Influence of Pulse Bursts on the Specific Removal Rate for Ultra-Fast Pulsed Laser Micromachining of Copper

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Abstract

Compared to single pulses the utilization of pulse bursts on steel samples was reported to be more efficient. But with regards to the specific removal rate it can be shown that a maximum value is achieved when the applied peak fluence equals exp(2) times the threshold fluence. The higher reported efficiency is caused by the reduced energy of the single pulses nearer to the optimum value.

Recent investigations on the application of pulse bursts on copper samples suggest an interaction of the single pulses in a pulse burst in terms of the specific removal rate. The specific removal rate drops to less than 50\% for a 2-pulse-burst consisting of two pulses of identical pulse energy, whereas the maximum specific removal rate for a 3-pulse-burst exceeds that of a single pulse by approx. 20\%.

The results of investigations on the variation of pulse energy for 2-pulse-bursts and 3-pulse-bursts regarding specific removal rate and surface quality are presented.

Keywords: ultra-fast; laser micromachining; pulse burst; copper; removal; ablation rate

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1. Introduction

Micromachining of metals, semiconductors and insulators with ultra-fast pulsed laser radiation has entered industry in a diversity of applications due to the achievable quality (Chichkov et al. (1996), Breitling et al. (2004), Dausinger et al. (2003) and Meijer et al. (2002)). At present the limiting factor for a wider spreading is the low throughput even though ultra-fast laser beam sources with an average power of up to 100 W are commercially available, laser systems comprising of succeeding amplifier stages deliver more than 1 kW average power (Russbueldt et al. (2010 and 2011)). Today’s challenge is to turn that high average power into throughput. Since the ablated volume per time and average power, the so-called specific removal rate, has a maximum for each material, wavelength and pulse duration as shown by Raciukaitis et al. (2009) and Neuenschwander et al. (2010), one possibility is to reduce the pulse duration to increase the efficiency. By applying pulses with a pulse duration of $t_H = 250 \text{ fs}$ the specific removal rate can be increased by approx. 75% for copper and by approx. 40% for steel compared to the efficiency of a pulse with a pulse duration of $t_H = 10 \text{ ps}$ (Schmid et al. (2011), Jaeggi et al. (2011), Neuenschwander et al. (2011), and Lauer et al. (2013)). Taking further into account that the optimum fluence is in the range of 1 J/cm² high average power can only be applied by increasing the spot size, increasing the number of parallel spots, e.g. by means of a DOE or SLM, by increasing the scan speed, e.g. by means of a polygon scanner, or by utilizing pulse bursts (Neuenschwander et al. (2014)).

Several publications deal with the application of pulse bursts and their benefit for microprocessing of steel (Hartmann et al. (2007), Knappe et al. (2009), Deladurantaye et al. (2011), Neuenschwander et al. (2015)). But most of them only focus on the absolute growth in ablation rate and are not taking into account the efficiency of the process. Increasing the average power $P_{\text{ave}}$ by a factor of two will lead e.g. to an increase of the ablated volume by 70% at a given repetition rate $f_{\text{rep}}$ and as a consequence to a higher throughput. This approach might be legitimate for industrial applications, even if it ignores the fact that the process now is 30% less efficient. If a 2-pulse burst with the same average power $P_{\text{ave}}$ and the same repetition rate $f_{\text{rep}}$ is applied the efficiency and the ablated volume can be increased at the same time due to the fact that the pulse energies of the individual pulses in the 2-pulse burst are lower and closer to the optimum.

Furthermore, the ablated volume per time for steel can be doubled by applying a 2-pulse bursts with an inter-pulse distance of $\Delta t_{\text{burst}} = 24 \text{ ns}$ and keeping the repetition rate, meaning to double the average power. Applying a 3-pulse burst, i.e. tripling the average power can be raised to 2.4 times of a single pulse at the same repetition rate. In principle this simple strategy works for copper as well, but the utilization of pulse bursts offer another way to increase efficiency. Whereas the application of a 2-pulse burst reduces the specific removal rate to less than that of a single pulse, the application of a 3-pulse burst increases the specific removal rate by approx. 20% as shown by Neuenschwander et al. (2015).

2. Ablation Process

Taking for granted the two temperature model as a basis for the mathematical description of the ablation process for laser micromachining the volume ablation rate $dV/dt$ per average power $P_{\text{ave}}$, further referred to as specific removal rate or efficiency, can be described as a function of the laser peak fluence $\phi_0$ of a Gaussian Beam (Momma et al. (1996 and 1997); Nolte et al. (1997), Anisimov and Rethfeld (1997), Christensen (2007) and Byskov-Nielsen (2010)):

$$
\frac{dV/dt}{P_{\text{ave}}} = \frac{1}{2} \frac{\delta}{\phi_0} \cdot \ln\left(\frac{\phi_0}{\phi_{\text{th}}}\right)
$$

where $\delta$ designates the energy penetration depth and $\phi_{\text{th}}$ the threshold fluence.

Fig. 1 shows the specific removal rate as a function of the laser peak fluence for steel (Neuenschwander et al. (2015)). The optimum peak fluence $\phi_{\text{opt}}$ maximizes the specific removal rate, i.e. the ablation process becomes most efficient.
It is given by

$$\phi_{0,\text{rep}} = e^2 \cdot \phi_{\text{th}}$$  \hspace{1cm} (2)

The maximum specific removal rate there can be written as

$$\left. \frac{dV}{dt} \right|_{\text{max}} = \frac{2}{e^2} \cdot \frac{\delta}{\phi_{\text{th}}} \cdot \frac{P_{\text{ave}}}{P_{\text{ave}}}$$  \hspace{1cm} (3)

and is only depending on material parameters and therefore fixed for a specific material. Increasing the average power $P_{\text{ave}}$ will increase the ablated volume per time $dV/dt$, but it will decrease the process efficiency.

The peak fluence $\phi_0$ can be expressed by the average power $P_{\text{ave}}$, the repetition rate $f_{\text{rep}}$ and the beam radius $w_0$ at the focal position (Raciukaitis et al. (2009), Neuenschwander et al. (2010 and 2012))

$$\phi_0 = \frac{2}{\pi \cdot w_0 \cdot f_{\text{rep}}} \cdot \frac{P_{\text{ave}}}{w_0}$$  \hspace{1cm} (4)

For a given beam radius $w_0$ the peak fluence $\phi_0$ can only be kept constant while increasing the average power $P_{\text{ave}}$ if the repetition rate will be increased by the same factor. For the optimum peak fluence $\phi_{0,\text{opt}}$ the ratio $P_{\text{ave}}/f_{\text{rep}}$ becomes

$$\frac{P_{\text{ave}}}{f_{\text{rep}}} = \frac{\pi}{2} \cdot \frac{w_0^2}{e^2} \cdot \phi_{\text{th}}$$  \hspace{1cm} (5)

and assuming the ablation threshold to be $\phi_{\text{th}} = 0.36 \text{ J/cm}^2$ for copper and the beam radius to be $w_0 = 16 \mu \text{m}$ the ratio $P_{\text{ave}}/f_{\text{rep}}$ amounts to $10.7 \text{ W/MHz}$. As a consequence applying an average power $P_{\text{ave}} = 50 \text{ W}$ the maximum efficiency requires a repetition rate $f_{\text{rep}} = 4.7 \text{ MHz}$, at which pulses can no longer be switched individually by today’s state-of-the-art ultra-fast lasers. The rise time of mostly utilized AOMs or EOMs in commercially available ultra-fast laser systems is higher than the time between two successive pulses at repetition rates over 2 MHz and therefore do pulses at higher repetition rates consist of unwanted pre- and post-pulses.

![Graph](image_url)

Fig. 1: Specific removal rate at $f_{\text{rep}} = 200 \text{ kHz}$ for steel, single pulse vs 2-pulse burst with varying inter-pulse distance $\Delta t_{\text{burst}}$.
But at the same time those lasers offer a way out of this dilemma. They are capable of applying so-called pulse bursts, in which up to eight single pulses, separated by the reciprocal seed frequency of the laser, are emitted as a single pulse train. Additionally the peak power of the pulses within the burst can be adjusted individually.

Applying a 2-pulse burst during the microprocessing of steel either the ablation rate can be doubled or the repetition rate can be halved if the inter-pulse distance is at least $t_{\text{burst}} = 24 \text{ ns}$ (Fig. 1).

Although for steel a 3-pulse burst does not reach the maximum efficiency of a single pulse, applying a 3-pulse burst is beneficial since the drop in efficiency by approx. $0.02 \text{ mm}^3/(\text{min W})$ is much less than that for increasing the average power $P_{\text{ave}}$ by a factor of three, which is approx. $0.04 \text{ mm}^3/(\text{min W})$ (Fig. 2, Neuenschwander et al. (2015)).

In comparison to that, copper behaves completely different. For a 2-pulse burst with an inter-pulse distance of $\Delta t_{\text{burst}} = 12 \text{ ns}$ the maximum efficiency drops drastically to less than half of that of a single pulse (Fig. 4), indicating an interaction between both pulses in rapid succession. On the assumption that the first pulses in a two pulse burst ablates as much as a single pulse and that the second pulse does not contribute to the ablation at all, the efficiency should drop to half of that of a single pulse. Since the efficiency of the 2-pulse burst is even lower, material has to re-deposited to the sample to explain the behavior. The situation becomes even more astonishing if a third pulse is added to the pulse train. The efficiency rises significantly by approx. 20% above that of a single pulse (Fig. 4). This observation underpins the statement that (at least for copper) the individual pulses in a pulse burst interact in terms of influencing the measurable effect.
The advantage gets lost when the inter-pulse distance is increased (Fig. 5). The efficiency decreases to a little bit below a single pulse.

This pronounced change in the efficiency that can be observed when changing from single pulse to a 2-pulse burst, and a 3-pulse burst on the one hand can be utilized to increase the maximum ablation rate and on the other hand to deepen the understanding of the ablation process itself.

3. Experimental Set-up

The experiments were performed on a FUEGO laser system with a pulse duration of $\tau_H = 10$ ps and an average power of $P_{ave} > 40$ W at its fundamental wavelength of $\lambda = 1064$ nm. Pulse bursts with up to 8 pulses can be selected and the energy of each pulse in a burst can be adjusted individually. The time spacing $\Delta t_{\text{burst}}$ between two pulses in a burst is based on the repetition rate of the seed oscillator of 82 MHz and amounts to $\Delta t_{\text{burst}} = 12$ ns.

The laser beam passes a quarter wave plate to create circular polarization and a magnification telescope before entering an intelliSCAN DE14 scan head. For the applied focusing f-theta-objective with a focal length of $f_{\text{ foc}} = 160$ mm the minimum beam radius was measured to be $w_0 = 16$ $\mu$m. The set-up was used in the synchronized configuration allowing defining the pitch $p$ in x- and y-direction at a preset repetition rate $f_{\text{rep}}$ of the laser resulting in a feed rate.
\[ v = p \cdot f_{\text{rep}}. \]  
\hspace{1cm} (6)

The pitch in x- and y-direction was set to the same value of \( p_x = p_y = p = w_0/2 = 8 \mu m \) and squares with a side length of \( s = 2.0 \, \text{mm} \) were machined into \( 50 \, \text{mm} \times 50 \, \text{mm} \times 2 \, \text{mm} \) copper plates DHP (C12 200).

The removal rate per average power, the so called specific removal rate, is defined by the laser repetition rate \( f_{\text{rep}} \), the pitch \( p \), the number of slices \( N_{\text{Sl}} \) and the depth \( d \) of the machined squares:

\[ \frac{dV / dt}{P_{\text{ave}}} = \frac{\Delta V}{E_p} = \frac{d \cdot p^2}{N_{\text{Sl}}} \cdot \frac{f_{\text{rep}}}{P_{\text{ave}}} \]
\hspace{1cm} (7)

At a fixed repetition rate \( f_{\text{rep}} \), pitch \( p \) and number of slices \( N_{\text{Sl}} \) a sequence of squares was machined with varying pulse height distribution for a 3-pulse burst as shown in Fig. 6.

(Fig. 6: Schematic representation of FlexBursts)

The individual pulse energy \( E_{H,i} \) was set by configuring the relative pulse height. To do so the amplification factor of each single pulse was varied while the resulting pulses were monitored by means of an oscilloscope. The absolute pulse energy \( E_{H,i} \) was set by calculating the total energy of all pulses \( E_{H,\text{total}} \) and choosing the average power \( P_{\text{ave}} \) according to the foreseen peak fluence \( \phi_0 \) at a given repetition rate \( f_{\text{rep}} \). The total pulse energy is given by

\[ E_{H,\text{total}} = \sum_i E_{H,i} \]
\hspace{1cm} (8)

For example, the average power \( P_{\text{ave}} \) for the configuration FlexB_100-050-100 at a given repetition rate \( f_{\text{rep}} \) was calculated by

\[ P_{\text{ave}} = E_{H,\text{total}} \cdot f_{\text{rep}} = \left( E_{H,1} + E_{H,2} + E_{H,3} \right) \cdot f_{\text{rep}} = \left( E_{H,\text{single}} + 0.5 \cdot E_{H,\text{single}} + E_{H,\text{single}} \right) \cdot f_{\text{rep}} = 2.5 \cdot E_{H,\text{single}} \cdot f_{\text{rep}} \]
\hspace{1cm} (9)

and the pulse energy of the single pulse \( E_{H,\text{single}} \) was taken from
\[
\phi_0 = \frac{2}{\pi \cdot W_0} \cdot E_{\text{H,single}}
\]

(10)

Consequently the specific removal rates of different pulse burst settings can be compared when plotting them against the peak fluence \( \phi_0 \).

4. Experimental Results and Discussion

The depth \( d \) of the machined squares was measured by means of a white light interference microscope (smartWLI from gbs). The average of 10 measurements in x-direction and 10 measurements in y-direction was used to calculate the specific removal rate. Fig. 7 shows the specific removal rate depending on the peak fluence for a 3-pulse burst. To exclude a dependency of the specific removal rate on the repetition rate \( f_{\text{rep}} \) and the number of slices \( N_{\text{Sl}} \), some series were repeated with a different repetition rate \( f_{\text{rep}} \) and different number of slices \( N_{\text{Sl}} \). The efficiency does not change when the repetition rate \( f_{\text{rep}} \) is increased from 200 kHz to 1000 MHz or when the number of slices \( N_{\text{Sl}} \) is increased from 32 to 64.

Fig. 7: Specific removal rate for copper for a 3-pulse burst

Fig. 8: Specific removal rate for copper for a 3-pulse burst, varying the height of the center pulse
For a 3-pulse burst with equal pulse height at single pulse level the efficiency is increased by approx. 20% compared to single pulse ablation (Model) at the optimum point, as already shown by Neuenschwander et al. (2015). With increasing fluence $\phi_0$ the specific removal rate drops faster for a 3-pulse burst than for a single pulse. The break-even point is approx. two times the optimum fluence $\phi_{0,\text{opt}}$ at $\phi_0 = 4 \text{ J/cm}^2$ where the 3-pulse burst becomes less efficient than a single pulse according to the model.

By varying the height of the center pulse in a 3-pulse burst the specific removal rate can be influenced as shown in Fig. 8. When the center pulse height of a 3-pulse burst is reduced to 75% of the height of a single pulse the efficiency does not decrease but stays at the level of a 3-pulse burst with equally high pulses. Reducing the height of the center pulse to half of that of a single pulse decreases the specific removal rate by more than 30%. The specific removal rate further drops if the height of the center pulse is lowered to 25% of the single pulse height. It stays at that level even if the center pulse height is set to zero. This situation represents a 2-pulse burst with double time spacing $\Delta t_{\text{burst}} = 2 \times 12 \text{ ns} = 24 \text{ ns}$.

In addition, Fig. 8 shows that the repetition rate does not affect the specific removal rate independent of the pulse burst configuration. Reducing the height of the center pulse to half of that of a single pulse at a repetition rate of $f_{\text{rep}} = 200 \text{ kHz}$ decreases the efficiency by the same factor as it does at a repetition rate of $f_{\text{rep}} = 1 \text{ MHz}$.

Since the physical effects of material removal by means of ultra-fast laser radiation are not understood yet and there is no adequate model to describe the ablation behavior of metals, the fundamental difference between the application of pulse bursts on steel and copper cannot be explained up to now. For copper, the most probable explanation today takes into account a shielding of the subsequent pulse by the ablated material. This means that the second pulse in a 2-pulse burst with a time spacing of $\Delta t_{\text{burst}} = 12 \text{ ns}$ is absorbed in a plume of ablated material, induces turbulences and destroys the plume which leads to a deposition of ablated material on the surface. If the energy of the second pulse is relative low, it might be absorbed in the plume, but does not destroy it, and the third pulse still is absorbed and affected by the ablated material in the plume. The lifetime of such a plume of ablated material seems to be longer than $72 \text{ ns}$ because a 3-pulse burst with a time spacing of $\Delta t_{\text{burst}} = 36 \text{ ns}$ still shows reduced efficiency.

Beyond a certain level, the pulse energy is sufficient to destroy the plume of shielding particles, such that the subsequent pulse does not get absorbed in the plume. Analyses of the surface of copper plates, which were machined by ultra-fast laser radiation, give a hint why the efficiency of this subsequent pulse is extra-ordinary high.

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**Fig. 9:** SEM images of machined copper surfaces according to Fig. 7 and Fig. 8; approx. optimum fluence $\phi_{0,\text{opt}} = 2.6 \text{ J/cm}^2$
the scale bar represents 20 microns, resp. 10 microns

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**Table:**

<table>
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<th>Repetition Rate</th>
<th>200 kHz</th>
<th>1000 kHz</th>
<th>1000 kHz</th>
<th>1000 kHz</th>
<th>1000 kHz</th>
<th>1000 kHz</th>
<th>200 kHz</th>
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</thead>
<tbody>
<tr>
<td>Layers</td>
<td>32 Layers</td>
<td>64 Layers</td>
<td>64 Layers</td>
<td>64 Layers</td>
<td>64 Layers</td>
<td>64 Layers</td>
<td>64 Layers</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.154 mm^3/(min·W)</td>
<td>0.162 mm^3/(min·W)</td>
<td>0.158 mm^3/(min·W)</td>
<td>0.114 mm^3/(min·W)</td>
<td>0.057 mm^3/(min·W)</td>
<td>0.054 mm^3/(min·W)</td>
<td>0.105 mm^3/(min·W)</td>
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</tbody>
</table>

Fig. 9 shows SEM images of machined copper surfaces with different 3-pulse burst configurations according to the results presented in Fig. 7 and Fig. 8. The upper line was taken at a magnification of 4000×, the line below at
10000×. The images shown represent the surfaces of squares machined closest to the optimum point at approx. \( \phi_{0,\text{opt}} = 2.6 \text{ J/cm}^2 \) for a single pulse. The corresponding specific removal rate is stated under the images. At first glance the surfaces do not show any fundamental differences in terms of topology and morphology. All surfaces have molten structures of same size and distribution. But regarding the surfaces in more detail they reveal variations in the form of the molten structures as shown in Fig. 10. Structures machined with a significantly lower specific removal rate of approx. one third of the highest specific removal rate measured, i.e. with pulse configurations 100-025-100 and 100-000-100, show solidified waves or droplets with a size of a few microns and partially meshes of much smaller droplets with sub-micron size. The surface of structures machined with the highest specific removal rate, i.e. with pulse configurations 100-100-100 and 100-075-100, is covered completely with craters of frozen exploding bubbles of different sizes from some ten nanometers to about one micron.

This leads to the suggestion that the surface temperature during processing with the latter burst configurations is considerable higher compared to a surface processed with the first burst configurations. Not least due to the fact that the provided total energy of those 3-pulse bursts differ by 20% to 50% this might appear logical. The transition from solidified waves corresponding to low efficiency to frozen exploding bubbles corresponding to increased efficiency seems to be smooth and fluent. The link between those two, the burst configuration 100-050-100, shows features of both as can be seen from Fig. 10. In contrast to that, the sudden rise in the specific removal appears to be less comprehensible.

<table>
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<th>Frequency</th>
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<th>Pulse Configuration</th>
<th>Specific Removal Rate</th>
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<td>64</td>
<td>100-100-100</td>
<td>0.162 mm³/(min W)</td>
</tr>
<tr>
<td>1000 kHz</td>
<td>64</td>
<td>100-050-100</td>
<td>0.114 mm³/(min W)</td>
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<td>1000 kHz</td>
<td>64</td>
<td>100-000-100</td>
<td>0.054 mm³/(min W)</td>
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</table>

Fig. 10: Magnification of SEM images of machined copper surfaces according to Fig. 7 and Fig. 8; approx. optimum fluence \( \phi_{0,\text{opt}} = 2.6 \text{ J/cm}^2 \)

Taking into account the absorbed energy in the material and not the total provided energy by the pulse burst, and combining it with the consideration of a shielding plume, the small differences in the surface structure and the increase in efficiency become less mystifying.

If the relative energy of the second pulse is too low to destroy the plume of shielding particles the third pulse gets absorbed in there, destroys the plume and deposits ablated material on the surface. The meshes of small droplets represent this deposited material.

If the relative energy of the second pulse is high enough to clear the path for the third pulse and the ablated material is deposited on the surface, the third pulse can be absorbed to a large extend in the workpiece. As a consequence, the surface on the one hand is heated up and on the other is modified in a way that the absorption is increased. This leads to a higher energy input into the material and thus to a higher specific removal rate. As the images illustrate, at least for copper ablation is a thermal process and far from being “cold”.
To support this allegation, the first and the third pulse in a 3-pulse burst were varied. In a first series these outer pulses were reduced similarly from 100% to 25% in steps of 25%. In addition, the first pulse individually was reduced to 50%.

![Fig. 11: Specific removal rate for copper for a 3-pulse burst, varying the height of the first and last pulse](image)

Fig. 11 shows the variation of the height of the first and the last pulse in a 3-pulse burst at a repetition rate of $f_{rep} = 200 \text{ kHz}$. The reduction of the first and last pulse down to 75% does not have an impact on the efficiency, i.e. the specific removal rate stays at the high level of a 3-pulse burst with similar individual pulse height. Reducing the height of the outer pulses in a 3-pulse burst to 50% decreases the efficiency to the level of a single pulse. If only the height of the first pulse in a 3-pulse burst is reduced down to 50% the efficiency does not decrease; it remains on the high level of an equally leveled 3-pulse burst. Not until the height of the first and last pulse is reduced to 25% the efficiency drops significantly below that of a single pulse.

Taking up again the aspect of total energy of the pulse burst the above mentioned facts do not fit the picture. The burst configuration 100-050-100 results in a reduced efficiency, whereas the burst configurations 075-100-075 and 050-100-100, which have the same relative total burst energy, lead to increased efficiency. Furthermore, the burst combination 100-025-100 already has the lowest efficiency and the burst configuration 050-100-050 has a normally high efficiency.

![Fig. 12: Images of machined copper surfaces according to Fig. 11; approx. optimum fluence $\phi_{0, opt} = 2.6 \text{ J/cm}^2$](image)

<table>
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<th>$\phi_{0, opt}$</th>
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<td>64 Layers</td>
</tr>
<tr>
<td>100-100-100</td>
<td>075-100-075</td>
<td>050-100-050</td>
<td>025-100-025</td>
<td>050-100-100</td>
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</tr>
<tr>
<td>0.157 mm$^3$/min W</td>
<td>0.156 mm$^3$/min W</td>
<td>0.143 mm$^3$/min W</td>
<td>0.101 mm$^3$/min W</td>
<td>0.156 mm$^3$/min W</td>
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</table>
Fig. 12 shows images of machined copper surfaces according to Fig. 11 at approx. the optimum fluence \( \phi_{\text{opt}} = 2.6 \text{J/cm}^2 \). No discoloration is visible. All surfaces appear bright and matt.

These results confirm the hypothesis that the second pulse in a 3-pulse burst is essential and crucial for the rise in efficiency. The first and the third pulse can be varied to a large extend without influencing the increased specific removal rate. If the second pulse is reduced to a relative height of less than 75% the efficiency drops drastically.

This leads to the suggestion that a variation or fluctuation in the individual pulse energy of the outer pulses in a 3-pulse burst to a certain extend does not change the efficiency of the process. On the one hand and especially from an industrial point of view, the process therefore is robust and stable against fluctuations in pulse energy \( E_{\text{eff}} \) and average power \( P_{\text{ave}} \) and is scalable to higher repetition rates \( f_{\text{rep}} \) and therefore to higher average power \( P_{\text{ave}} \). On the other hand, the efficiency of the process can be increased by applying the appropriate pulse burst configuration with a determined second pulse in the 3-pulse burst at a relative height of 100%.

5. Conclusion and Outlook

The presented experiments verified, continued and detailed the experiments published by Neuenschwander et al. (2015). Applying a 2-pulse burst with an inter-pulse distance of \( \Delta t_{\text{burst}} = 24 \text{ns} \) drops the efficiency to less than half of the efficiency of a single pulse ablation. Even introducing a third pulse in the middle with up to 25% height of a single pulse does not increase the efficiency. This confirms the assumption that the specific removal rate reacts sensitively to the height of the center pulse between 25% and 75% of the single pulse height. The efficiency or the specific removal rate can be influenced and in the particular case of copper increased by varying the height of single pulses in a pulse burst. According to the results the height of the center pulse in a 3-pulse burst is decisive and should only be varied in the range of 100% down to 75% of that of a single pulse. In this configuration a 3-pulse burst increases the efficiency by approx. 20%.

Finally, investigations on the residual heat remaining in the workpiece after microprocessing with ultra-fast laser radiation are ongoing and will be intensified.

References


