High Throughput and High Precision Laser Micromachining with ps-Pulses in Synchronized Mode with a fast Polygon Line Scanner

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ABSTRACT

To be competitive in laser micro machining, high throughput is an important aspect. One possibility to increase productivity is scaling up the ablation process i.e. linearly increasing the laser repetition rate together with the average power and the scan speed. In the MHz-regime high scan speeds are required which cannot be provided by commercially available galvo scanners. In this work we will report on the results by using a polygon line scanner having a maximum scan speed of 100 m/s and a 50 W ps-laser system, synchronized via the SuperSync™ technology. We will show the results concerning the removal rate and the surface quality for working at the optimum point i.e. most efficient point at repetition rates up to 8.2 MHz.

Keywords: ps-Pulses, Polygon Line Scanner, Synchronized Mode, Micromachining, High Repetition Rates, High Average Power

1. INTRODUCTION

According to the two temperature model for laser micro machining with a Gaussian Beam the volume ablation rate per average power, also called as removal rate, can be described as a function of the laser peak fluence ϕ_0[1-3]:

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

where δ is the energy penetration depth and ϕ_{th} the threshold fluence. In Figure 1 the removal rate as a function of the laser peak fluence for copper is shown. It can be clearly seen that there is an optimum peak fluence $\phi_{0,opt}$ with a maximum removal rate. This optimum shows the point, where the ablation process is most efficient, which is well known in the literature[1-4] and be calculated as follow:

$$\phi_{0,opt} = e^2 \cdot \phi_{th} \qquad (2)$$

If the used peak fluence is below this optimum, the ablation process is very inefficient. For higher peak fluencies the material is overheated and the machining quality decreases.

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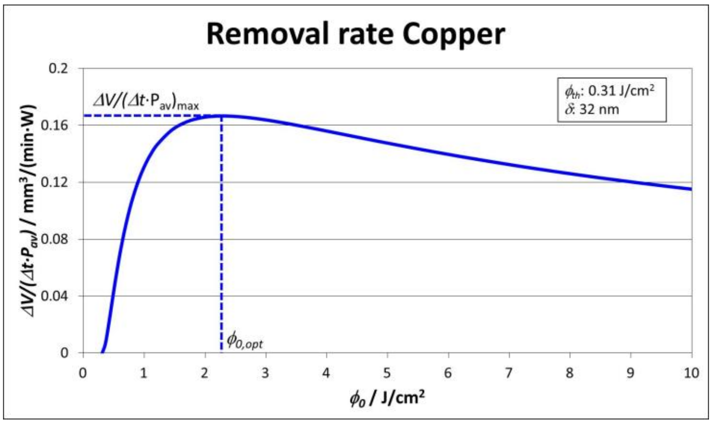

Figure 1: Removal rate for Copper in function of the laser peak fluence

Increasing the throughput is a key-factor for the industrialization of laser micro machining processes. This can be done in various ways. An obvious method is to increase the pulse energy to get higher ablation. But the downside of this approach is a rough surfaces and a bad quality[4], respectively, due to the fact that the working point is far away of the optimum point as expressed in equation (2), and the process is not as efficient as possible. A preferable approach is working with the optimum fluence. In the case of metals this peak fluence is relatively small. But in order to be able to use the full power range of an available ps-laser systems, for example 50-100 W average power and more[5,6], it is possible to parallelize the process. By doing so, the initially high pulse energy is divided down to the optimum energy. For example by using diffractive optical elements the high power beam is divided down onto several beams with optimum energy[7-14]. Another possibility is to work at high repetition rates to directly generate the required pulse energy for a single beam. If the repetition rate is increased, then the scan velocity has to be increased by the same factor as well in order to set the overlapping of two consecutive pulses as constant. Consequently a high deflection speed of the scanner is needed. Using common spot radii of about 20 µm and working with 75 % overlapping at a repetition rate of 1 MHz, then already a scan speed of 10 m/s is needed, which is about the maximum scan speed of a common galvo scanner. But using the full power range of the available ps-laser system, the repetition rate has to be increased again in the range of 10 MHz. This requires scan speeds of 100 m/s and more. Therefore other fast beam steering units have to be used like acousto-optic deflectors[5,15] or polygon line scanners[16,17] where the laser beam is deflected via a fast rotating polygon mirror wheel. After the mirror wheel the beam is focused with a flat field optic onto the work piece. The result is a fast unidirectional motion of the laser spot on the work piece. The rotation speed of the wheel must be controlled very precisely to obtain a constant marking speed. A linear stage aligned perpendicular to the scan line of the polygon line scanner gives the possibility to address a 2D-area. To create a 3D-structure a so called 2.5D-process is used, where the structure is divided into several layers. Each layer of the structure is convert into a black-and-white bitmap (Figure 2a), where each pixel represents one potential laser pulse. White pixels mean laser on and black pixels laser off or vice versa. Additionally the coordinates of the start position, e.g. the upper left corner of the bitmap, and the pitches in X- and Y-direction have to be defined as shown in Figure 2 b.

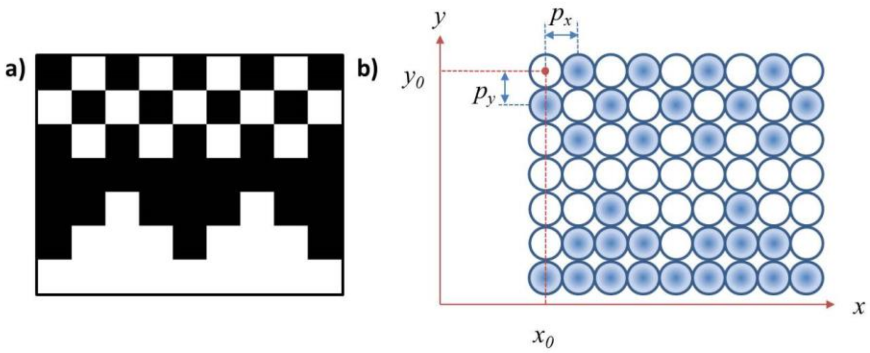

Figure 2: a) Basic black and white bitmap; b) Representation of the structuring information of the b/w-bitmap with the start position in the upper left corner.

Due to the MOPA design of the laser system different situations can happen at the beginning of the marking. If the acceleration of the beam start at once with the opening of the gating module, then at the beginning of the marked lines multiple pulses appears and results in deep acceleration-marks at the bottom (see Figure 3a). The acceleration problem is not applicable for a polygon line scanner due to the continuous rotation of the mirror wheel. If the beam is switched on, when the beam deflector already has the correct scan speed e.g. the continuous rotation of the polygon mirror wheel, then a jitter of about one spot radius of the first pulse appears due to the MOPA-design of the laser system (Figure 3b). This leads to a smaller taper angle compared with the situation with the acceleration-marks. Therefore for high precision laser micro machining a synchronization of the deflection unit and the laser pulse train is necessary (Figure 3c).

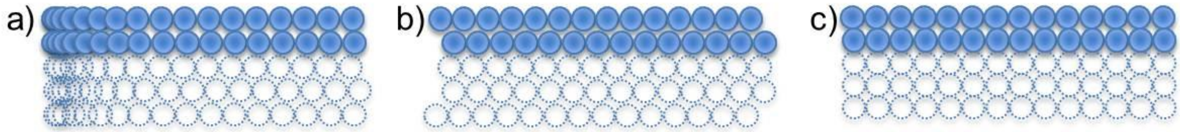

Figure 3: Begin of the marking a) standard setup; b) Sky-writing; c) Synchronized

This is solved by using the SuperSync™ technology of the used Time-Bandwidth Laser. The scan parameters have to be adapted to the new situation of a synchronized marking. The strategy was developed in previous works by using a synchronized galvo scanner[18-21]. A scanning strategy found to give high-quality results using a marking speed resulting in a pulse overlap of 75 %, equal to a pitch of a fourth of the beam radius w_0. For multiple passes, due to the synchronization, the laser pulses hit the sample at the same positions. This leads to a wave-like surface pattern. To avoid this periodic surface pattern, the starting point of each layer is shifted by a random value, which is generated by using a normal random distribution in a much smaller range than the jitter of the unsynchronized setup.

2. EXPERIMENTAL SETUP

The line scan engine LSE170A from Next Scan Technology is used in combination with a FUEGO 10 ps-laser of Time-Bandwidth Products. Additionally two linear axes, with 100 nm resolution from Jenny Science AG are used. The first axis is for the motion perpendicular to the scan line of the polygon i.e. cross scan direction. During the marking this axis is fully driven by the LSE170A controller via quadrature encoder signals in a slave mode. The second axis (direction parallel to the scan line of the polygon) is introduced to work with the developed scan strategy by using the normal random distribution for the starting points. Figure 4 shows a photograph of the polygon line scanner with the two linear axes.

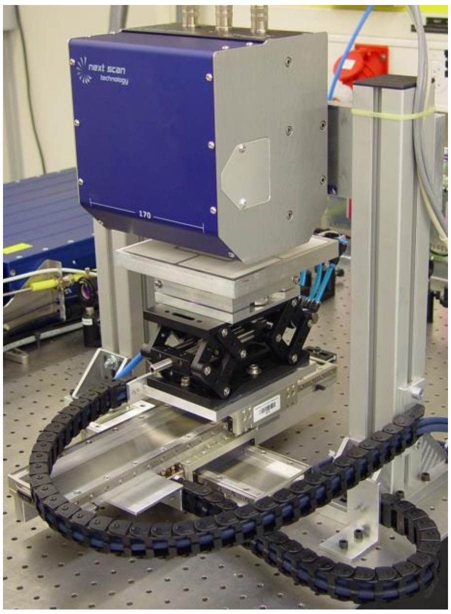

Figure 4: Polygon line scanner with the two linear axes

The used line scanner has an 8 facet mirror wheel, a scan length of 170 mm and offers scanning speeds from 25 to 100 m/s, which corresponds to a marking of 100 to 400 lines per second with a duty cycle of 70 %. The FUEGO laser system is working with repetition rates in the range from single-pulse up to 8.2 MHz. At 1064 nm wavelength a maximum average of 43.5 W (measured in front of the line scanner) can be used. The used beam radius in the focal plane is 28.9 um with an M^2 of 1.2 for 1064 nm, both measured with a slit scanning beam profiler from Thorlabs. The focus position was always set on the surface of the work piece. All the experiments were performed with the optimum fluence which is calculated according to equation 2. In order to compare the achieved ablation rates with the rates at smaller repetition rates an $\text{IntelliScan}_{\text{de}}$14 galvo scanner from Scanlab was used. Focusing the beam with a 160 mm f-theta optic leads to a beam radius in the focal plane of 16.2 um with an M^2 of 1.3. The determination of the ablation rate was done according to[4,22], by measuring the structure depth to calculate the ablated volume. As sample material Cu-DHP (in US: C12 200) and stainless steel 1.4301 (in US: AISI 304) were used. For testing the stability of the velocity control we used black-coated paper. For the used materials following peak fluences were used, calculated according to equation 2 based on the threshold fluence measured in[23].

Table 1: Threshold fluences and optimum peak fluences for the used metals

Material	**Threshold fluence / J/cm^2**	**Optimum peak fluence / J/cm^2**
Stainless steel 1.4301	0.055	0.4
Copper Cu-DHP	0.31	2.26

3. EXPERIMENTAL RESULTS

There is clear evidence that the control of the polygon line scanner is optimized for the higher scanning speeds. For lower speeds the positioning drift at the line end is significantly higher as for the fastest speeds (see Figure 5). As a consequence for high-quality surface structuring higher scan speeds, meaning higher pulse repetition rates should be used.

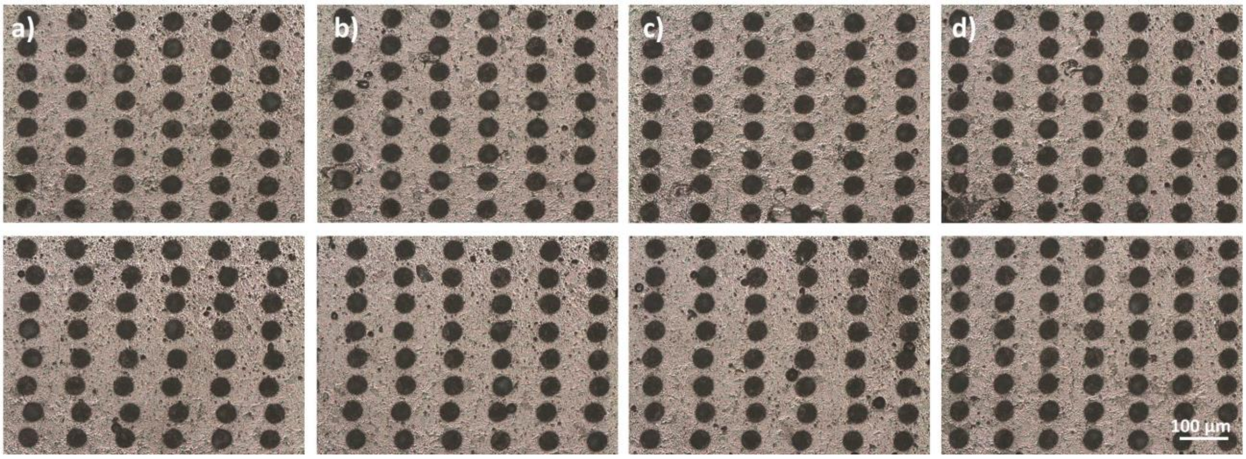

Figure 5: S-facet distortion for different scan speeds machined on black-coated paper at 2MHz with a constant hole to hole distance; top: beginning of the lines; bottom: end of the lines; a) 25.6m/s; b) 52.3m/s; c) 71.8m/s; d) 95.0m/s

Working at higher repetition rates shows the limitation of the used gating module of the laser system, in our case an AOM. At 3 MHz repetition rate a first small pre-pulse appeared. If this pre-pulse has enough energy to reach the threshold fluence of the work piece, it can already ablate material. Increasing the repetition rate involves an appearing of more pre- or post-pulses. By using a photodiode in front of the laser system the emitted pulses can be shown on an oscilloscope. A comparison of 2 MHz and 4.1 MHz is shown in Figure 6. For both repetition rates only one laser pulse is demanded. In the case of 4 MHz one pre-pulse and one post-pulse appear which both ablate the black-coated paper. The laser on signal which enables the gating module rests for both repetition rates at 100 ns pulse width. For higher repetition rates more and more pulses are guided through the gating module when only one pulse is demanded. The limit is at about 2 MHz repetition rate. In order to increase the limited repetition rate for real single pulse on demand improvements in the gating module of the laser system have be done.

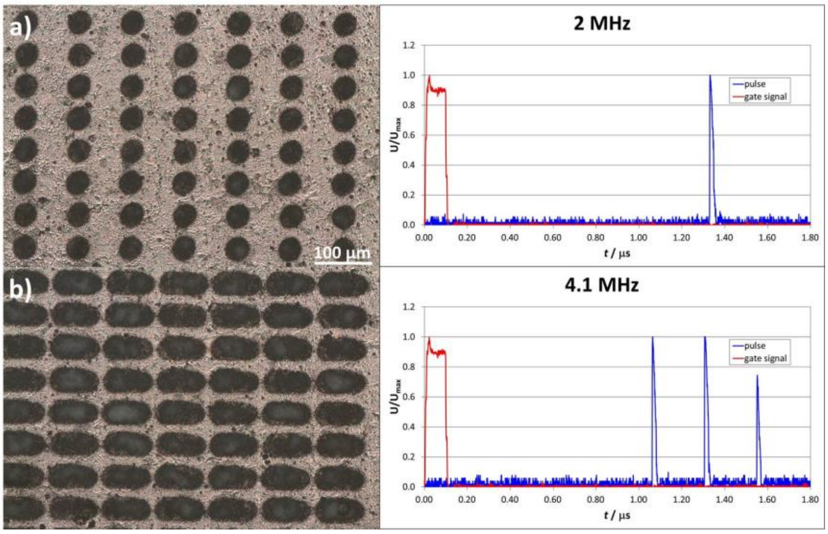

Figure 6: Gating problem at high repetition rates; left: ablated structures; right: Photodiode measurements; a) 2MHz, 95m/s; b) 4.1MHz, 95m/s

Nevertheless structuring tests were performed as well with repetition rates higher than the limit for real single pulse on demand. The influence of the gating module is only detected, when individual pulses have to be switched on and off. For series of consecutive pulses it is possible to correct this error by switching on the laser one pixel later in case of the pre-pulse and switching off the laser one pulse earlier for suppressing the post-pulse problem. But the minimum size of the marking is enlarging due to the gating problem. Microscope images of the pyramids machined in stainless steel are shown in Figure 7. The pre- and post-pulses are not turned-off by adapting the strategy. Due to the emission of multiple pulses instead of a single pulse, the tip of the pyramids is no longer a top point for the higher repetition rates. For all structures a periodical line pattern is observed due to the pyramidal error of the mirror wheel[24].

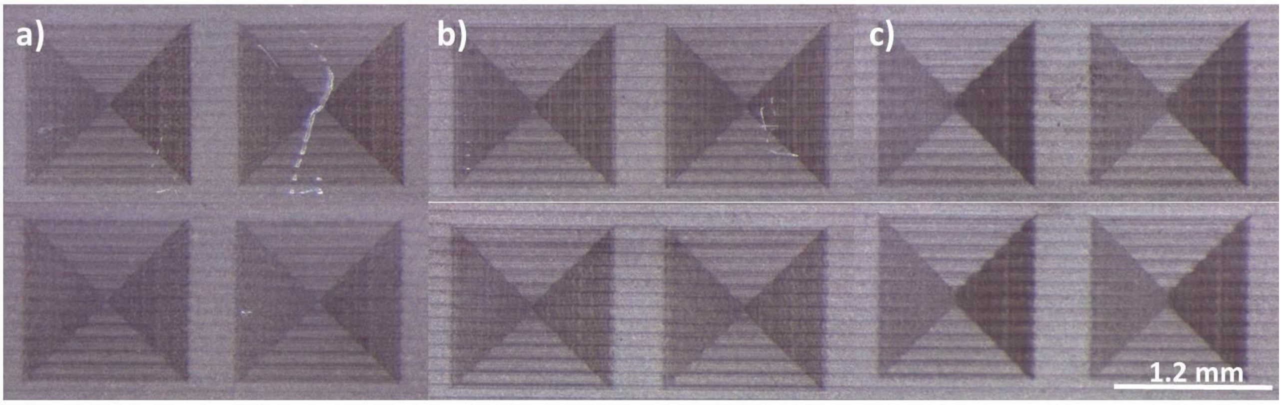

Figure 7: In stainless steel machined pyramids: top: beginning of the scan line; bottom: after 10.6cm of the scan line; a) 2MHz 25.6m/s; b) 4.1MHz 47m/s; c) 8.2MHz 94m/s

This error describes the angle error from facet to facet due to fabrication tolerances. If this error is not corrected, e.g. by a fast deflector in front of the polygon mirror wheel, the pitch from scan line to scan line varies. This results in a wavy surface of the structure as seen in Figure 8. The period of the deep marking is about 100 µm which correspond to 8-times the used pitch of 12.5 µm.

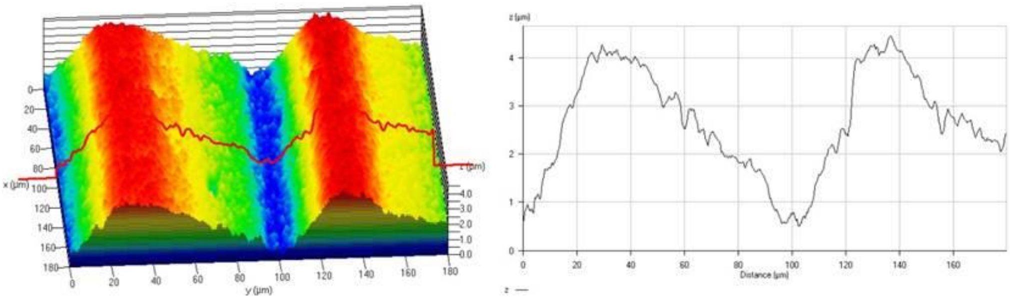

Figure 8: Wavy surface due to the uncorrected pyramidal error. Structure machined in stainless steel at 2MHz, 25m/s, 100 layers

The used line scanner has no correction of the pyramidal error. Therefore, to create a smooth surface, the strategy has to be adapted. The results of this optimization are shown in Figure 9. One possibility is to work with a single facet only, such that a perfect polygon is simulated. The drawback for this strategy is that the marking time is increased by a factor of 8. Also the thermal load of the work piece is different, compared to a perfect polygon, where all 8 facets can be used. An adequate simulation is rather difficult. But for feasibility-studies of structures with a smooth surface, this is a way to go. Another possibility is to average out the pyramidal error. The controller of the used polygon scanner works such that the first line of a structure is always marked by the same facet. Using a one-line offset for each new layer shifting the starting facet by one leads to a averaging of the facet error. This strategy can only be used, when multiple layers have to be machined. For single layers and for drilling on the fly applications, this strategy is not suitable. Figure 9 shows a comparison of these three strategies. The difference for the thermal load between using 1 facet and 8 facets has no influence on the melt formation shown in the detail view in Figure 9. Also the removal rate is unaffected of this difference. If single pulse extinction is require, the available repetition rate is limited to about 2 MHz. Working with an optimum pulse overlap of 75 % results in a scanning speed of about 25 m/s. To take advantage of higher scan speeds, where the line scanner is optimized for an interlaced scanning mode can be used[25]. The main bitmap is divided e.g. into four sub bitmaps containing column 1,5,9…, column 2,6,10…, column 3,7,1… and column 4,8,12… . These bitmaps are then marked with 100 m/s marking speed and 2 MHz repetition rate. Between two sub bitmaps the starting point is shifted by 12.5 μm with the second linear stage. The marking time is increased, but the positioning accuracy at the end of the scan line is significantly improved.

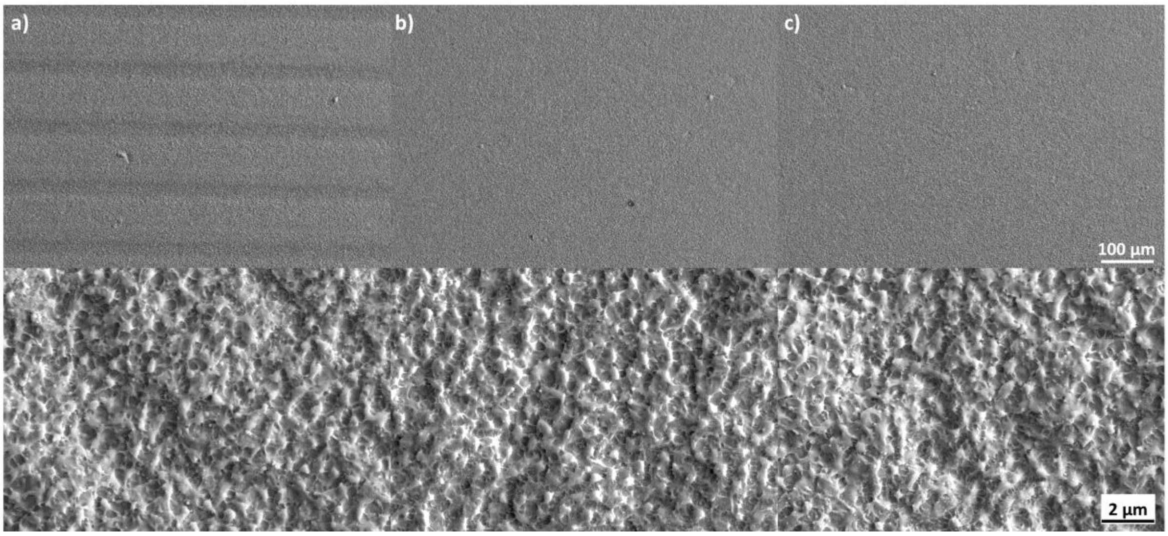

Figure 9: SEM images of the surface quality for 3 different strategies machined at 2MHz repetition rate; bottom: detail view 20000x; a) 8 facets; b) 1 facet; c) 8 facets, averaging of the pyramidal error

In further experiments, the removal rate in dependence of the used repetition rate is investigated for different materials. With the galvo scanner the structures for a repetition rate up to 1.21 MHz were ablated while for higher repetition rates the line scanner was used. For copper the removal rate is unaffected of the repetition rate up to 1.21 MHz repetition rate (see Figure 10a). For a repetition rate of 2 MHz, working at the optimum peak fluence would have required an average power of 72 W which is exceeding the power limit of the used laser system. Figure 10b shows the results for stainless steel. Due to the smaller threshold fluence less average power is needed such that data for repetition rates up to 6.83 MHz could be acquired. At a repetition rate of about 300 kHz the removal rate decreases until a constant level is reached at about 66 % of the primary removal rate.

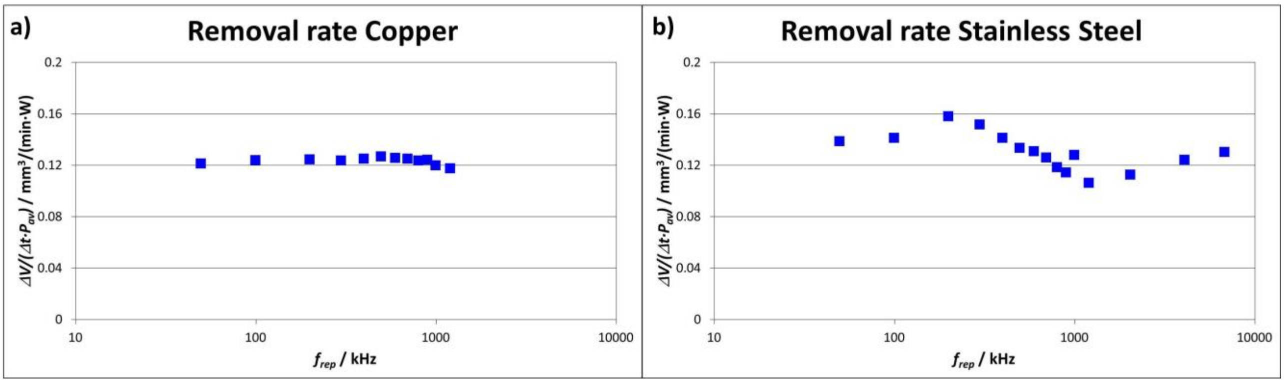

Figure 10: Influence of the repetition rate on the removal rate, due to shielding effects and heat accumulation a) Copper; b) Stainless steel

This decrease can be explained by particle shielding[26-28]. The increase of the removal rate in the MHz-regime can be explained by heat accumulation. This effect is known from percussion drilling[28] Because of the different machining strategy with less overlapping of the pulses compared to percussion drilling, this slight increase appears not before the MHz-regime.

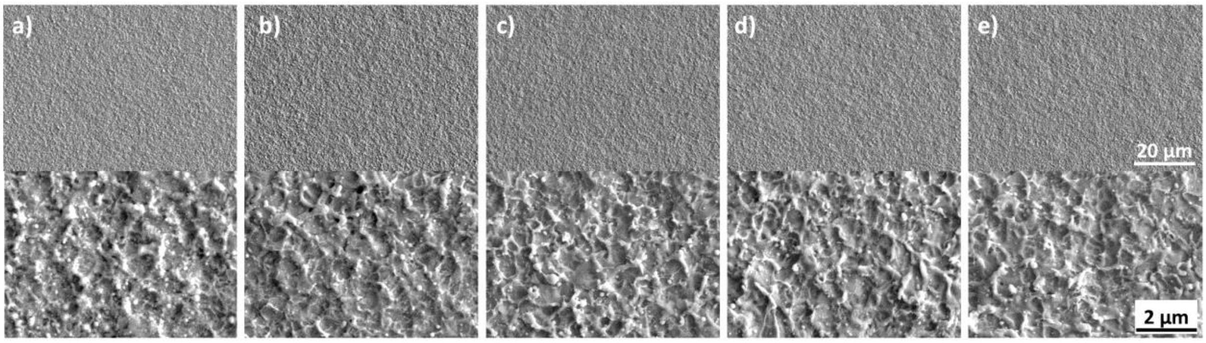

Figure 11: SEM images of the surface quality for copper, top: 2000x, bottom: 20000x a) 50kHz; b) 200kHz; c) 600kHz; d) 1MHz; e) 1.21MHz

If heat accumulation takes place a strong increase of the melt formation on the surface should be observed for higher repetition rates. As seen in Figure 11 this is not the case for copper which can be interpreted as proof for the absence of heat accumulation for the tested repetition rates. For stainless steel (Figure 12) the melt formation changes with higher repetition rates. The round melting droplets are larger than for the lower repetition rates. This indicates an influence of heat accumulation for repetition rates higher than 1 MHz, which correspond to the increasing removal rate for this range of the repetition rate.

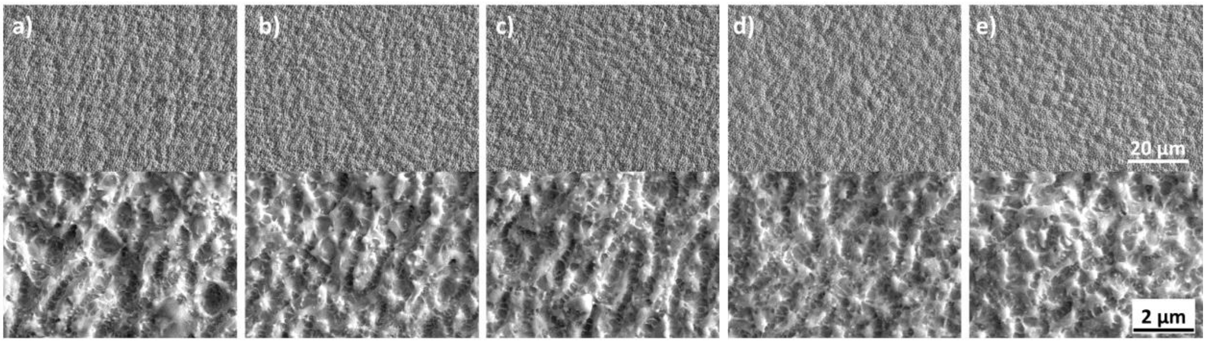

Figure 12: SEM images of the surface quality for stainless steel, top: 2000x, bottom: 20000x a) 200kHz; b) 600kHz; c) 1MHz; d) 2.05MHz; e) 6.83MHz

The higher thermal diffusivity of copper explains the independence of removal rate and the melt formation for increasing repetition rate. These results are confirmed by Ancona et al.[28]. According to them a simulated value for the repetition rate where heat accumulation has an influence on percussion drilling of copper is about 4 MHz or higher. This means for our application that due to the smaller overlapping of the pulses the limiting repetition rate should be still higher than 4 MHz. A comparison of the surface roughness for the different repetition rates for stainless steel shows an almost constant curve progression for all measured roughness parameters as shown in Figure 13. The surface roughness data of the line scanner results cannot directly be compared to the values obtained with the galvo scanner, due to the different applied spot sizes. The influence of this factor needs further investigations. But a significant difference for the surface roughness is not observed. In a final experiment, a real 3D-structure is machined into stainless steel with 25.6 W average power (measured in front of the polygon scanner) at a repetition rate of 4.1 MHz taking in count the gating problems at that high repetition rates. With a pitch of 14.5 microns i.e. a scan speed of 59.45 m/s and working with the optimum fluence and the facet-averaging strategy, the topography of Switzerland[29] is ablated with 2233 different layers. The final result without any post processing is shown in Figure 14. The dimensions are 107.7 mm x 65.5 mm with a maximum depth of about 115 µm.

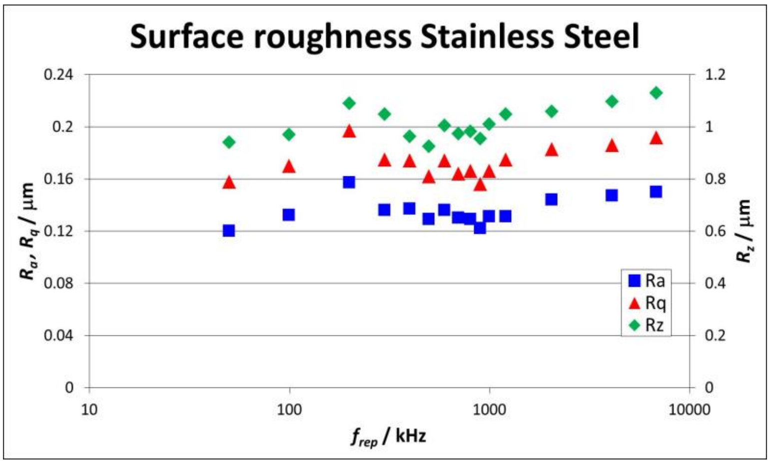

Figure 13: Influence of the repetition rate on the surface roughness R_a, R_q and R_z for stainless steel measured with an LSM

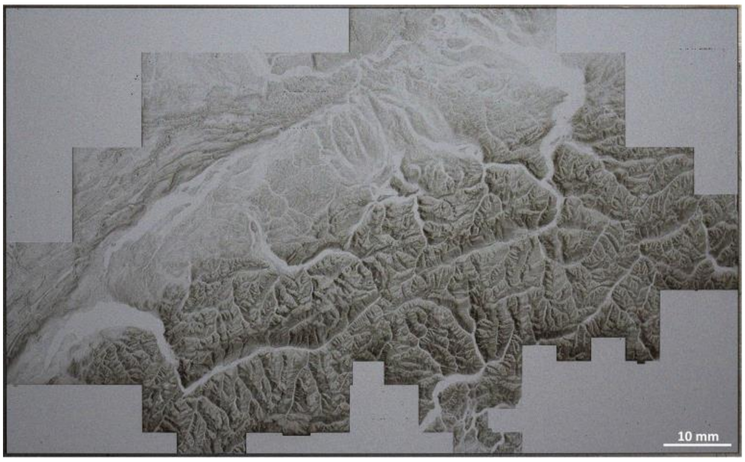

Figure 14: Photography of the machined topography of Switzerland in stainless steel

4. CONCLUSION

Polygon line scanners are very attractive beam deflecting devices if high marking speeds are demanded. Via the SuperSync™ technology the synchronization of the tested LSE170A with an ultra-short pulsed system in MOPA arrangement becomes possible. The spot positions at the line start were always synchronized for all tested marking speeds, whereas for low marking speeds the control of the line scanner is not optimized which leads to the S-distortion at the end of the scan lines. By adapting the scanning strategy also the uncorrected pyramidal error can be suppressed. The averaging of the pyramidal error improves the quality of the machined 3D-structures and has no influence on the marking time compared to the strategy using only one facet. Besides all these considerations the correction of the pyramidal error rests essential. It has to be done inside the polygon scanner device e.g. by adding an additional controllable fast deflector. Some improvements on the gating module of the laser system should give the possibility to work with real pulse on demand even at high repetition rates in the 10 MHz regime. Finally one can conclude that the structuring strategies developed on the synchronized galvo scanner can successfully be transferred to the synchronized polygon scanner and 3D-structures with high-quality can be machined successfully. A market for this kind of high precision large area machining could be the manufacturing industry of injection molds or embossing tools. With a correction of the pyramidal error also decoating applications, where only one layer has to be removed, can benefit from high-speed polygon scanners.

5. ACKNOWLEDGEMENT

This work was supported by the European Union in the FP7 project APPOLO. Special thanks to Josef Zuercher for the help with the SEM Images and Manfred Schneeberger for his work during the installation of the line scanner setup.

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