is clad with  $\text{Cr}^{4+}:\text{YAG}$  absorber (concentration of  $\text{Cr}^{4+}$  ions is 0.46 at.%) that limits the amplified spontaneous emission. Due to lack of large aperture Pockels cells capable of handling 1 kW of average power, having a small thickness, high damage threshold and operating at 10 Hz, the input pulse is injected into and ejected out of the power amplifier by the multi-pass spatial filter (injection and ejection plano-convex lens focal length is 1 m, left and right plano-convex lens focal length is 2 m, pinhole diameter 1.75 mm for short lenses and 3.5 mm for long lenses, beam off-axis deviation 0.3 in horizontal and vertical plane). The amplifier is fully relay imaged, i.e. the laser beam is relay imaged into the appropriate amplifier head after each pass. The spatial filter between amplifier heads consist of plano-convex lenses with focal length of 2.5 m and pinhole diameter of 4.37 mm. The spatial filter between the second amplifier head and the deformable mirror uses plano-convex lenses with focal length of 1.5 m and pinhole diameter of 2.6 mm. After second pass the beam is deviated into the U-turn reverser where a Pockels cell (PC) is placed. The path of the beam in the PC is assumed to be 10 mm. The purpose of this PC is to limit the amplified spontaneous emission and the parasitic oscillations. After the 4<sup>th</sup> pass, the energy of the pulse is increased from 165 mJ to ~ 110 J. The detailed optical layout is in Fig.2.



**Fig. 2** Optical layout of 100 J laser system with two 50 J amplifier heads. The layout shows the amplifier heads with laser slabs (Yb:YAG), the dichroic beam splitters (DBS), the pumping modules (PD), the spatial filters (SF), the multipass spatial filter (MFS), the polarizers (P), the Pockels cells (PC), and the deformable mirror (DM).

An alternative layout of the amplifier is currently under investigation, and it consists of a cryogenically-cooled 10 J pre-amplifier followed by a 100 J power amplifier. This design offers lower risk during the construction of the system because the codes can be experimentally benchmarked on the 10 J preamplifier before construction of 100 J amplifier. However, the construction cost for such system is higher.

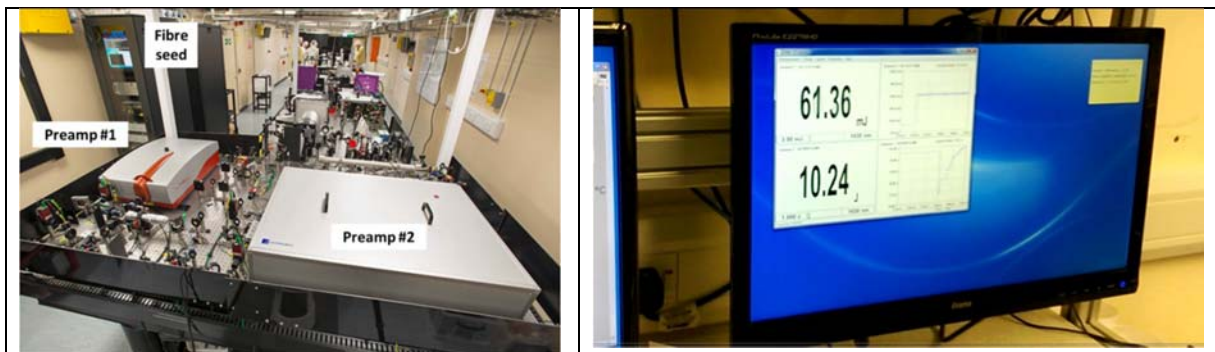
### 3 The laser state of the art and the HiLASE preparations of application laboratory for surface treatments.

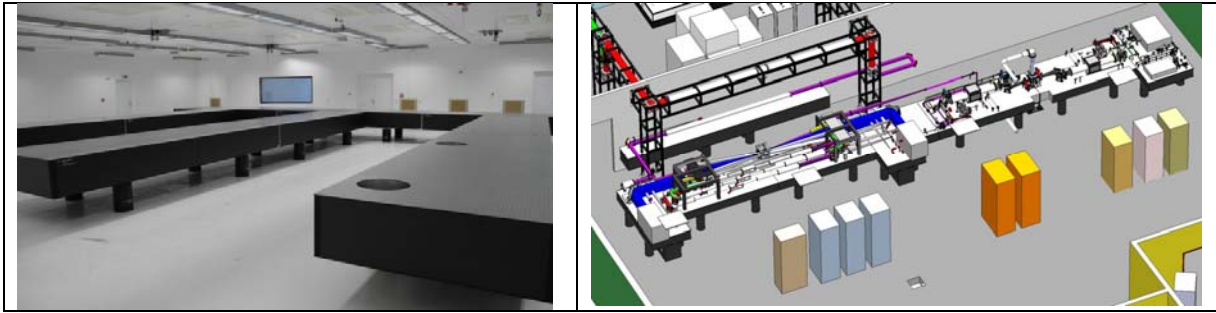
Following the concept proposed in the previous paragraph, the HiLase team in close cooperation with Central Laser Facility at STFC Rutherford Appleton Laboratory (CLF) is developing the laser system [10]. On the Fig 3. the laser setup in the CLF is shown . Recently stable operation at over 10J at 1030 nm after the first amplifier was achieved [11].

Furthermore, long term shot-to-shot energy stability of 0.85% rms at 7 J output was demonstrated during extended operation over 48 hours [12.] corresponding to almost 2 million shots.

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.

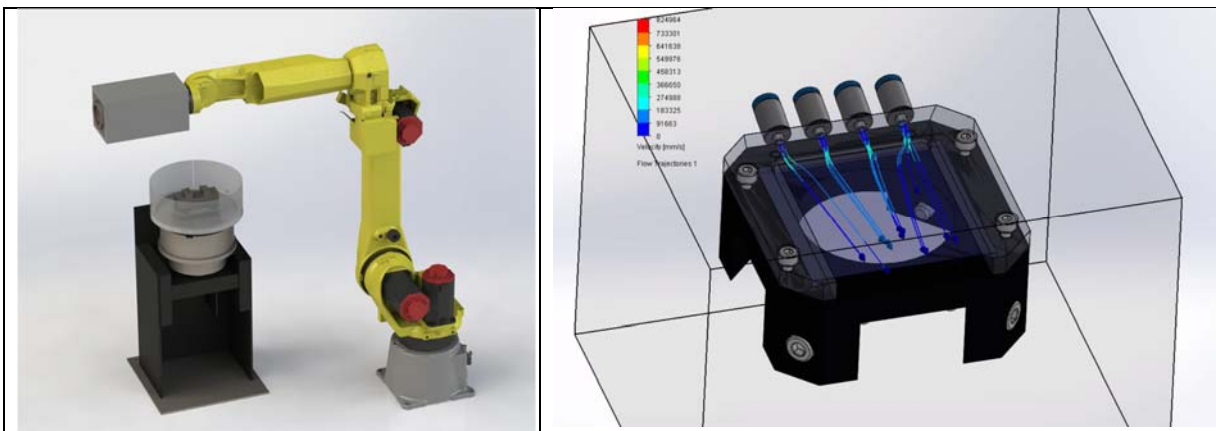
In the design of the HiLASE building, the laboratory for surface treatments is localized on one floor above the laser hall. As a consequence, the laser beam delivery system required to be development. For the laser beam delivering system, which should preserve laser pulse energy and beam quality, two concepts are under investigations. The first concept is based on usage of mirrors which are mounted in the system of tubes which can be further evacuated if the energy losses in the air are so high. In the second concept, the beam delivery system, based on fibres, is under consideration. The second concept, although is already used for lasers with mJ energy level [13] is more challenging and calling for deep studies and investigations. Nevertheless, we should mentioned that the concept of fibre laser development is of great importance also for out of lab applications.





**Fig. 3** 100J system under development in the in the CLF (up left) with recent demonstration of amplification to 10J before the main 100J amplifier (up right). The HiLASE clean room ISO 7 standard already prepared for housing the 100J system (down left) with drawing of future laser beam delivery system.

Beside the laser beam delivery system, the station for surface treatments is also under design. In order to be one step closer to treatments required by industry, the station is equipped with industrial type of a position table as well as with a robot, allowing testing of applications of these technologies in 3-D space. Beside applications related to laser surface treatments, this experimental station will be also, with minimal changes, suitable for other laser applications such as welding, cleaning, drilling and etc. The special advantage of the proposed concept is acceptance of big samples which weight can go up to 300 kg. 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 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. 4)



**Fig. 4** Simulation of future laser processing station (left) and nozzle system for efficient protection of the output focusing lens against splashing water.

#### 4 Development of the characterization technique based on gradual electrolytic surface etching

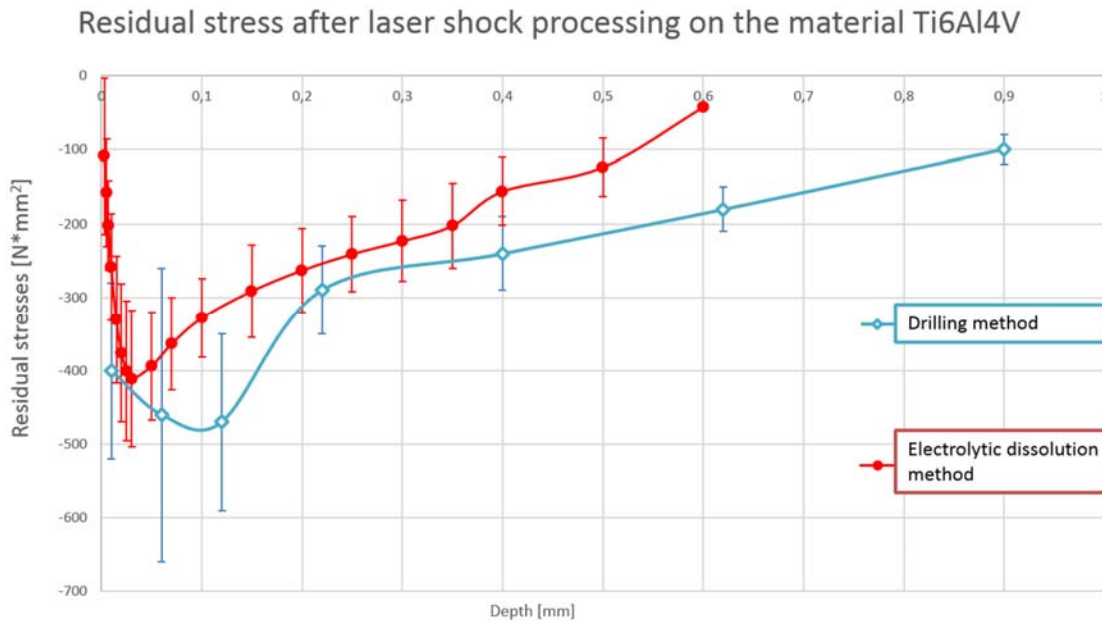
In close cooperation with the Department of Machining, Process Planning and Metrology of Czech Technical University, the new characterization technique for measurement of residual stress is under development. Samples made of Ti6Al4V were treated by 1064 nm laser pulses of 2J by covering  $\text{cm}^2$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

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 from 0.03 to 0.04 mm below the surface. 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 shotpeening). 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.

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. 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 profiles were measured, was cleaned and degreased. The prepared sample was immersed in the bath and after the temperature compensation of the sample and it was electrochemically dissolved. 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 tempered and stirred, the supply current was stabilized and together with voltage continuously monitored. The DC power supply with voltage stabilization was used and current was continuously monitored. In a particular case voltage in a range 10 to 15 V was applied. Provided effective tempering and stirring, DC current is constant during measuring individual sample. DC current value can differ due to depletion of electrolyte. It is appropriate to maintain temperature between 25 and 30 degrees of Celsius.

Deformation of the sample  $\varepsilon$  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  $\varepsilon(z)$ . On the basis of weight loss and linear removal rate it is possible to determine reached depth of etching and to calculate residual stress profile. 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 incremental layer of thickness  $\Delta H$  is the residual stress  $\sigma = \text{constant}$ . By removing layers  $\Delta H$  at the flat sample the residual stress causes the same deflection as if it acted external force  $F$ . [14]



**Fig. 5** Residual stress after laser shock processing on the material Ti6Al4V

## 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 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 fully operation, the HiLase application laboratory for surface treatments will be open for any advance investigations selected by scientific community or by industrial application.

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## List of symbols

$P$	pressure	(GPa)
$\sigma_{y^{dyn}}$	dynamic yield strength	(N.mm <sup>-2</sup> )
$X$	number of cycles	(-)
$\sigma_{max}$	maximum stress	(N.mm <sup>-2</sup> )
$\nu$	Poisson's ratio	(1)
$\gamma$	wavelength	( $\mu$ m)
$E$	pulse energy	(J)
$T$	pulse duration	(ns)
$n$	spot size	(mm <sup>2</sup> )
$f$	repetition rate	(Hz)

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