Experimental investigations on ultrashort laser ablation for micro and nanomachining of materials

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Abstract. With the advantage of ultrashort pulse width and ultrahigh peak power, subpicosecond lasers can provide extremely precise machining, and therefore has been widely applied in micro and nanoscale manufacturing. We present the results of the experimental parametric study on efficiency, accuracy and quality of subpicosecond laser micromachining of materials, that have a potential for application in innovative devices and technologies. The laser micromachining process was performed with a Yb:KYW subpicosecond laser and a Ti:S femtosecond laser. The study contains a comparison between the two methods, and results analysis using advanced metrology techniques, such as 3D microscopy.

1. Introduction

The so-called ultrafast or ultrashort pulse lasers provide unique material processing possibilities. It is due to pulse duration, which is shorter, than the conduction time of the machined material. That offers an opportunity for a cold ablation, which usually appears with pulses shorter than 10 ps [1]. Ultrashort pulse durations became available since the development of mode-locked lasers and the chirped pulse amplification (CPA) technique [2,3]. Pulse energies in the range of millijoules became easily obtained via CPA. Since then, a numerous groups studied the subject of ultrafast ablation processes analytically and numerically. Considering the energy transfer from electrons to the lattice occurs via carrier-phonon scattering on a timescale estimated from several hundred femtoseconds to a few picoseconds, the physics of the ablation process in a subpicosecond regime differs from the ablation caused by longer laser pulses [4].

According to Liu et al. [5], who first studied the ablation dynamics with pulse width varying from 10 ns to 100 fs, the ablation threshold is lowering with a decreasing pulse duration. The low ablation threshold with ultrashort lasers translates into near zero heat affected zone (HAZ), minimal burring and debris, very high accuracy and the ability to produce small, precise features in target materials. However, it must be carefully considered, if the micromachining efficiency and quality always improves with the shortening of the laser pulse. Femtosecond ($10^{15}$) pulse lasers targeting development of new technology, appeared in research labs years ago. The ability to process almost any material with almost no side effects and no post processing tools, enabled innovation in the area of micro and nanotechnology. Still, these complex and difficult to calibrate systems, are considered unstable and not reliable enough for fully commercial use. The efficiency of the micromachining process depends, on the one hand, on the laser radiation parameters, such as pulse duration, wavelength, pulse energy, repetition rate or irradiation time, and on the other hand on the target material properties.

In this article, we consider two categories of ultrafast lasers:
• A lab-designed subpicosecond Yb:KYW laser (L1), that emits 650 fs pulses.
• A commercial-type femtosecond Ti:S laser (L2), that emits 35 fs pulses.

We have undertaken the problem of subpicosecond laser interactions with matter, under variable laser pulse parameters and considering various materials (metals and plastics). In laser irradiated material samples, a various features, such as crater profiles, ablated volume, local changes in crystallography and chemistry, surface modifications are related to various dynamical mechanisms and the ablation threshold and ablation rates can be readily obtained from the analysis of the final state of material [6]. Therefore, a detailed analysis of the irradiated materials were performed, using various microscopy techniques.

2. Experimental setup
The laser micromachining of materials was carried out using two abovementioned lasers. One, available at the Centre for plasma and laser engineering, at the Institute of Fluid-Flow Machinery PAS (Poland) and another, available at the Laboratory of metal vapor lasers at the Institute of Solid State Physics BAS (Bulgaria). Figure 1 presents the micromachining experimental setups for both lasers.

![Figure 1. The Experimental setup for L1 (left) and L2 (right) ultrafast laser micromachining.](image)

The subpicosecond Yb:KYW laser offers 100-400 kHz repetition rates and power level up to 15 W, as long as the possibility of generating three different wavelengths of UV, VIS, IR range, of which 1030 nm and 345 nm were used as stable for the the micromachining processes. The femtosecond Ti:S laser provides a 1 kHz beam with a tunable wavelength from 266 nm to 800 nm. Three different wavelengths from these range were used. The summary of micromachining parameters is presented in Table 1.

From the laser output, the beam is passing through the optical collimator and focusing system, containing of mirrors and lenses adequate for the applied laser wavelength. The concept of micromachining implies, that the output laser beam, after passing through the optical collimator, will be directed into the positioning system. To move and focus the UV laser beam on the surface of the workpiece, an optical scanner with focusing lens was used for L1 setup. The scanner is equipped with two galvanometric mirrors that deflect the laser beam, making it possible to move according to a given pattern in the XY plane. The samples are put on the z-axis adjustable table, directly beneath the scanning area, on the exact level of the laser beam focus [6].

|                      | Yb:KYW (L1)       | Ti:S (L2)                        |
|----------------------|-------------------|----------------------------------|
| Wavelength           | 1030/345 nm       | 266/532/800 nm                   |
| Repetition rate      | 100 – 400 kHz     | 1 kHz                            |
| Output power         | < 15 W            | < 15 W                           |
| Pulse width          | 650 fs            | 35 fs                            |
| Scanning speed       | 0,7 mm/s – 13 mm/s| 7 mm/s – 100 mm/s                 |

For other wavelengths, a galvo-scanner could not be applied, due to optical elements limitations. Instead, two high-precision linear motors were provided to move the sample in the XY plane and a separate focusing optics, dedicated for the given wavelength range, is used. The L2 setup is using the
Aerotech planar table for the same purpose. Varying the laser pulse energy during the experiment is realized differently in each setup. In the L1 case, the laser output power is dependent on the current set to the amplifier. In the L2 setup, a variable ND filter is used to adjust the pulse energy.

3. Results
The section presents visual and numerical results of the performed experiments. Using L1 and L2 lasers working in a configuration as in Figure 1, micromachining of materials was performed with variable wavelength, repetition rate, pulse energy and scanning velocity. During the process, in each case the target material was scribed with approx. 1 cm long, straight line. Stainless steel, aluminum, copper, nickel, zinc, brass, nylon and polypropylene were used as target materials. The Nikon Eclipse microscope was used to measure a post-machining crater dimension and HAZ range on the surface of each sample. A Hirox KH8700 3D microscope was applied to visually judge the surface of the irradiated material and examine a cross-section profile, i.e. measure the depth of the crater.

![Figure 2. Numerical results of L1 and L2 laser micromachining of materials with variable output power.](image)

The results revealed very good efficiency and accuracy of the micromachining process. Shortening the duration of the laser pulse to the range of tens of femtoseconds results in near zero HAZ, which translates into the high quality of the cut and no unwanted effects in the surrounding area (i.e. cracks, deformations, debris). However, the heat transfer in the subpicosecond (hundreds of fs) range is also very insignificant and does not affect the crater itself, resulting in a clean and precise cut.

The crater diameter is increasing with the increase of laser fluence and a decrease of pulse repetition rate. Decreasing of the repetition rate, however, will affect the depth of the crater, whereas changing the output power with a repetition rate remaining constant, makes much smaller difference in the crater depth. Both lasers offer wavelength choices of IR, VIS, UV. Certain wavelengths work best for specific materials. One can select the wavelength based on a particular feature size required, the smallest focus spot size achievable is directly related to the wavelength. The use and argument for different wavelengths matched to different materials is less obvious for shorter pulses. The normal material
absorption dependency on wavelength would no longer apply, due to the multiphoton absorption domination.

Figure 3. 3D analysis results of L1 laser micromaching of aluminum with variable output power.

Figure 4. Numerical results of L1 laser micromaching of materials with variable pulse repetition rate.

Figure 5. 3D analysis results of L1 laser micromaching of aluminum with variable repetition rate.
Figure 6. The Experimental setup for L1 (left) and L2 (right) ultrafast laser micromachining.

Figure 7. Numerical results of L1 and L2 laser micromachining of materials with variable velocity.

The crater diameter increases with decreasing scanning speed, but the depth of the crater is not significantly affected. Higher micromachining velocity means less time for laser-matter interaction and heat transfer. An optimal velocity must be determined for each material, depending on its parameters. It is especially visible with copper, which has a specific heat of higher value than other materials examined. For shorter pulses, faster micromachining rates were applied. The material samples seem to be less affected by scanning speed in the femtosecond regime.
4. Conclusions

Longer (subpicosecond) laser pulses gave more predictable results. The laser fluence – crater size characteristics are more coherent in this case. However, the 650 fs micromachining reflects attributes of both, femtosecond and picosecond regime.

The experimental and theoretical investigations so far, lead to some improvement in the physical understanding of the ultrafast laser ablation phenomena. The dynamics of the ablation process can be roughly divided into several stages: energy absorption, energy transfer to the lattice and subsequent material removal. The first step of the ablation process is deposition of energy into the material. The primary absorption mechanism involves excitation of electrons from the valance to the conduction band and free carrier absorption. The interband excitation can occur through multiphoton and avalanche ionization, with high enough laser intensity. Nonlinear absorption is very important in femtosecond interaction due to the high intensity of the incoming radiation [7].

During the laser-mater interaction all of the processes occur simultaneously and it is difficult to estimate the contribution of each one. Due to the complexity of the process, it is also difficult to calculate or measure the effective penetration depth of the radiation. Therefore, the pulses of subpicosecond regime should be considered “good enough” for micro and nanomachining of materials.

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