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Comparison of high rate laser ablation and resulting structures using continuous and pulsed single mode fiber lasers

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Abstract

This paper compares high rate laser ablation and resulting structures of aluminum by using both a continuous wave and a ns-pulsed single mode fiber laser of high average laser power. Two different scan technologies were applied for fast deflection of the laser beams. In this work, 2.5D laser processing was studied by using a high aperture galvanometer scanner with a maximum scan speed of 18 m/s. By contrast, considerably higher scan speeds up to 1,000 m/s were achieved by using the in-house developed polygon scanner system.

The ablation rates and the processing rates per unit area were analyzed by means of the depths of line-scan ablation tracks and laser processed cavities. In addition, SEM photograph of the machining samples will be presented in order to evaluate the machining quality. Finally the feasibility of this high rate technology for industrial application is demonstrated by machining examples.

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Keywords: ns-laser; cw-laser; 2.5D processing; polygon scanner; high rate; ablation

1. Introduction

Up to now, Laser micro structuring is one of the most common laser applications. It is typically carried out using a pulsed fiber laser system with an average power of a few ten watts and some 10 kHz (Hügel 2009). Pulsed lasers are applied due to several advantages. They offer a cost-effective solution to yield high Laser power and

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corresponding process specific high intensities. Further they can be easily integrated in setups for industrial applications.

However since the last few years new high power fiber laser systems are available. They show much higher pulse repetition rates at an average power of some hundred watts and the same advantages concerning integration and handling. Therefore the processing time significantly decrease. But with such a laser source, effects like heat accumulation of the processed material become more obvious. An alternative and possible new way is to apply continuously emitting lasers. Ebert and Hartwig et al. (2009) has shown that high brilliance and high power cw lasers could be used for ablation cutting and structuring of cavities. It turned out that 2.5 D micro structuring can be done by cw radiation.

By high power lasers process specific energies can be supplied in much shorter times. Therefore high deflection velocities are necessary to take advantage of the high power laser system. Up to the present for fast deflection of laser beams mainly galvanometer driven laser scanning systems are preferred. The attainable velocity is depending of the chosen focal length of the f-theta optic attached to the scanning system. Large focal lengths result in high deflection velocities within the corresponding focal plane. However, the detrimental effect especially for micro machining is the correlation to the spot diameter, which results in decreased accuracies and disproportionately lower intensities for larger focal lengths.

Common available galvanometer scanner systems mainly contains two single axis one for each direction of deflection. A single axis is a system of the galvanometer itself and the respective mirror. During laser processing the deflecting mirrors have to be accelerate, moved to the intended position and finally decelerate. Synchronously to the beam deflection the laser has to be modulated. To yield the demanded material processing the material affecting energy has to have to a certain extent. Therefore the power of the laser has to be chosen in correlation to the indentent deflecting velocity. However, the acceleration and deceleration phase of the galvanometer results in uncertain amount of energy transferred to the material. A solution is to append acceleration and deceleration tracks to the respective scan vector. Non processive appended tracks are time consuming even when high deflection velocities are required caused by the correlation between appended track length and scanning speed. For Micro structures with a high complexity a large amount of scanning tracks are necessary. As a consequence, with an increasing deflection velocity the effective processing time depends more on the complexity of the structure than on the deflection speed itself.

Applying a polygon scanner system is a conceivable possibility. Such systems can achieve a much higher and constant deflection velocity and line frequencies (scanning tracks) independent complexity of the indented structures. The effective processing time depends directly from the required number of necessary single scan tracks to produce the intended structure. For industrial purpose such systems are still in developing.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>c</td>
<td>specific heat capacity</td>
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<tr>
<td>f</td>
<td>focal length</td>
</tr>
<tr>
<td>f_p</td>
<td>pulse repetition rate</td>
</tr>
<tr>
<td>\lambda</td>
<td>thermal conductivity</td>
</tr>
<tr>
<td>P_{av}</td>
<td>average Power</td>
</tr>
<tr>
<td>Q_p</td>
<td>pulse energy</td>
</tr>
<tr>
<td>\rho</td>
<td>specific density</td>
</tr>
<tr>
<td>\tau_p</td>
<td>pulse duration</td>
</tr>
<tr>
<td>v</td>
<td>scanning speed</td>
</tr>
</tbody>
</table>

2. Setup

Two high power fiber laser setups were used. One consisting of a cw single mode fiber laser YLR-400-LP-AC with a maximum power of 400 W at a central wavelength of 1070 nm. Deflection and focusing was realized by using the galvanometer scanner Raylase Superscan LD 30 with attached f-theta optics of a focal length of 160 mm.
The measured beam propagation factor was $M^2 = 1.1$. The laser beam is linearly polarized. The internal trigger frequency of the laser source is slow for a high speed application; therefore the laser is externally switched by acousto-optical modulators. Marquardt (2009) shows that this setup allows rise and fall times up to 180 ns.

The second laser setup is a pw single mode fiber laser IPG-HP-1-30x240-500-500 with a maximum average output power of 500 W and a central wavelength of 1065 nm. The beam propagation factor is $M^2 = 1.5$. The beam is randomly polarized. The shortest pulse duration is 30 ns and the maximum pulse energy is 1 mJ at 500 kHz at 240 ns. Caused by the fiber based laser buildup, the peak power is below 10 kW. For deflection both deflection system were used: an in-house developed polygon scanning system and the above mentioned galvanometer scanner. The focusing f-theta optics attached to the polygon system has a focal length of 420 mm. For the galvanometer scanner a f-theta optics with a focal length of 220 mm was used.

### Table 1. Setup overview.

<table>
<thead>
<tr>
<th></th>
<th>Galvanometer system</th>
<th>Polygon system</th>
</tr>
</thead>
<tbody>
<tr>
<td>laser</td>
<td>pw laser</td>
<td>cw laser</td>
</tr>
<tr>
<td>focal length [mm]</td>
<td>230</td>
<td>160</td>
</tr>
<tr>
<td>spot diameter d86 [μm]</td>
<td>32</td>
<td>29</td>
</tr>
<tr>
<td>maximum scanning speed [m/s]</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>max. average Power on sample [W]</td>
<td>480</td>
<td>367</td>
</tr>
<tr>
<td>max. intensity on sample [MW/cm²]</td>
<td>995</td>
<td>56</td>
</tr>
</tbody>
</table>

### 3. Test conditions

The experiments are made on pure aluminum samples with a thickness of 1 mm. Aluminum was chosen because of the determinated physical properties and the high industrial relevance as a lightweight material.

### Table 2. Material properties of aluminum.

<table>
<thead>
<tr>
<th></th>
<th>2702 kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>specific density</td>
<td></td>
</tr>
<tr>
<td>thermal conductivity</td>
<td>220 W(m·K)</td>
</tr>
<tr>
<td>Specific heat capacity</td>
<td>896 J/(kg·K)</td>
</tr>
<tr>
<td>melting temperature</td>
<td>660 °C</td>
</tr>
<tr>
<td>evaporation temperature</td>
<td>2450 °C</td>
</tr>
<tr>
<td>latent heat of fusion</td>
<td>3890 kJ/Kg</td>
</tr>
<tr>
<td>Latent heat for evaporation</td>
<td>10900 kJ/Kg</td>
</tr>
</tbody>
</table>

### 4. Results and discussion

#### 4.1. Cw laser

As visible in Tab.1, the achievable intensities affecting the material are a one magnitude smaller compared to the pulsed laser system. Therefore the amount of residual melt phase should be noticeable higher. This assumption is clearly visible in Fig. 1. However, a small amount of material is already evaporated during laser processing. Indirectly observable by the resulted formation resolidified melt. If evaporation takes place besides the liquid phases, the melt is accelerated by the rapid expansion of the vapor and/or the plasma plume.
Due to the limited heat conductivity for high scan velocities the melt is mainly ejected in opposite direction to the respective scan vector. If line scans are applied next to each other an overlay of these single track effects occurs, resulting in an apparently self-organizing structure of the material. First results shown, that depending of the chosen parameters these structures grow above the sample surface.

![Fig. 1. SEM-picture of self-organizing structures. The arrow shows scanning vector direction. Filled with line scans from the right to the left Parameters: v= 5 m/s, I= 28 MW/cm², line distance 10 μm, 10 scan passes, area 10x10 mm².](image)

To initiate a significant grow obviously a certain amount has to shifted. Fig. 2 illustrates this behavior by a series of single area scans. Primarily, the resolidified melt formation / wall like structures occur noticeable after a certain number of parallel scans, when the amount of deposited melt within a track reaches a certain level. It turned out, the height of and the distance between the walls align to the scanning direction is depending on scanning speed and applied intensity. Only a few repetitions are necessary to generate these formations.

![Fig. 2. Photo series of self-organization of the structure after every scan pass. The photos were made between passes. The arrow shows a scanning vector direction. Filled with line scans from the left to the right. Parameters: v= 5 m/s, I= 56 MW/cm², line distance 10 μm, area 10x10 mm².](image)

By understanding the principally mechanism behind these quasi-self-organizing structures, a well-aimed shaping of the resolidified material can obtained (Fig. 3).

For the illustrated specimen a special machining strategy was developed (Fig 3(a)), that allows to control the resulting formation. As Fig. 2 showed, long scan tracks primarily results in a consecutive shifting of melt out of the scanning track. Therefore, the scan vectors has to split into small elements to stop further movement of melts out of the track. Suitable lengths of these “micro” - vectors are all distances smaller compared to the resulting ones in the quasi-self-organized structures (Fig. 2). This distance depends on the applied intensities and scan velocity.
Fig. 3. (a) schematic diagram of applied machining strategy for controlled shifting of molten material, therefore small scan vectors in y-direction, respectively perpendicular to the up forming walls, were applied row by row (b) machining sample; Parameters: \( v = 5 \text{ m/s} \), \( I = 28 \text{ MW/cm}^2 \), length of single vector 200 \( \mu \text{m} \), line distance 25 \( \mu \text{m} \), 10 scan passes, thickness of the walls on top 50 \( \mu \text{m} \), height over and depth under sample surface about 200 \( \mu \text{m} \), machining time 3 min for 5 x 5 mm\(^2\).

4.2. Pw laser

4.2.1. Galvanometer scanner

Caused by the limited deflection velocities of the galvanometer scanning system, only by a significant reducing of the average power a micro structuring was possible. Due to the high pulse overlap primarily a deep drilling occur. As a detrimental effect the laser radiation is guided into deeper layers of the material and leads to a more volumetric absorption. Just like a deep welding process a noticeable amount of melt is yielded and seals the previously generated deep ablation crater.

4.2.2. Polygon scanner

4.2.2.1. Single track ablation

By applying a polygon scanner much higher scanning velocities can achieved. Caused by decreasing pulse overlap the primarily depth of drilling is significantly reduced and the laser radiation is absorbed mainly superficial. The smaller, close to the surface, amount of molten material is partly ejected by the rapid expansion of vapor and plasma plume. With increasing scanning velocity and pulse distance the ejection of molten material becomes more effective and turns into an ablation process. The part of material which is ejected in liquid phase decreases and material removal in gaseous phase increases. For sublimation a lot of energy is required so the removal rate decreases. However an increased quality due to less amount of remaining resolidified melt can be observed. Fig. 4 shows the resulting ablation depth by an increasing number of scans for different high deflection velocities of the laser beam.

Fig. 4. ablation track depth depending on repetitions and scanning speed; \( f_p = 2 \text{ MHz} \), \( P_{av} = 480 \text{ W} \), \( \tau_p = 30 \text{ ns} \), \( I = 0.58 \text{ GW/cm}^2 \).
As visible in Fig. 4, the ablation of deep structures are dividable into two stages for all curves. In a first stage (Fig. 4.; aprox. till 100 repetitions) a rapid ablation until a depth corresponding to the applied velocity occurs. In further processing the ablation rate is significant but obviously constant decreased. In generally, the achievable depth is inversely proportional to scanning velocity. Above 70 m/s the finally achievable depth for 1000 repetitions is almost the same. Besides the difference between the resulting ablations rates (rising of the curves) of the first and the second stage are smaller for higher velocities.

Fig. 5 a cross section view of a series of ablated single tracks with a different numbers of repetitions shows the characteristic resulting shapes at an average velocity of 20 m/s.

**Fig. 5.** Light microscope images of a test series by a variation of repetitions. $f_p=2 \text{ MHz, } v= 20 \text{ m/s, } P_{av}= 480 \text{ W, } t_p= 30 \text{ ns, } I= 0.58 \text{ GW/cm}^2$.

Caused by the high pulse overlap (pulse distance = 10 μm) a noticeable amount of molten and resolidified material is observable. For a low number of repetitions, resulting in a flat angle of the wall within the ablation track, the expanding vapor and plasma plume is able to eject the molten material (Fig. 5. (1 to 5 rep.) corresponding to the model in Fig. 6. (A)) and finally results in a high ablation rate. Further irradiations lead to a steadily increasing of the wall angle and depths. Therefore the ejection of molten material is partly inhibited and results in an up forming burr of resolidified material (Fig. 5. (10 to 20 rep.) corresponding to Fig. 6. (B)). At depths where the ejection of molten material is significant lower than remaining amount within the track the molten material is just shifted to the wall, start to form a funnel (Fig. 5. (50 rep.) corresponding to Fig. 6. (C)). For further irradiations the laser radiation is guided and reflected by the shape of the funnel and mainly absorbed at the walls. At this stage the resulting material removal is just caused by the directly evaporated amount (Fig. 5. (100 to 1,000 rep.) corresponding to Fig. 6. (D)) and leads to the significant decreasing of the ablation rate (Fig. 4) for a larger number of repetitions. At higher scan velocities, the pulse overlap decreases resulting in a significant lower heat accumulation and a decreasing amount of molten material and leads to a mainly evaporated driven ablation (straighten curves in Fig. 4 for higher velocities).

**Fig. 6.** schematic of processes of expulsion of molten material with increasing number of repeats; (A) after a small number of repetitions, circle-segment like removal, shallow wall angle (B) increasing depth and wall angle, decreasing expulsion of material (C) deposition of molten material on the walls, transition to funnel form; (D) laser beam is guided to the ground of the track because of being reflected on the walls, no expulsion of molten material, merely evaporation.
4.2.2.2. Ablation of larger areas

If overlapping scanning tracks were applied next to each other the propagation of the removed material is not inhibited. For average powers the process behavior within the ablating area is still that one corresponding to Fig. 6. (A). This leads to a high performance of the ablation process (Fig. 7) and the ablation rate per repetition does not decrease as in Fig 4.

![Diagram of ablation depth of structured areas against number of repetitions. Parameters: liner distance 5 μm, τ=30 ns, Q=0.23 mJ, f= 2 MHz, I= 0.58 GW/cm².](image)

To yield a flattened surface within the ablated area a line distance of 5 μm (maximum resolutions of the polygon scanner system) have to be chosen. Already at a line distance of 10 μm the quality of the surface decreases noticeable and a line distance of 60 μm (focal diameter 42 μm) and scan velocities of more than 80 m/s the tracks were separated.

![Optical micrograph of processed areas. Energy per area unit 48 J/mm², τ= 30 ns, Q= 0.23 mJ, f= 2 MHz, I= 0.58 GW/cm², line distance 5 μm. A) v=20 m/s, occurring of quasi-self-organized structures caused by overheating and shift of the molten material B) v=100 m/s C) 120 m/s D)180 m/s.](image)

Besides the flatness, the decreasing amount of remaining molten and resolidified material within the ablated areas is clearly observable. At relatively low scan velocities (Fig. 8. (A)) similar structures comparable to the quasi-self-organizing as a result of applying continuous lasers (Fig 1.) occur. Only the perturbation is obviously stronger due to the higher applied intensities.
Under consideration of the specific heat capacity and the latent heat for fusion and evaporation, an exemplary energy amount of 48 J/mm² should be sufficient to evaporate material to a depth of 1.3 mm. Taken into account a an average absorption of 10% for aluminum results in an ablation depth driven by merely evaporation of approximately 130 μm. This resulting depth is visible in Fig. 9 for scan velocities above 100 m/s.

Fig. 9. Ablation depth of structured areas with a constant energy per area unit. Constant energy input is realized with increasing number of scans with increasing scan speed. Energy per area unit 48 J/mm², \( t_p = 30 \text{ ns} \), \( Q_p = 0.23 \text{ mJ} \), \( f_p = 2 \text{ MHz} \), \( I = 0.58 \text{ GW/cm}^2 \), line distance 5 μm.

At lower velocities the ablation rate is obviously increased by the amount of expelled molten material, due to a melt pool affecting plasma and vapor expansion. The material is ejected, when the following pulse interacts with the previously generated melt pool, as the temperature field and phase state simulations from Streek (2013) in Fig 10. shows.

Fig. 10. Comparable temperature field and phase state simulation to Fig. 9 of aluminum irradiated with a moving laser beam of a) 20 m/s b) 50 m/s and c) 100 m/s for several pulses, \( f_p = 2 \text{ MHz} \), \( t_p = 30 \text{ ns} \), \( I = 0.5 \text{ GW/cm}^2 (I_{peak} = 1 \text{ GW/cm}^2) \). The simulation shows a cross section view of the irradiated material. Latent heats and loss of material by boiling was taken into account, not considered is the dynamic of the melt phase.

As the simulation shows, for relatively low scan velocities (Fig. 10. (a)) the overlap of the consecutive melt volumes corresponding to a spatially limited accumulation of the heat leads noticeable to a deeply molten amount of material. At increasing velocities the resulting melt pool is spread along the scanning direction. Besides a reduction of the melt pool deep is observable Fig 10. (b).
A scan velocity of 100 m/s result in strictly divided melt phases and (visible in the temperature field of the material) heat affected zones (Fig. 10. (c)). No further heat accumulation occurs and thermal influence of two consecutive pulses by a scanning speed above 100 m/s can be neglected.

By using the whole length (300 mm) of the possible scan vector supported by the polygon scanner system and scan speeds faster 100 m/s, the yielded removal rate would 2.7 mm³/s driven by a direct evaporation.

4.2.2.3. Machining samples

![Image](a.png) ![Image](b.png)

Fig. 11. (a) ablation of stairs, 5 stairs, every step has an increasing depth of 50 μm. The maximum depth is 250 μm, hole processed area 5x300 mm², v= 140 m/s, line distance 5 μm, 29 repetitions per step, processing time 6.9 min (b) grating, line distance 60 μm, v=80 m/s, 80 repetitions, processed area 3 x 300 mm², depth 85 μm, processing time 34 s; Laser parameters for both samples: I= 0.58 GW/cm², f_p= 2 MHz, τ_p= 30 ns.

Fig. 11. shows the implementation of the result to a micro structuring process. In Fig. 11. (a) the previous determined processing parameters were applied for 2.5 D structuring. An example for surface structuring by ablation, in form of a grating is presented in Fig. 11. (b).

5. Conclusion

The first investigations of quasi-self-organized melt structures applying a high power cw laser shows the possibility to directly control the spatial deposition, this allows micro structuring of large areas without or merely partial ablation.

Secondly, the applying of high power pulsed lasers is in combination with high scan velocities suitable for micro structuring of aluminum. Removal rates of 2.7 mm³/s with defined and well reproducible ablated average layer thickness per scan is possible with scanning velocities of more than 100 m/s. Caused by the high pulse repetition rate the molten material does not resolidify until the next pulse. The only way to avoid a formation of a melting pool is to choose a pulse-to-pulse distance higher than the pulse diameter. The results are supported by a temperature field and phase state simulation. Further the implementation of the result for 2.5 D micro structuring was presented.

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