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Scaling of Ablation Rates. Ablation Efficiency and Quality Aspects of Burst-Mode Micromachining of Metals.

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Abstract

Considering the energy efficiency and the ablation quality, ultra-short double-pulse laser micromachining of stainless steel is examined for ps and fs pulses. Pulse delays from 0.3 ns up to 220 ns are realized with the help of an external delay line or a linear MOPA laser system. Burst-mode ablation is found to be less efficient for all investigated double-pulse delays. Keeping the single-pulse fluence and the overall incident energy constant, a drastic decrease of the ablation rate is observed when the double-pulse delay is reduced. Despite the lower ablation efficiency, ultra-short double-pulse laser ablation offers the possibility to machine strongly reflective and smooth surfaces and thus can improve the ablation quality.

Keywords: burst-mode ablation; ablation efficiency; metals; surface quality; double pulses; ultra-short pulses

1. Introduction

In recent years, material processing using ultra-short laser pulses, especially for micromachining of metals, has become an established production technology. Today, laser systems in the ultra-short pulse regime are used for many industrial applications, like machining of lambda probes or drilling of injection nozzles [König, 2011]. In 2013, scientists from Bosch, TRUMPF, Jena University and Fraunhofer IOF were honored with the German innovation award for their collective effort for the introduction of the ultra-short pulsed laser technology into serial production.

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Meanwhile, industrially proven ultra-short pulsed laser systems with several tens of Watt of average power and pulse durations down to some hundred femtoseconds are commercially available. Lab systems nowadays even achieve average powers in the kW regime [Negel et al., 2013] and pulse energies up to several hundred millijoules [Metzger et al., 2014]. The average power does not seem to restrict the productivity of ultra-short pulsed lasers, as it did ten years ago. However, due to physical (heat accumulation [Bauer et al., 2015], plasma shielding [König et al., 2011]) and technological (limited speed and dynamics in beam deflection [Jaeggi et al., 2014]) limitations, scaling the ablation rate only by increasing the pulse energy or the repetition rate is quite difficult.

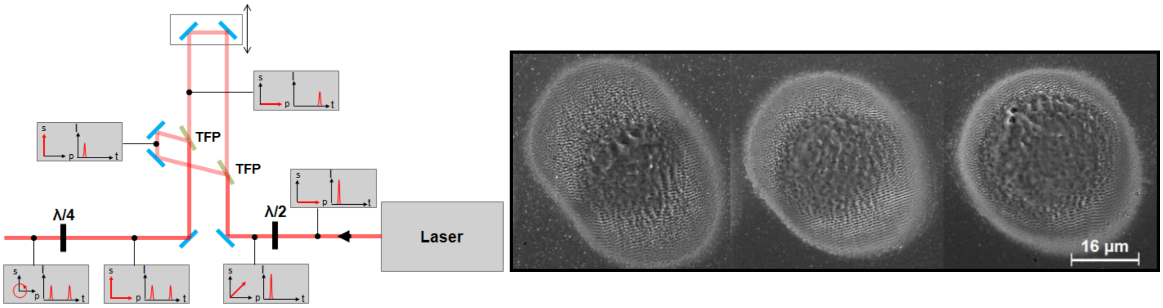
As shown in several publications, there is a maximum energy efficiency of the ablation process for each material, mainly depending on the applied fluence [e.g. Raciukaitis et al., 2009]. For steel, the optimum fluence resulting in the best efficiency is typically below $\phi_0 = 1\,\mathrm{J/cm^2}$. As a consequence, efficient micromachining with typical spot diameters $2w_0 < 100\,\mu\mathrm{m}$ and several tens of watts of average power can only be achieved by increasing the repetition rate or machining in parallel using beam splitting or diffractive optical elements (DOEs). Both possibilities have their respective advantages and disadvantages: Scaling productivity by increasing the repetition rate can affect the process performance due to particle shielding and heat accumulation effects [Ancona et al., 2009]. Furthermore, it demands for high beam deflection speeds which can be realized using polygon scanners [Jaeggi et al., 2014]. However, this technique is not appropriate for all applications. As one promising approach, DOEs can be used for power scaling by increasing the pulse energy. They enable processing identical structures in parallel but have a reduced flexibility. Spatial light modulators are more flexible but are still limited in average power and refresh rate.

Another way to realize moderate and efficient single-pulse fluences at a high average power is the use of pulse groups with pulse delays Δt in the range of a few ns, so-called bursts. In [Neuenschwander et al., 2015], pulse delays between $\Delta t = 12\,\mathrm{ns}$ and $\Delta t = 60\,\mathrm{ns}$ are studied for the ablation of stainless steel. No setting was found which increases the ablation rate using double pulses compared to single pulses. Furthermore, a decreased pulse delay was found to reduce the energy efficiency of the ablation process. The often-reported increase in ablation rate using bursts [Knappe et al., 2010] was identified to result from fluences closer to the optimum fluence for each pulse in the burst. It is also shown [Neuenschwander et al., 2015] that bursts enable machining of smooth and reflective surfaces at fluences, where single-pulse ablation leads to the formation of bumps and cavities. In this context, single-pulse ablation does not refer to the ablation using one single pulse, but to *conventional* processing without pulse groups.

In this research work, we focused on burst-mode micromachining using double pulses in the pulse delay range below $\Delta t = 12\,\mathrm{ns}$. Considering both, the energy efficiency and the ablation quality, we compared single-pulse ablation to double-pulse ablation at pulse delays down to $\Delta t = 0.3\,\mathrm{ns}$.

2. Experimental Set-Up

For the generation of the investigated double pulses, different experimental set-ups were used. The short pulse delays ($\Delta t < 8\,\mathrm{ns}$) were realized with the help of an external delay line which is schematically depicted in Fig. 1 (a): A pulse coming from the linearly polarized regenerative amplifier (TruMicro 5050 Femto Edition) is split into two pulses of equal pulse energy. By varying the length of one light path, double-pulse delays from $\Delta t = 0.3\,\mathrm{ns}$ up to $\Delta t = 8\,\mathrm{ns}$ could be realized at a pulse duration of $\tau = 0.9\,\mathrm{ps}$ (FWHM, sech² fit). The energy distribution among the pulses was controlled by measuring the average power for each optical path. The pulse delay Δt was monitored using a photodiode. To ensure that the split pulses are spatially aligned, double-pulse ablation experiments were performed on polished stainless steel (Fig. 1 (b)).



(a) (b)

Figure 1: (a) Double-pulse generation using an external delay line. Each laser pulse is split into two pulses of equal pulse energy. The pulse delay was adjustable between Δt=0.3 ns and Δt=8 ns. (b) Double-pulse ablation sites on stainless steel. In the rightmost picture, the split, delayed and recombined pulses are well-aligned.

A double-pulse delay of Δt = 13.4 ns (corresponding to one resonator round-trip) was generated directly from the regenerative amplifier by adjusting the timings of the pockels cell. For this pulse delay of Δt = 13.4 ns, experiments were performed at pulse durations of τ = 0.9 ps and τ = 7.1 ps.

Even longer double-pulse delays, up to Δt = 220 ns, were realized with the help of a linear master oscillator power amplifier (MOPA) system at a pulse duration of τ = 20 ps. Due to a repetition rate of 50 MHz of the seed laser, the shortest pulse delay was Δt = 20 ns in this case.

For the ablation experiments, the circularly polarized Gaussian beam was focused on the 1 mm thick samples made of stainless steel (EN steel number 1.4301). An f = 100 mm f-theta lens was used when working with the regenerative amplifier. Here, the spot diameter was $2w_0$ = 30 µm. Since the MOPA fiber-based laser system was limited to a pulse energy of E_p = 10 µJ at a pulse duration of τ = 20 ps, an f = 56 mm lens was used here and the beam was focused to a spot size of $2w_0$ = 22 µm. All experiments were performed at the fundamental wavelength of λ = 1030 nm.

For the evaluation of the ablation rate and the processing quality, squares with a dimension of 1 mm were scanned with a hatch line distance of 8 µm, a scanning speed of 2.5 m/s and 150 repetitions. For the single pulses, a repetition rate of f_{rep} = 800 kHz was used. This was compared to double pulses with a varying pulse delay Δt at a repetition rate of f_{rep} = 400 kHz. Thus, the total number of incident pulses and the processing time were kept constant and – for a fixed pulse energy – the influence of the temporal distribution of the pulses could be studied. The respective ablated volumes were measured using a laser-scanning microscope. To evaluate the energy efficiency, they were set in relation to the laser energy applied for ablation.

3. Results and Discussion

3.1. Energy Efficiency for Single-Pulse Ablation

For the ablation of metals using ultra-short laser pulses, the ablation depth depends logarithmically on the applied fluence [Nolte et al., 1996]. As previously reported [e.g. Neuenschwander et al., 2013], the energy efficiency of the ablation process – the ablated volume per applied energy – can be derived to give:

$$\frac{\Delta V}{E} = \frac{\delta}{2 \cdot \Phi_0} \cdot \ln^2\left(\frac{\Phi_0}{\Phi_{\text{thr}}}\right) \quad (1)$$

Here, δ denotes the energy penetration depth, ϕ_{thr} the threshold fluence and ϕ_0 the peak fluence of the Gaussian beam which can be calculated from the pulse energy E_p and the spot radius w_0:

$$\Phi_0 = \frac{2\,E_p}{\pi\,w_0^2} \tag{2}$$

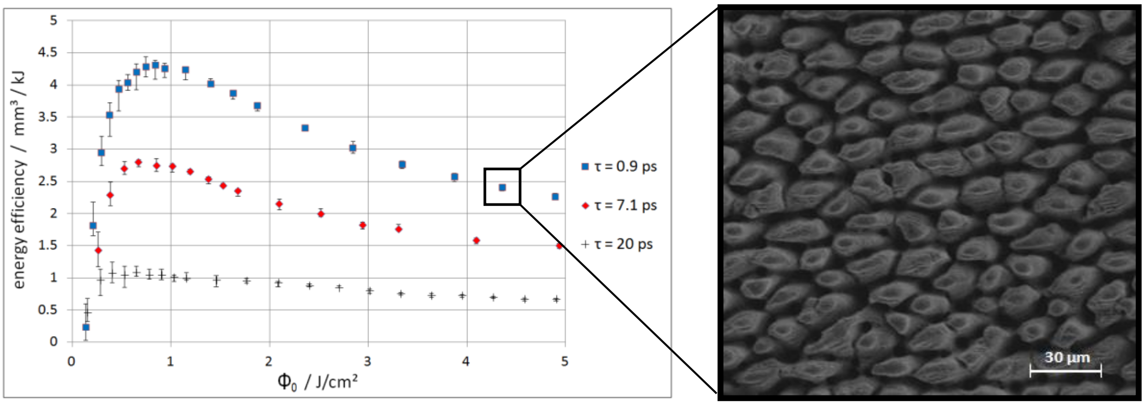
Figure 2 (a) shows the dependence of the energy efficiency on the applied fluence for several pulse durations τ. The measurements were performed at a repetition rate of $f_{rep} = 100$ kHz, a scanning speed of 0.4 m/s, a hatch line distance of 8 µm and 100 repetitions. As can be seen in the graph and also be derived from Eq. (1), the energy efficiency $\Delta V/E$ is maximized for a certain fluence. Increasing the pulse duration from τ = 0.9 ps to τ = 20 ps results in a decrease of the energy efficiency by more than a factor of four. As a constant ablation threshold ϕ_{thr} for metals has been observed for pulse durations up to several tens of picoseconds [Stuart et al., 1996] [Neuenschwander et al., 2012], the increased energy efficiency for shorter pulse durations can only be explained by a higher energy penetration depth δ according to Eq. (1).

Considering the ablation quality, it is discussed in [Bauer et al., 2015] that even for ultra-short laser pulses a significant part of the absorbed energy stays in the material as residual heat. For high repetition rates and spatial overlaps, this may lead to heat accumulation effects affecting the surface quality (Fig. 2 (b)).

3.2. Energy Efficiency for Double-Pulse Ablation

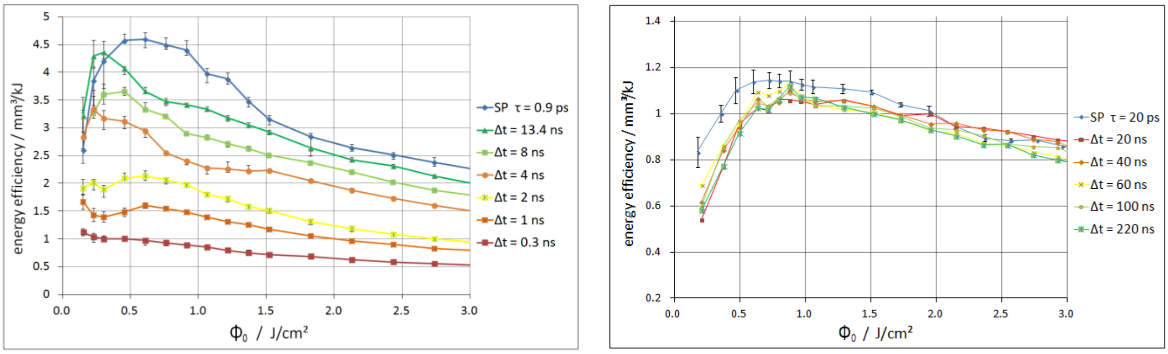
The energy efficiency for single-pulse ablation is compared to double-pulse ablation as described in section 2. The results for pulse delays of $\Delta t = 0.3$ - 8 ns (external delay line) and $\Delta t = 13.4$ ns (regenerative amplifier) at a pulse duration of τ = 0.9 ps are shown in Fig. 3 (a). For all pulse delays Δt investigated here, the energy efficiency for double-pulse processing was found to be reduced compared to processing without pulse groups. Reducing the pulse delay results in a drastic decrease of the energy efficiency. The shortest pulse delay ($\Delta t = 0.3$ ns) even leads to a reduction of the energy efficiency by a factor of almost five compared to the ablation using single pulses.

The results for pulse delays between $\Delta t = 20$ ns and $\Delta t = 220$ ns (MOPA, τ = 20 ps) are depicted in Fig. 3 (b). Here, only slight differences can be observed between the respective pulse delays. For a pulse delay of $\Delta t = 60$ ns or above, the energy efficiency is comparable to the ablation using single pulses.



(a) (b)

Figure 2: (a) Energy efficiency $\Delta V/E$ for single-pulse ablation on stainless steel for different pulse durations τ, (b) bump formation on stainless steel at $\phi_0 = 4.3$ J/cm².



(a) (b)

Figure 3: Energy efficiency for the ablation of stainless steel evaluated at different peak fluences ϕ_0 of the individual pulses. Single-pulse processing (SP) at $f_{rep} = 800$ kHz is compared to double-pulse processing at $f_{rep} = 400$ kHz and varying pulse delays Δt. The lines serve as a guide to the eye. (a) $\tau = 0.9$ ps, Δt controlled by external delay line/regenerative amplifier. (b) $\tau = 20$ ps, Δt realized with MOPA-system.

The results for pulse delays larger than $\Delta t = 20$ ns are in good agreement with those in [Neuenschwander et al., 2015] but cover an even wider range of pulse delays. The often-reported increased ablation rate when using bursts results from fluences closer to the optimum in energy efficiency for each individual pulse in the burst.

Figure 4 shows the energy efficiency of double pulses related to those of single pulses for pulse delays up to $\Delta t = 60$ ns. Since the pulse duration affects the maximum energy efficiency (compare Fig. 2 (a)), each double-pulse efficiency is compared to the respective single-pulse experiment with the same pulse duration and pulse delay. At a pulse delay of $\Delta t = 13.4$ ns, this relative energy efficiency gives comparable results for pulse durations of $\tau = 0.9$ ps and $\tau = 7.1$ ps. Figure 4 also contains a measurement from [Neuenschwander et al., 2015] for a pulse delay of $\Delta t = 12$ ns and a pulse duration of $\tau = 10$ ps which, as well, is in good agreement with our results. Thus, it is legitimate to plot the relative efficiencies measured at different pulse durations in one graph.

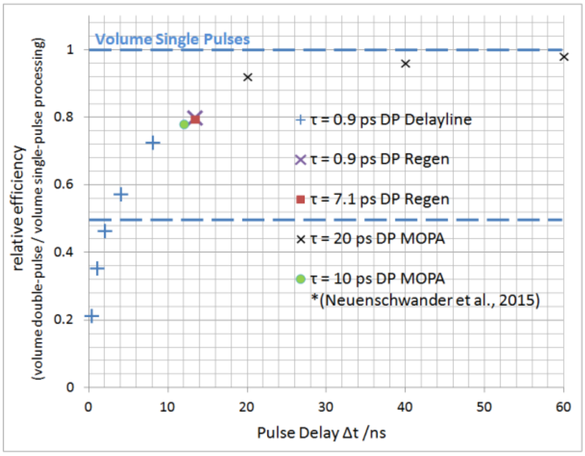


Figure 4: Relative energy efficiency (double pulses related to single pulses) for $\phi_0 = 0.6$ J/cm². A decreasing pulse delay from $\Delta t = 20$ ns to $\Delta t = 0.3$ ns results in a drastic reduction of the energy efficiency.

Keeping the single-pulse peak fluence at $\phi_0 = 0.6$ J/cm² (optimum for single pulses) and the overall incident energy constant, a drastic decrease of the relative efficiency is observed when the double-pulse delay Δt is reduced. Decreasing the pulse delay from $\Delta t = 40$ ns down to $\Delta t = 0.3$ ns results in a drastic decrease of the efficiency by almost a factor of five. For a pulse delay of $\Delta t < 2$ ns, the ablated volume of double pulses is even reduced below the value of single-pulse ablation with half of the total energy.

For pulse delays $\Delta t > 40$ ns, the energy efficiency for double-pulse processing is comparable to the efficiency reached with the respective single pulses. Increasing the pulse delay to even longer values results in a saturation of the energy efficiency.

Possible reasons for the reduced energy efficiency using double pulses are plasma and particle shielding

[Ancona et al., 2009], as well as modifications of the surface which affect the energy coupling for the subsequent pulses. The absorption in arising, dense plasma is assumed to be dominant within the first nanoseconds and depends on the applied fluence [König et al., 2005]. On longer time scales, plasma shielding for moderate fluences can be neglected and particle shielding may be a dominant effect, reducing the efficiency.

Assuming shielding to be the main reason for the reduced double-pulse energy efficiency, a drop below 50% of the single-pulse efficiency for pulse delays $\Delta t < 2$ ns cannot be explained. Even if the second pulse was completely shielded by plasma and/or particles, a drop below a relative efficiency of 0.5 would only be explicable if shielding also affected the following double pulses.

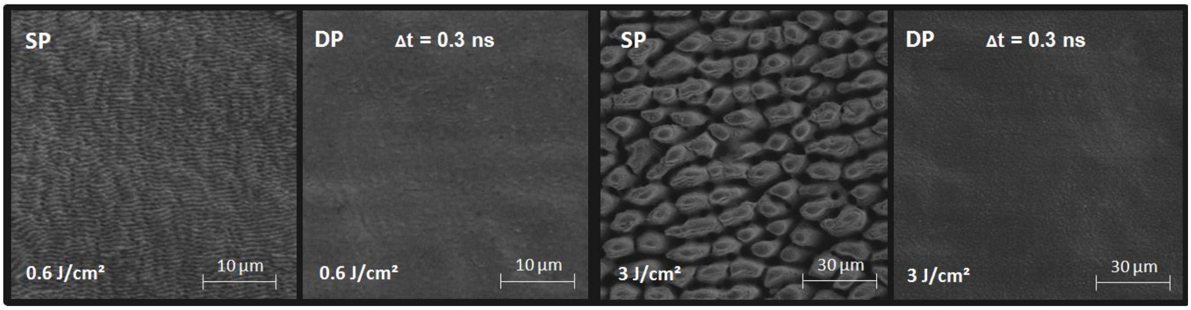
For double-pulse ablation, the effect of an ablation depth below half of the depth of the same number and energy of single pulses is also reported in [Donelly et al., 2009] and [Roberts et al., 2010]. For a pulse delay $\Delta t < 1$ ns, a complex interaction of the delayed pulse with the ablation plume produced by the first pulse is observed [Donelly et al., 2009]. In [Roberts et al., 2010], the authors suggest a repulsion of nano- and mesoparticles generated by the first pulse due to absorption of the ablated mass by the second pulse. It is assumed that the second pulse creates enough momentum that some parts of the nascent plume are driven back on the surface.

Another reason for the reduced energy efficiency might be an altered energy coupling due to surface modifications caused by double-pulse processing. When processing at moderate fluences without pulse groups (Fig. 5 (a)), nanostructures appear which possibly influence the energy coupling of the following pulses [Vorobyev et al., 2005]. When machining with double pulses, those nano- and microstructures cannot be observed (Fig. 4 (b)). They are presumably molten and smoothened.

3.3. Ablation Quality

Considering the ablation quality, a very smooth and reflective surface can be observed for all surfaces processed using double pulses. This high reflectance starts at a certain fluence which is lower the shorter the pulse delay Δt is chosen. The shorter the pulse delay used, the more reflective the surfaces appear to the eye.

At moderate fluences (depicted in Fig. 5 (a) and 5 (b)), the use of double pulses leads to a noticeable surface enhancement. The laser-induced periodic surface structures (LIPSS) typical for ultra-short pulsed laser ablation of metals [in't Veld et al., 2010] are not observed anymore.



(a) (b) (c) (d)

Figure 5: Surface quality of single-pulse compared to double-pulse processing at a pulse delay of $\Delta t = 0.3$ ns. (a) Single-pulse machining at optimum, moderate fluence creates LIPSS. (b) Corresponding surface ablated with double pulses is distinctly smoother. (c) Single-pulse machining in high fluence regime far above optimum results in the formation of bumps and cavities. (d) Corresponding double-pulse surface at a fluence of 3 J/cm² has no bumps and a low surface roughness.

When processing with single pulses and the given parameters, bump formation (as shown in Fig. 2 (a)) occurs for fluences higher than about $\phi_0 = 1\,\mathrm{J/cm^2}$. Here, the influence of the double pulses on the processing result is even greater. As it can be seen from the comparison of Fig. 5 (c) and 5 (d), double-pulse processing at similar and higher fluences still results in a high ablation quality, while the energy efficiency is reduced (as discussed in section 3.2.). For the investigated fluences (up to $\phi_0 = 3\,\mathrm{J/cm^2}$), there was no bump formation for double-pulse processing with pulse delays $\Delta t < 8$ ns. For longer pulse delays, some bump formation occurred but – compared to single-pulse processing – at distinctly higher fluences.

4. Conclusion

Double-pulse ablation of stainless steel was investigated for pulse delays from $\Delta t = 0.3$ ns up to $\Delta t = 220$ ns. For all investigated pulse delays, the energy efficiency was found to be reduced compared to single-pulse processing. A drastic decrease of the energy efficiency is observed when the double-pulse delay Δt is reduced, especially in the range between $\Delta t = 0.3$ ns and $\Delta t = 20$ ns. For pulse delays $\Delta t < 2$ ns, the double-pulse energy efficiency even drops below half of the efficiency for single-pulse processing.

Concerning the ablation quality, double-pulse ablation was observed to be advantageous. The shorter the double-pulse delay Δt is chosen, the smoother and more reflective the processed surfaces appear. Also, the formation of bumps and cavities occurring for single-pulse ablation at high fluences can be prevented when processing with double pulses. The precise physical reason for both phenomena – the enhanced surface quality and the reduced energy efficiency when processing with double pulses – has not yet been clarified and needs to be further investigated.

In conclusion, double-pulse ablation of stainless steel is less efficient but offers the possibility to machine strongly reflective and smooth surfaces. Compared to single-pulse ablation, pulse groups can also facilitate the use of higher average powers. Therefore, double-pulse ablation might be beneficial for power scaling in some cases. The higher ablation quality and the reduced energy efficiency have to be carefully weighed against each other and a suitable pulse delay Δt has to be chosen.

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