Ultrashort-pulsed laser processing with spatial and temporal beam shaping using a spatial light modulator and burst modes

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Abstract. We report on the effect of simultaneous spatial and temporal beam shaping on the ablation rate, ablation efficiency and the resulting surface characteristics of micromachined stainless steel using ultrashort-pulsed lasers. Beam shaping and the use of pulse bursts are promising methods to allocate the over the last decades increasing laser power of ultrashort-pulsed lasers in ablation processes. While the individual effects of beam shaping and pulse bursts on the ablation characteristics have recently been examined, the combination of both has not yet been adequately investigated. Using a spatial light modulator to generate different spot distributions with up to six spots and different separations it is possible to spatially distribute the available laser power. In combination with temporal beam shaping using a 200 kHz repetition rate and pulse bursts with a 40 MHz intra-burst rate, we investigate the influences in a scanning-based process and find an increasing ablation rate and efficiency for higher fluences. Subsequently using bursts in combination with a multi-spot beam profile, we found a distinctive emergence of cone-like protrusions and a smoothing effect for fluences between 1.5 J/cm² and 3 J/cm² with six spot beam profile.

1. Introduction
The use of ultrashort-pulsed lasers has been proven to exhibit advantages for high quality requirements in laser micromachining. Especially processing stainless steel has been investigated for several years to optimize removal rates and the processed surface quality by using different laser parameters [1–3], pulse durations [4; 5], beam profiles [6–8] or machining strategies [9]. However, for industrial use often the throughput of ultrashort-pulsed laser based machining approaches is not high enough. And since for steel the preferable fluence level for efficient machining is determined to be within the range of 0.2–0.4 J/cm², a simple increase of the available average to several hundred Watts does not advance micromachining [1; 2]. Quite the contrary, a higher fluence results in negative effects like heat accumulation [10; 11], plasma shielding [12] and as a consequence in a lower ablation efficiency [11].

An approach to distribute the available laser power is by using spatial beam shaping technology [13; 14]. Optical beam shaping can be achieved by different solutions like digital mirror devices, deformable mirrors, diffractive optical elements, acusto-optic deflectors and spatial light modulators (SLM) [15]. With these optical elements it is possible to shape the beam towards the desired spatial intensity distribution including multi-beam arrays, top-hat profiles and Bessel beams [16–18].
In the time domain, also the burst mode emerges to be a promising method of increasing the throughput of ultrashort-pulsed laser processes due to an increasing removal rate [19–21]. With the possibility to distribute the energy of a single pulse to a certain number of sub-pulses, the potentially available fluence can be split over the sub-pulses to maintain efficient material removal per sub-pulse. Using a MHz burst, two intra-burst pulses have a distance of a few nanoseconds, whereas in GHz burst regime the delay of two pulses is in the picosecond range. [22] While for a delay of a few nanoseconds, the residual heat of a preceding pulses can lead heat accumulation effects with an adverse effect on the removal rate [23; 24] a delay in the picosecond range may results in stronger shielding effects induced by plasma formation [20; 25].

While the individual effect of beam profiling and pulse bursts on the ablation characteristics have recently been examined by various studies, the combination of both has not yet been adequately investigated. In the context, here we investigate the combination of different beam profiles and pulse burst in the MHz regime in a scanning based process on stainless steel with particular focus on the ablation rate, ablation efficiency, and surface characteristics.

2. Experimental

We use an Yb:YAG laser (Amplitude Tangor) with a wavelength of 1030 nm and a maximum power of 100 W. The laser is integrated into a micromachining system (Pulsar Photonics, RDX-1000), which uses a galvo scanner (Scanlab, IntelliSCAN®14) and a F-Theta lens (QiOptiq, LINOS F-Theta Ronar) with a focal length of 100 mm. The focal diameter \(d_0\), measured by a high-resolution CCD camera (IDS, UI149xLE) is 41 µm (1/\(e^2\)). The respective fluence is calculated by \(\Phi = E_p / (\pi \cdot r_0^2)\), with \(E_p\) being the pulse energy and \(r_0\) the radius of the focal beam.

Experiments are performed using a pulse repetition rate of 200 kHz with 800 fs pulse duration (FWHM, measured after laser aperture by an autocorrelator) and a scanning speed of 2968 mm/s, resulting in a pulse overlap of 64%. While the intra-burst repetition rate is given by the oscillator frequency at a constant value of 40 MHz, the laser can emit burst packages with a size of 200 maximum, dependent to the used repetition rate. The SLM based beam shaping module (cf. Fig.1) allows dynamic beam shaping to generate different spot distributions with a maximum frame rate of 60 Hz. To protect the LCOS-SLM (Hamamatsu X15223), an effective active liquid cooling system is integrated. Required computer generated (CGH) holograms are calculated using an iterative flourier.
transform algorithm. After the initial calculation of the CGH, the uniformity of the single sub-beams in the focal plane is further improved by a feedback loop based weighted Gerchberg-Saxton algorithm [26]. As the diffraction efficiency for each CGH differs, we control the total reflective power from the SLM using a power meter (Gentec EO, UP25N 100H H9) to ensure equal power impingement for each beam profile. The ultrashort-pulse laser is used to ablate a defined geometry, i.e. a cavity in a precise layer-by-layer ablation process by scanning the laser spot over the sample. The bidirectional hatched area has a size of 2 x 2 mm². By adding an additional rotation of α = 11° after each hatch, we obtained a homogenous irradiated surface after 50 scans. The ablated stainless steel (X5CrNi18-10) structures are analyzed by a laser-scanning microscope (Keyence, VK-X200series) and a scanning electron microscope (Tescan, Maia3 TriglarTM).

3. Results and discussion

3.1. Ablation rate and efficiency

Ablation characteristics shown in Fig. 2-5 are studied by employing different laser powers and burst package sizes in a scanning based process with 50 layers in a fluence range between 0.28 J/cm² and 2.8 J/cm². For the differently used beam profiles with a constant spot separation of 90 µm, the laser power range is customized on the spot number to retain the same fluence per spot.

The results shown in Fig. 2 reveal a higher ablation efficiency for a single pulse and a lower number of bursts for fluences below 1.5 J/cm², where the graphs intersect. This is in accordance to previous studies by Jaeggi et al., showing a similar devolution in a fluence zone around 1.5 J/cm² for a spot radius of 16 µm with a wavelength of 1064 nm on stainless steel [27]. Above this level, the ablation efficiency decreases with a low gradient for the single pulse and burst two, while for higher bursts the ablation efficiency increases slightly to a maximum of 0.2 mm²/min W. However, the optimum fluence is shifted to higher values using of a higher number of bursts, concurring with investigations of Kramer et al. [19]. As shown in Fig. 3, for a fluence of 0.6 J/cm² all beam profiles show a similar trend of the ablation rate with a decreasing character for higher burst numbers. The comparatively low fluence of 0.6 J/cm² results in a high ablation rate for a single pulse and lower rates for a higher number of bursts, because the used energy is equal or below the optimal fluence of 0.3 J/cm² [6] for the machined material, agreeing with studies using a single spot process [22]. This behaviour is supported by the increasing negative slope for a higher number of spots and thus the distribution of the energy used over several sub pulses.
Based on these results, we following study the influence of a different number of sub beams in the same fluence range to detect any influence of the combination of temporal and spatial beam shaping on the ablation efficiency and ablation rate. Due to an intensity uniformity of minimum 0.95 regarding the multi spot profiles, the fluence in each spot is almost the same.

As depicted in Fig. 4 both, the three and the six spot beam profile exhibit the same characteristics. A low fluence in combination with bursts tends to result in a decreasing ablation efficiency, while for a higher fluence bursts from two to five induce an ablation efficiency higher than a single pulse, a typically behaviour for using a single spot [25]. As depicted in both charts, the disparities for the tested bursts are very small for fluences between 2.2 and 2.8 J/cm² also observed for a fluence of 2.5 J/cm² for two to 10 bursts form Lickschat et al. [22].

In Fig. 5 we illustrate the achievable ablation rates for a spot number from one to six and bursts from one to five for a fluence of 2.8 J/cm². Using the six spot profile and a burst number of three, we achieve a maximum of 7.7 mm³/min, which corresponds with a factor of 1.4 as compared no burst usage. For almost all investigated beam profiles a burst number of tree results in the highest ablation rate, which can be concluded from an optimum in terms of process efficiency. The lower ablation rate of burst 2 could be due to the absorption of the second impinging pulse by the still existing plasma formation, so

**Figure 4.** Ablation efficiency for a three (left) and six (right) spot profile and fluencies between 0.28 and 2.8 J/cm² for different bursts. The ablation efficiencies are calculated of the basic surface level and the average depth of the ablated geometry, the calculated process time and the used laser power.

**Figure 5.** Ablation rate for a fluence of 2.8 J/cm² for different bursts and number of spots. The ablation rate is calculated of the basic surface level and the average depth of the ablated geometry after 50 scanning layers.

**Figure 6.** Effect on the roughness of different bursts, a single spot and fluencies between 0.28 and 2.8 J/cm². The measured surface is a rectangle of 80x60 µm on the bottom with 50 layers ablated volume, recorded with a 150x enlargement.
that it hardly produces any ablation. The use of burst 4 and thus the division of the pulse energy into four sub-pulses leads to a lower ablation efficiency (Fig. 4) and thus also to a lower ablation rate.

However, we found no negative influence using multi spot beam profiles with a separation of 90 µm and bursts with a repetition rate of 40 MHz, but a possibility to distribute a laser power of 45 W for six spots in an efficient micromachining process with a maximum ablation rate of 7.7 mm³/min, which is a great value compared to those reported in literature.

3.2. Surface characteristics

Equal to the prior documented parameters ablation rate and –efficiency, another important aspect for micromachining processes for industrial applications is the surface quality. In particular, ultrashort-pulsed lasers are distinguished for low surface roughness, but with an increasing available laser power and resulting high process fluences this advantage is competing with machining time.

Figure 6 shows the influence of bursts one to five for a fluence between 0.28 and 2.8 J/cm² using a single spot. While the increasing roughness of the single pulse shows an almost linear increase in a typical range [28; 29], burst two and three commute at a constant roughness around 0.6 µm above a fluence of 1 J/cm². Using burst four and five, the roughness increases to the highest value of 1.7 µm, leveling down for fluences above 1.5 J/cm to the measured minimum of 0.3 µm. Lickschat et al. measured a surface roughness in the same range for a burst of four and five with a pulse duration of 1 ps on stainless steel [22].

As illustrated in Figure 7, obviously, higher fluence results in larger roughness for multi spot ablation processes using no burst mode, similar to previous studies using the same laser setup but different beam distributions [6]. For the tested bursts, the results show a corresponding behavior with a slightly drift of the maximum roughness to higher fluence, increasing the number of spots. However, expecting the high ablation rate above 7 mm³/min for a six spot profile, a burst of three and a fluence of 2.5 J/cm², we reached a comparatively low roughness of around 1.5 µm. This low roughness might be attributed to the removal of the previously generated CLP structures (Fig. 8) and possibly to a melting of the material due to higher heat accumulation, which resembles a smoothing effect. In combination, the high removal rates achieved in conjunction with a low roughness demonstrates the high potential of the combined burst and multi spot ablation.

To investigate the different slopes regarding the influence of bursts, fluence and the spot number, in Figure 8 we depict different surfaces, taken with a scanning electron microscope for the single spot and the 4 spot beam profile. Apparently, the variation of roughness can be identified by structure formations influenced by the fluence, the number of burst and the spot number. Using a single spot and higher bursts, the formation of so called cone like protrusions (CLP) is reinforced for a fluence of 1.4 J/cm². After exceeding this fluence, the CLPs are ablated and a smooth surface results, corresponding to the
results shown in Fig. 6 and previous studies [22; 30]. The ablation of material at too high peak fluencies causes a pronounced formation of cavities, craters and CLPs. This behaviour can be deferred to higher fluences using bursts [31]. As the surfaces ablated with the four spot profile show in Fig. 8, these effect can be reinforced with the consequence of distinct CLP formations until a fluence of 0.8 J/cm². Comparing the first and fourth column in Figure 8 shows that the use of a higher average power distributed over four spots results in a more pronounced emergence of CLPs even without the use of bursts. This effect increases with the use of burst three and five, which leads to the emergence of CLPs already in the range of lower fluences and generally larger CLPs in the higher fluence range. Furthermore, using SLM based beam shaping, higher diffraction orders occur around the obtained beam profile, or scattered radiation between the spots. Although these do not reach high fluences, so that no material is ablated, they can still heat it before the ablation process through the spots. These assessments are consistent with studies by other authors that identify heat accumulation as one of the driving factors in the formation of CLPs [32].

Figure 8. Illustrations of the different surfaces after 50 layers ablation, taken with a scanning electron microscope. Resulting surfaces for various fluences and numbers of bursts are shown using a single spot (left part) or a four spot profile (right part).
4. Conclusion
We have demonstrated the combination of spatial and temporal beam shaping and their effects on ablation efficiency, ablation rates and surface characteristics in a scanning based ultra-short pulsed laser ablation micromachining process on stainless steel. To increase the maximum ablation rate and for investigation of effects induced of a 40 MHz burst and different spot distributions, we combine bursts from one to 5 with a maximum of six spots, finding ablation rates up to 7.7 mm³/min with an ablation efficiency of 0.2 mm³/min-W. Due to the high ablation efficiency and a suitable pulse interaction behaviour, the highest ablation rates are achieved with Burst 3. We found no negative effects regarding the ablation rate and efficiency using spot numbers from one to six but a correlation between the charts of the corresponding bursts and an efficient way to distribute a laser power of 45 W with six spots in a micromachining process. In addition, we show different roughness characteristics between a single pulse and the usage of bursts, with only a minor drift to higher fluences, increasing the number of spots. Compared to a single spot process with the highest used fluence, combining bursts of two or three and a multi-spot results in a lower surface roughness during a higher removal rate. Furthermore, we note reinforced formation and size of cone like protrusions in some fluence zones when we use the multi-spot profiles and bursts, which could be related to increased heat accumulation resulting from higher average power, higher orders or scattered radiation due to the SLM based beam shaping or the heat influence of the bursts in MHz range. Finally, both a higher removal rate and a low roughness can be achieved by the right combination of temporal and spatial beam shaping, using bursts and multi-spot profiles.

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