Investigation on Laser Micro Ablation of Steel Using Short and Ultrashort IR Multipulses

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Investigations on laser micro ablation of steel have been made using multipulses instead of single pulses. The aim is to improve the efficiency of laser micro ablation by increasing the ablation rate and quality at the same time. For the improvement of the multipulse laser ablation a flash-lamp pumped Nd:YAG laser with 20 to 100 ns pulse duration is used which can supply multipulses with a specially triggered pockels cell at 10 Hz. A mayor increase of ablation by distribution of energy on several pulses is observed. Further investigations have been made with a commercial ps laser system with a pulse duration of 12 ps at a repetition rate of 100 kHz. The used bursts consisted of up to four pulses with interpulse separations Δt between 20 ns and 100 µs. A cut-off frequency $\nu_{\text{cut-off}}$ up to which the double pulse ablation equals single pulse ablation is defined by plasma enhanced absorption of the second laser pulse. For the comparison of multipulse and single pulse ablation the geometry and the roughness of the irradiated area have been detected by white light interference microscopy.

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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 increasing the efficiency of drilling of different materials with ultra short pulses [1-3], but also with ns up to ms pulses [4-9]. These investigations have been carried out either to drill deep holes through the sample or to investigate single shot ablation. In our work pulse bursts were used for 3 dimensional surface ablation of samples of the steel grades 1.4301 (Stainless Steel 304) and C75 using ns- and ps- laser radiation with single up to four pulse bursts.

2. Experimental setup

For the experiments with ps and ns pulse bursts two different setups have been used.

2.1 Setup for machining with ns pulse bursts

The experiments with ns pulse bursts were carried out with a flash-lamp pumped Nd:YAG laser (λ = 1064 nm, HY1200, Lumonics) that generates several pulses within one flash-lamp discharge (called pulse bursts) at a repetition rate ν = 10 Hz. The pulse duration in single pulse operation was 20 ns and increases up to 80 ns for multi-pulse mode. The interpulse separation Δt between the pulses in a bursts can be set between 0.3 µs and 100 µs, while the number of pulses per burst can be varied between 1 and 4. The focus diameter was measured to 55 µm.

The burst energy E_B, defined as the sum of the pulse energies within one pulse burst, was kept constant during the investigations. Within one burst the energy is distributed uniformly among the pulses.

The experiments were carried out in stainless steel (1.4301). The sample surface, cleaned with alcohol before treatment, was a technical surface. The ablated geometry for the experiments was a groove with an overall length of 3 to 4 mm. The laser beam was focused on the surface of the sample which is moved by linear stages with constant velocity of 4 respectively 10 mm/min to generate the groves. The irradiated laser energy per millimeter translation of the sample was kept constant, during the test two different values were used.

2.2 Setup for machining with ps pulse bursts

The experiments with ps pulse bursts were carried out with a diode pumped Nd:YVO_4 MOPA (Master Oscillator Power Amplifier, Rapid, LumeraLaser) laser with two amplification stages (λ = 1064 nm). The laser operated at a repetition rate ν = 100 kHz and at a pulse duration of 12 ps.

Due to the special design of the implemented pockels cell well defined pulse bursts could be generated. The interpulse separation Δt could be set to n-times 20 ns. Experiments were carried out with single and double pulses, the burst energy E_B in the pulse burst was distributed equally on both pulses in the burst.

For the ablation experiments the laser radiation was positioned on the surface of the steel C75 by a galvanometer scanner system. The ablated geometry were pockets, generated by ablating meandrian squares at a scan speed of 200 mm/s per line, a line distance of 10 µm (overlap ca. 70 %) and 200 layers.

2.3 Diagnostics

For the determination of the ablation results different methods were used: The depth, width and cross section of the groves, generated during the experiments with ns pulse bursts, were either measured by white light interference microscopy (WIM) (Newview 200, LygoLOT) of the surface or by light microscopy of the cross section.

The depth of the ablated squares were measured with a tactile technology after ablation of every 10 layers. The roughness of the surfaces is measured with WIM. Before measurement of the roughness the samples were etched with HCl (30%).

3. Results and discussion

When two laser pulses with short interpulse separation Δt are used for ablation, different processes can influence the interaction of the second pulse with the surface of the material. The radiation of the first pulse is absorbed by the sample, material is removed and a plasma is generated. At high pulse energies and high vapourization rates the second pulse can be absorbed in the plasma without interacting with the surface. At lower energies the plasma generated by the second pulse can expand with larger velocity away from the surface due to atmospheric preconditioning from the first pulse. Plasma assisted ablation can occur resulting in an increase of the ablation and/or a decrease of roughness. Also the interaction area can be preconditioned, so that the second laser pulse can ablate more effectively. This preconditioning can be both changes in physical and optical properties of the surface (preconditioning of the interaction area) and change of the properties of the atmosphere and of the ablated material (atmospheric preconditioning). Which of these possible processes play a dominate role has to be examined.

3.1 Machining with ns pulse bursts

Using ns-Laser pulses the ablation depth is significantly increased by distributing the burst energy E_B of the laser pulse into several pulses of lower energy within one pulse-burst. In Fig. 1 the ablation depth in steel for pulse bursts with one to four pulses per burst with a cumulated pulse energy of E_B = 2 mJ for two different translation velocities is shown. For smaller translation velocities more pulses are applied on the same area and therefore the ablated grooves are deeper. Due to distribution of the energy to several pulses in the burst the ablation depth can be increased such significantly, that the melt cannot be removed and therefore the grooves are nearly filled with melt. Therefore no measurements with four pulse bursts at 4 mm/min are possible, see Fig. 1. Three different reasons are possible for that increase in depth of the ablation:

- Changing from single pulse mode to multipulse mode the pulse duration of the laser radiation increases for increasing number of pulses from 14 ns (single pulse) to 80 ns (triple pulse). The greater pulse duration changes the conditions for melting and vaporisation, e.g. more melt and less vapour is generated.
- More optical energy is absorbed in the sample by less absorption of the laser pulses in the plasma due to splitting of the energy.
- Change of conditions for ablation due to pre-conditioning of the interaction volume, as mentioned in paragraph 3, by short interpulse separation Δt.

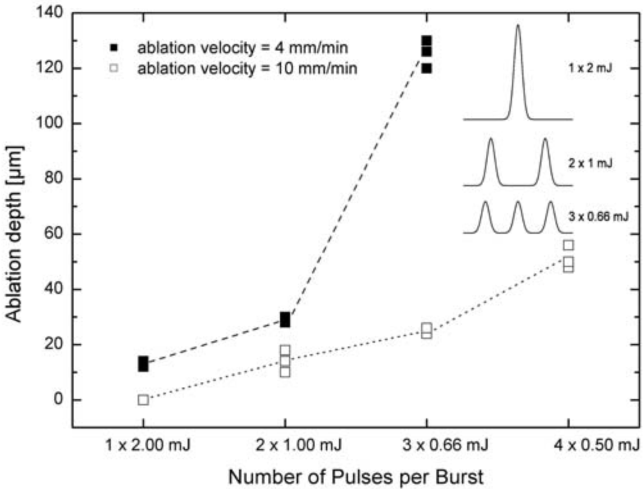

Fig. 1 Ablation depth in steel (1.4301) for single to four pulse bursts at same total energy for two different ablation velocities (λ = 1064 nm, τ = 20 to 80 ns, ns pulse bursts, E_B = 2 mJ, ν = 10 Hz).

The dependence of the ablation depth from the pulse energy and pulse duration was investigated for single pulse ablation of craters generated with one laser pulse in steel and aluminium. For the pulse durations of concern (20 to 100 ns) the ablation depth increases with increasing pulse duration at same pulse energy (Fig. 2). A possible reason for the increase of the depth is a more effective removal of the melt with greater pulse durations and less absorption of the laser radiation in the plasma which results in more optical energy for heating the metal. The ablation depth increases with increasing energy for each pulse duration and material.

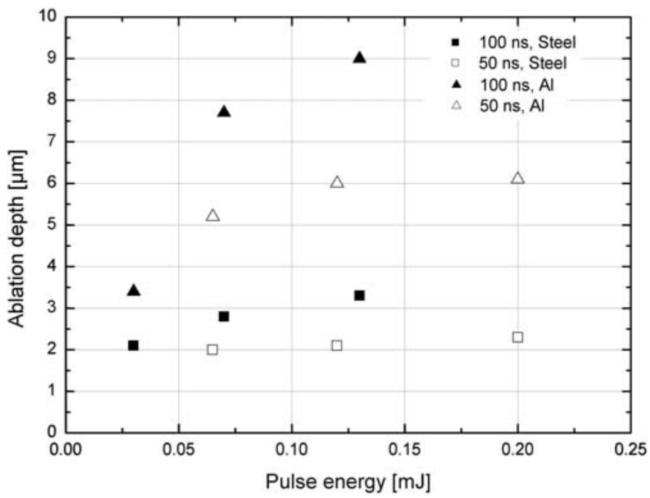

Fig. 2 Ablation depth for single pulses craters in aluminium and steel as a function of the pulse energy for two different pulse durations (λ = 1064 nm).

To identify the dependence of the ablation depth from distribution of the energy in several pulses the following experiment was carried out: the ablation by multipulses in a burst is compared to the ablation caused by a series of single pulses having the same pulse energy as a single pulse within the burst and applied as often as the number of pulses in the burst [9]. The depth for multipulse ablation is increased up to 30 % compared to the ablation depth by series of single pulses. The increase of the ablated volume due to multipulses is up to 70 %.

A variation of the interpulse separation Δt of a double pulse burst in the range of 300 ns to 80 µs shows that the ablation efficiency gets greater with smaller interpulse separation Δt [9]. It is shown that due to variation of interpulse separation Δt the ablation depth can be increased about 20 % for small interpulse separations Δt compared to large interpulse separations Δt. The ablated volume can be increased by 35 %. During the ablation with pulse bursts a cumulative heating of the sample during the burst is expected, resulting in an increase of melting and ablation.

At the ablation of steel with multipulses the depth of ablation can be increased by a factor of 10. This improvement of ablation can be ascribed as shown above to the increase in pulse duration, the distribution of energy on several pulses and the small interpulse separation Δt with subsequent preconditioning of the sample.

For the measured increase in the ablation depth with ns pulse bursts, the most dominant effect is the distribution of the energy on several pulses. This can be explained by a reduced self-absorption of the laser radiation in the plasma formed during ablation. The depth gets greater with greater number of pulses per burst.

The ablation depth increases with larger pulse durations by a factor of ca. 2. This can be explained due to less self-absorption of the laser pulse in the plasma as the plasma density gets smaller and therefore the optical energy decreases that is absorbed in the plasma. Also the melt is removed more effectively due to the larger heating time of the plasma that expels the melt.

By decreasing the interpulse separation Δt the ablation depth with double pulses increases about 20 %. This increase can be explained due to cumulative heating of the surface during the pulse burst. This heating results in a bigger amount of melt that gets expelled more effectively by the following pulses in the burst. Also due to the pre-conditioning of the interaction volume (paragraph 3) less energy is needed for vaporisation and expulsion of plasma as there is a reduction of the density in atmosphere close to the sample surface. Additional the ejecta e.g. droplets of the first pulse get heated and are more effectively removed from the surface [7].

3.2 Machining with ps pulse bursts

For micromachining with ps-Lasers the ablation depth per layer is investigated for double pulses as a function of the interpulse separation Δt. For small burst energies (E_B = 4 µJ, Fig. 3) the distribution of the energy into two pulses increases the ablation depth only slightly. For smaller energies than E_B = 4 µJ the ablation depth is even smaller for double pulses than for single pulses of same total energy as the energy of the pulses in the burst gets close to the ablation threshold.

For machining with larger burst energy (E_B = 22 µJ, Fig. 4) distributing the energy into pulse burst increases the ablation depth by about 50%. The comparison of ablation depth for double pulses at a burst energy E_B with two times the depth of the single pulse ablation at the energy $E_B/2$ (which means the same applied energy per area) shows, that by using pulse bursts the ablation depth can only slightly be increased up to 10 %. The ablation depth approaches a constant value for larger interpulse separations Δt. At large burst energies and small interpulse separation $\Delta t < 100$ ns the ablation depth with double pulses decreases with decreasing interpulse separation Δt and gets even smaller than two times the ablation depth with single pulses of half burst energy $E_B/2$.

As shown in Fig. 3 and Fig. 4 the ablation depth with double pulses can not significantly be increased compared to twice the ablation depth with single pulses of the half burst energy $E_B/2$. It only is grater when compared to the depth machined with single pulses of same burst energy E_B.

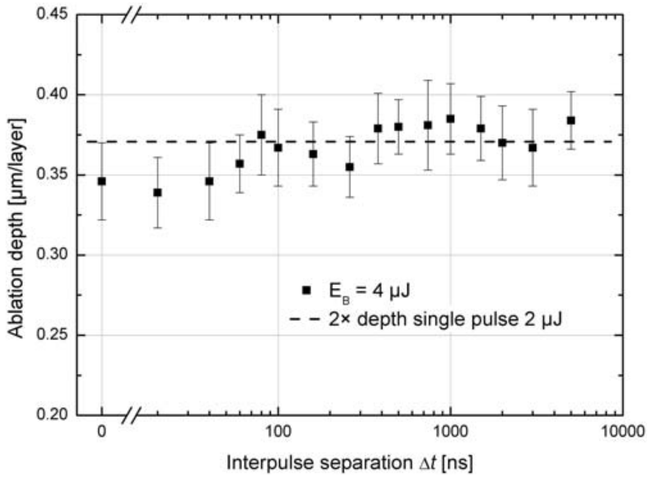

Fig. 3 Ablation depth in steel (C75) with 4 µJ ps-double pulse bursts as a function of the interpulse separation Δt (λ = 1064 nm, τ = 12 ps, E_B = 4 µJ, ν = 100 kHz).

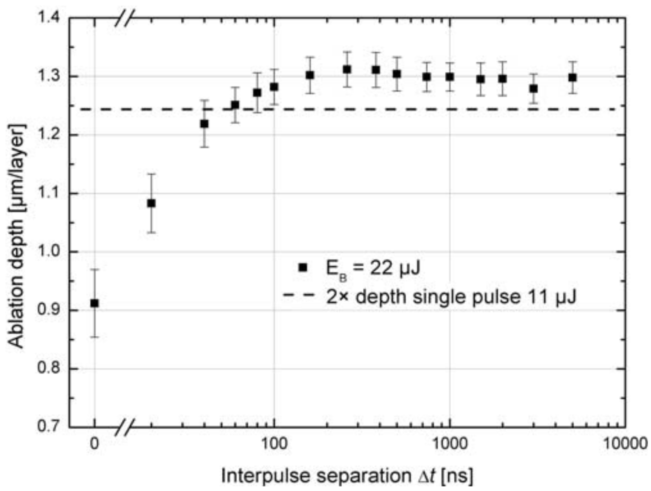

Fig. 4 Ablation depth in steel (C75) with 22 µJ ps-double pulse bursts as a function of the interpulse separation Δt (λ = 1064 nm, τ = 12 ps, E_B = 22 µJ, ν = 100 kHz).

Evaluating the roughness of the ablated areas depending on the interpulse separation Δt results in curves which can be divided into three sections (Fig. 5 and Fig. 6):

- Section I: For 0 ns < Δt < 40 ns the roughness is smaller than for larger interpulse separation Δt.
- Section II: For 40 ns < Δt < 400 to 700 ns the roughness is much larger than for any other interpulse separation Δt, but gets smaller with greater interpulse separation Δt.
- Section III: For Δt > 400 to 700 ns the roughness gets smaller than in the first section and is in the range of the roughness for ablation with single pulses at half burst energy E_B.

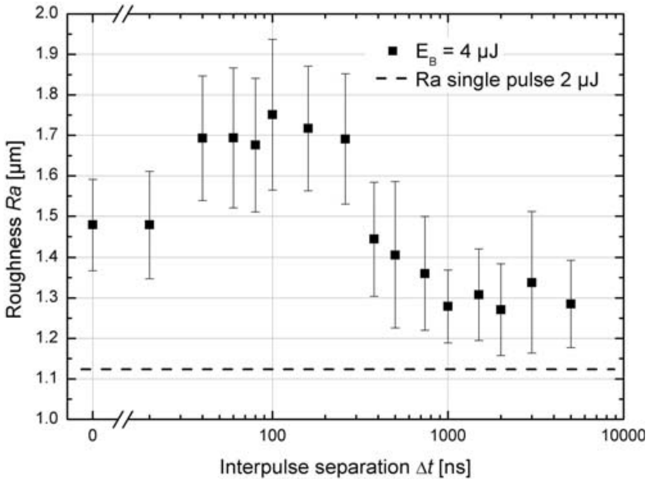

Fig. 5 Roughness *Ra* of the ablated area as a function of the interpulse separation Δt generated with 4 µJ ps-double pulse bursts (λ = 1064 nm, τ = 12 ps, E_B = 4 µJ, ν = 100 kHz).

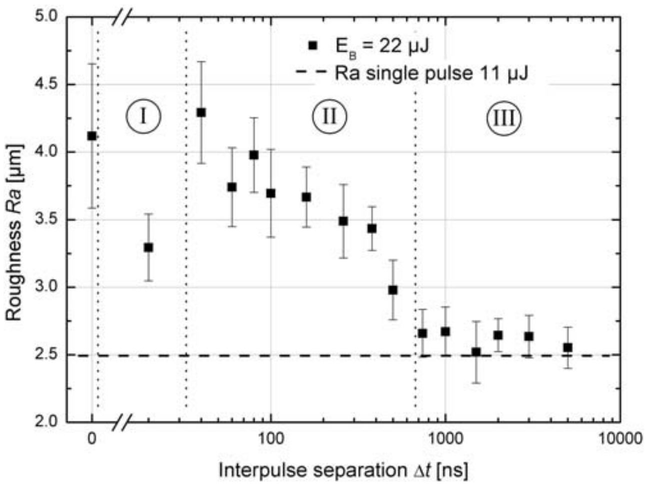

Fig. 6 Roughness *Ra* of the ablated area as a function of the interpulse separation Δt generated with 22 µJ ps-double pulse bursts (λ = 1064 nm, τ = 12 ps, E_B = 22 µJ, ν = 100 kHz).

Comparing the roughness and the ablation depth the three sections can be explained as follows:

Section I

At very small interpulse separations 0 ns < Δt < 40 ns a strong absorption of the second pulse in the plasma is expected. Less optical energy of the second pulse is transmitted through to the plasma to the sample, the plasma itself remelts the surface and assists the ablation and decreases roughness.

Section II

Setting the interpulse separation between 40 ns < Δt < 400 to 700 ns influences the ablation negatively. The ablation depth increases with greater interpulse separation Δt till it gets constant. At the same time the roughness is increased, too, and decreases with greater interpulse separation Δt. A high-energy plasma is generated remelting the surface explosively due to the interaction of the second laser pulse with the plasma. The larger the interpulse separation Δt is the smaller becomes the influence of the plasma and the roughness.

Section III

Increasing the interpulse separation Δt > 400 to 700 ns the probability of interaction of the second pulse with the plasma generated by the first pulse gets significantly smaller. The ablation depth with double pulses equals to twice ablation depth with single pulses of $E_B/2$. The threshold interpulse separation Δt_{tr} defines a cut-off frequency $\nu_{cut\text{-}off}$: for $\nu < \nu_{cut\text{-}off}$ the ablation with double pulses equals to single pulse ablation with half burst energy. This means that the plasma generated by the first pulse has no detectable influence on the second pulse. The thus defined cut-off frequency $\nu_{cut\text{-}off}$ ranges between 1 and 3 MHz.

4. Conclusions

Machining with ns multipulse bursts of same burst energy E_B the ablation depth is increased by a factor of 10. The most dominant effect is the distribution of the energy on several pulses which reduces the absorption of laser radiation in the plasma. This enlarges the absorbed energy into the surface and therefore the expel of melt gets greater. Further the increasing pulse duration of the pulses in the burst lead to more effectively melt removal. The third reason for the total increase of the ablation depth with multipulses is the short interpulse separation Δt that leads to a pre-conditioned interaction volume that supports melt ejection.

For the ablation with ps double pulses three sections of ablation are defined. For the ablation with very short interpulse separation 0 ns < Δt < 40 ns a deviation of the ablation depth and roughness *Ra* has been detected that has to be investigated in future. For interpulse separation between 40 ns < Δt < 400 to 700 ns the plasma interacts in a negative manner with the sample e.g. by increasing the roughness *Ra*. For interpulse separation Δt > 400 to 700 ns the ablation of double pulses equals to the ablation with single pulses of half burst energy E_B. Therefore a cut-off frequency $\nu_{cut\text{-}off}$ = 1 to 3 MHz can be defined up to which the plasma has no detectable influence on the ablation. This cut-off frequency $\nu_{cut\text{-}off}$ could be a well limit for the maximal frequency for laser ablation with ps laser pulses.

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