Investigation on laser micro ablation of metals using ns-multi-pulses

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Abstract. Laser ablation with pulse bursts was studied to increase the ablation rate of steel. Pulse bursts consisting of different numbers of pulses between one and three were used. The microablation with pulses from a multi-pulse Nd:YAG laser with a pulse duration between 20 ns and 60 ns, interpulse separations in the range of 0.1 to 80 µs and burst energies of up to 2 mJ was studied. The process was characterized in terms of ablation rate, ablation geometry, dynamic of plasma expansion and plasma parameters.

1. Introduction
The use of laser pulse bursts instead of single pulses for laser ablation has been investigated by a number of researchers mainly for faster drilling of different materials with ultra short pulses [1-3] but also with ns to ms pulses [4-6]. These investigations have been carried out either to drill deep holes through the sample as fast as possible or to investigate single shot ablation. In our work pulse bursts were used for surface ablation of samples of the steel grades 1.4301 (Stainless Steel 304) and C75.

For the analysis of the ablation process, Laser-Induced Breakdown Spectroscopy (LIBS) was used for chemical analysis of the ablated material and diagnostics of the plasma parameters, electron temperature and electron density [4,7-9].

2. Experimental setup
The experiments were carried out with a flash-lamp pumped Nd:YAG laser generating several pulses during one flash-lamp discharge (called bursts). The pulse duration was 20 ns in single pulse operation and up to 50 to 60 ns for multi-pulse mode at a repetition rate of 10 Hz. The interpulse separation in a burst can be adjusted between 0.1 µs and 100 µs while the number of pulses per burst is varied between 1 and 3. In all experiments the focus diameter was detected to 55 µm.

For the experiments the burst energy, defined by the sum of the pulse energies within one burst, was kept constant. Within one burst the energy is distributed equally among the pulses.

For the observation of the plasma dynamics the emission has been detected by an ICCD camera (4Picos, Stanford Computer Optics) with a minimal exposure time of 0.2 ns was used. The plasma emission was imaged by high-speed photography using a 10x objective and CCD chip (resolution 26 µm/px).

The spectroscopic signal was measured with an echelle spectrometer (LLA ESA 3000) having a spectral resolution of about 0.01 nm and a minimal exposure time of 40 ns. The plasma was imaged with a concave mirror into an optical fiber which is connected to the spectrometer. The ablation depth,
ablation width and cross section of the ablated geometry (u- or v-shaped) were measured with optical microscopy or white-light interferometry.

3. Results and Discussion

For the experiments the laser radiation was focused on the surface of the bulk sample which was moved with constant velocity to generate ablation grooves. The laser energy irradiated per millimeter translation of the sample was kept constant. The overall length of the grooves amounts to 3 to 4 mm. The geometry of the cross section of the grooves was determined at the half length of the grooves to exclude faults from effects at the beginning and end of the ablated groove. The ablation caused by a burst with 2 mJ burst energy (double and triple pulse burst, see figure 1) is compared to the ablation caused by a series of single pulses having the same pulse energy as one pulse of the burst and applied as often as pulses were in the burst (for example: one triple pulse burst of about 2 mJ – corresponding to 3 pulses within that burst with 0.67 mJ each - compared to the ablation caused by 3 scans using single pulses with 0.67 mJ each). Using bursts with double or triple pulses results in significantly greater ablation depths compared to one single pulse with the same energy as the pulse burst. A variation of the interpulse separation $\Delta t$ between the pulses of a double pulse burst shows that reducing $\Delta t$ results in greater cross sections and increased ablation rates as seen in figure 2.

A larger amount of melt ejection is observed when using an increasing number of pulses within the pulse burst.

![Figure 1: Ablation depth and cross section in steel 1.4301 for single, double and triple pulse bursts compared to ablation of one, two, three and four pulses with a total energy of 2 mJ. (SP: single Pulse, MP: multi pulse).](image1)

![Figure 2: Depth, width and cross section for ablation in steel 1.4301 with double pulse bursts as a function of the interpulse separation. The burst energy amounts to 2 mJ.](image2)
From the spectral observation of the plasma emission, the electron densities were determined for different pulse bursts and compared to single pulses using the Stark broadened Fe I line at 492.05 nm [10]. For time after irradiation $t_{\text{delay}}$ up to 800 ns the electron density was significantly greater for single pulse ablation than for double and triple pulse bursts as seen in figure 3.

![Figure 3: Electron density of the laser-induced plasma as a function of time after irradiation $t_{\text{delay}}$ of the last pulse of a burst for the ablation of C75 steel with 2 mJ burst energy. The interpulse separation is $\Delta t_1 = 1 \mu$s for double pulses and $\Delta t_1 = 1.3 \mu$s, $\Delta t_2 = 1 \mu$s for triple pulses. LTE = local thermodynamic equilibrium.](image)

The electron temperature for the same pulse bursts is shown in figure 4 (determined from a Boltzmann plot using Fe atomic lines) and figure 5 (determined from a Boltzmann plot using Fe ionic lines). While the electron temperature determined from atomic lines is greater for time after irradiation $t_{\text{delay}}$ up to 800 ns when having more pulses per burst, the electron temperature determined from ionic lines is always smaller for pulse bursts than for single pulses at the same delay time.

![Figure 4: Electron temperature determined from Fe atomic lines as a function of time after irradiation $t_{\text{delay}}$ for C75 steel with 2 mJ burst energy. The interpulse separation is $\Delta t_1 = 1 \mu$s for double pulses and $\Delta t_1 = 1.3 \mu$s, $\Delta t_2 = 1 \mu$s for triple pulses.](image)
Observing the plasma dynamics by high-speed photography (figure 6) shows the following pulses interacts mainly with the sample surface and not with the plasma. The plasma produced by ablation with single pulses cools down close to the sample surface while the plasma of multi-pulses lifts from the surface. Also the plasma generated by ablation with multi-pulses has a larger volume and the emission can be detected longer than generated by single pulses. The evidence is seen in figure 6 for single, double and triple pulses with a burst energy of 2 mJ and interpulse separations of $\Delta t_1 = \Delta t_2 = 2 \mu s$. The inverse-Abel function of the plasma expansion is shown in figure 6 for 1, 5, 10 and 15 $\mu$s after the last pulse of the burst. The intensity of the emission - number in the upper right corner of the pictures - is scaled relative to the summoned plasma emission for single pulses at 10 $\mu$s.

Based on the experiments carried out and the observations of the plasma expansion and electron density measurements the following qualitative ablation model – shown schematically in figure 7 – can be described. The pulses of a burst interact only partially with the plasma formed by ablation of the preceding pulses and interact with the heated or even molten (for small interpulse separations) surface. With the following laser pulses the removal of material by vaporization and melt ejection is increased because of a locally reduced gas density in the interaction region caused by the preceding pulses of a burst and the reduced energy need for heating and melting of the surface (ablated mass for multi-pulse ablation is greater than for single pulse ablation: $m_{mp} \gg m_{sp}$ as per figure 1). The vaporized material expands faster from the surface indicated by the faster expansion of the plasmas generated by subsequent pulses of a burst compared to the first one ($V_{mp} \gg V_{sp}$). Plasma cooling at the surface is therefore significantly reduced compared to single pulse ablation ($\Delta r_{sp} < 0$, $\Delta r_{mp} > 0$; $\Delta r$ is the change of the distance surface-to-plasma center as per figure 6).

The increased ablation rate can be attributed to three effects. First, the dominant interaction was detected between the laser pulse and surface, with nearly no interaction with the plasma of the preceding pulses of a burst. Second, vapour ejection increases because of a locally reduced particle density close to the interaction volume left by the effect of the preceding pulses of a burst. Third, an increased melt ejection occurs due to the preheated surface.
Figure 6: Plasma emission for single, double and triple pulses shown at discrete times after the last pulse.

Figure 7: Schematic description of plasma expansion for the ablation process with single and multi-pulse ablation.

4. Conclusions
Laser ablation with multi-pulses instead of single pulses increases the ablated volume. The plasma generated by single pulse ablation cools down on the sample surface while the plasma generated by multi-pulse ablation can lift off the sample surface. Using single pulses the plasma density is larger within the first few hundred ns after irradiation of the last pulse. During the same time the electron temperature determined from atomic lines is smaller for ablation with single pulses than for ablation with multi-pulses while the electron temperature determined from ion lines is always greater for single pulses.

The increased ablation rate can be ascribed to the dominant interaction only between laser pulse and surface and not with the plasma of previous pulses. Further contributions come from an increase of the vapour ejection due to a locally reduced particle density close to the interaction volume left by the effect of the previous pulses of a burst and the increase in melt ejection due to pre-heated surface.

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