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Novel strategy for ultrafast pulsed laser micromachining of rotational symmetric metallic parts

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Abstract

Ultra-fast lasers have already been used to machine rotational symmetric metallic parts for several years but did not prevail against much cheaper fiber lasers. The limiting factor up to now is the dynamics of the rotary and linear axes, that are used to move the part underneath the stationary laser beam. Although the quality of the surface machined with ultrafast pulsed laser radiation is better than that machined with fiber laser radiation, an overall economic consideration mostly did not justify the utilization of ultrafast pulse lasers for this kind of application. Therefore, new and innovative concepts are needed to exploit the potential of ultrafast pulse lasers, in particular high repetition rate and the steadily increasing average power. The realization that will be presented uses a high-end galvanometric scanner to move the laser beam at speeds of several ten meters per second across the constantly rotating part. The most important part is the synchronization of the laser, the scanner and the axes.

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Keywords: ultrafast lasers; laser micro machining; galvanometric scanner; synchronization; efficiency;

1. Introduction

The size and complexity of modern ultrafast laser systems have been reduced, going along with a rise in user-friendliness, while the average power of such systems has been increasing over the recent years and cutting-edge ultrafast pulse laser systems provide an average power of 50 W or more.

Ultrafast pulse lasers therefore have found their niches, e.g. cutting of glass, but they were not able to replace fiber laser in the field of tube cutting in particular. Although the quality of the cut exceeds that of fiber lasers and the expense for rework is drastically reduced, the gain in cycle time is too small to justify the use of ultrafast pulse laser systems at present.

One key factor is the processing speed that is limited by the dynamics of the rotary and linear axes used for positioning of the tube material underneath the stationary laser beam. Since feed rate and acceleration are restricted, a higher average power cannot be applied to reduce the cycle time for a given material and geometry.

One approach is to split the movements differently and to avoid varying accelerations. Ultrafast pulse lasers can exploit their full potential for ablation and therefore it is obvious to use ultrafast pulsed laser radiation for the machining of tube material in this manner as well (Neuenschwander 2010). Machining by ablation is performed layer by layer whereas cutting in the common sense means following a given contour. This fundamental process-related difference implies a modification in the mechanical setup. The laser beam is no longer kept stationary but is moved over the tube by means of a galvanometric scanner or a polygon scanner. The tube itself

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is being positioned or turning at a constant low speed by a rotary axis.

In case of a constantly rotating tube of a given material and a given contour of the cut, the cycle time is defined by the total volume of the tube, i.e. the length, the diameter and the wall thickness of the tube, and the average laser power. The specific ablation rate needs to be determined for the tube material and can be adapted by different irradiation strategies, e.g. the application of pulse bursts (Kramer 2016). The specific ablation rate shows a maximum at the so-called optimum peak fluence $\phi_{0,opt}$ as shown in Fig. 1.

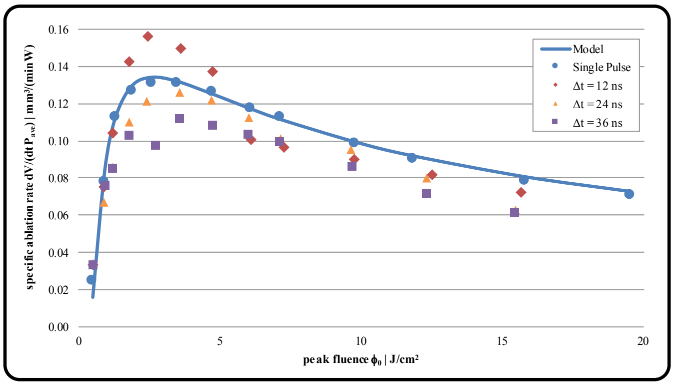

Fig. 1. Specific ablation rate $dV/(dt \cdot P_{ave})$ for copper CU-DHP C12 200 (Kramer 2016).

Taking the specific ablation rate $dV/(dt \cdot P_{ave})$ for granted, the time t for the complete ablation of a given volume in dependence of the applied average power P_{ave} can be calculated according to equation (1).

$$t(P_{ave}) = \frac{V}{dV/(dt \cdot P_{ave})} \cdot \frac{1}{P_{ave}} \quad (1)$$

While the volume of a tube is given by equation (2)

$$V_{tube} = \pi \cdot (D - b) \cdot b \cdot l \quad (2)$$

with D: diameter of tube
b: wall thickness of tube
l: length of tube

the ablation time $t(P_{ave})$ reads

$$t(P_{ave}) = \frac{\pi \cdot (D - b) \cdot b \cdot l}{dV/(dt \cdot P_{ave})} \cdot \frac{1}{P_{ave}} \quad (3)$$

The ablation time $t(P_{ave})$ according to equation (3) is reciprocally depending on the average power P_{ave}, i.e. when the average power P_{ave} is doubled the ablation time $t(P_{ave})$ is halved.

Fig. 2 graphically shows this dependency for three different specific removal rates. For the lowest specific ablation rate $dV/(dt \cdot P_{ave}) = 0.19\, mm^3/(min \cdot W)$, a duty cycle of 100% and the current cycle time $t_{cycle} = 220\, s$ the required average power amounts to $P_{ave} = 30\, W$. Increasing the average power to $P_{ave} = 60\, W$ reduces the ablation time to $t_{cycle} = 110\, s$. Taking into account a realistic duty cycle of 50%, an average power of $P_{ave} = 60\, W$ is needed to achieve to current cycle time.

If the specific removal rate can be increased with the application of pulse burst or is fundamentally higher for a different material, the average power P_{ave} needed shifts to lower values (Kramer 2017).

If the specific ablation rate is three times higher, i.e. $dV/(dt \cdot P_{ave}) = 0.56\, mm^3/(min \cdot W)$, the average power needed can be reduced to the same extend and then is $P_{ave} = 10\, W$, respectively $P_{ave} = 20\, W$.

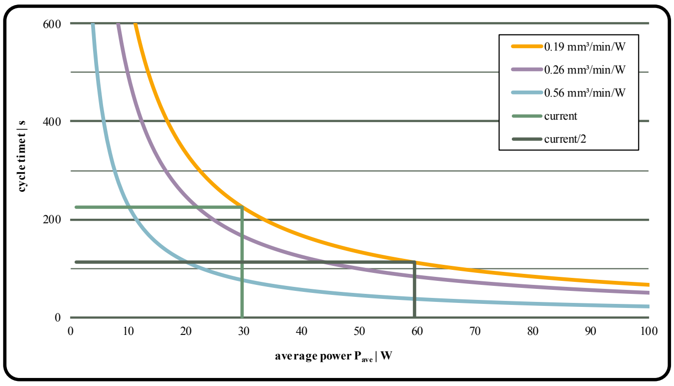

Fig. 2. Process potential represented by the cycle time t for three different specific ablation rates $dV/(dt \cdot P_{ave})$

The general approach is depicted schematically in Fig. 3. The tube is mounted on a carrier and both pieces are fixed by a clamping device, that is mounted to a motor and drive of a rotary axis. This axis turns the tube constantly at a preset speed while the laser beam is scanned at high speed across the tube by means of a galvanometric or a polygon scanner. The tube is machined layer by layer and a cut can be performed by ablating the full wall thickness of the tube.

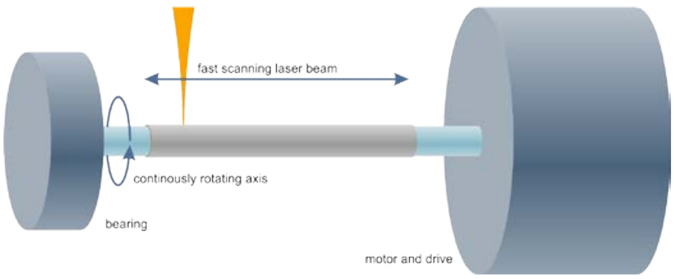

Fig. 3. Schematic drawing of principal setup

Two challenges have to be addressed:

- Every single laser pulse needs to be placed in an accurate and reproducible manner.
- Even for a high number of layers/revolutions, e.g. 1000, the pattern must not move to guarantee an acceptable precision.

To tackle these challenges a synchronization of the laser pulses, the positioning of the scanner and the moving axis is essential.

2. State-of-the-Art

2.1. Cutting with Fixed Optics

At present tubes are cut with a stationary laser beam while at least one linear axis (axial direction of the tube) and one rotary axis (radial direction of the tube) are positioning the tube following the given contour of closed sub-patterns (Momma 1999). The laser energy melts the material which is then blown out of the cutting kerf by means of a gas jet as shown in Fig. 4.

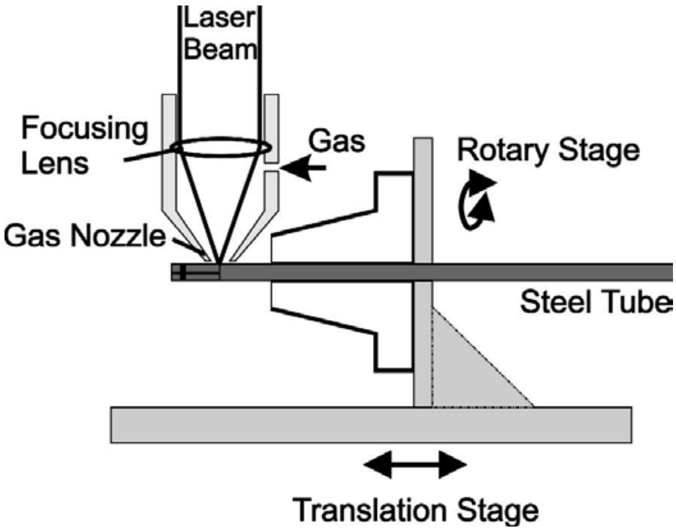

Fig. 4. Principle of current tube cutting technology (Momma 1999)

At the start of each contour the laser beam has to drill through the tube wall before the contour can be cut. On the one hand, the cycle time is depending on the mean cutting speed, that is in turn depending on the dynamics of the axes and on the wall thickness. And, on the other hand, it is depending on the number of sub-patterns to be cut since the piercing at each contour start takes time.

2.2. Ablating with Galvanometric Scanner

2.2.1. General

Galvanometric scanners are used to move the laser beam two-dimensional across the workpiece at a high speed of several meters per second (Wienken 2015). Current applications are marking engraving and ablating. The desired shape is typically filled with so-called hatch patterns which can be modified and repeated several times for deeper engraving.

2.2.2. Sub-Pattern Processing

For sub-pattern processing, a flat projection of the complete pattern is divided into its individual and closed sub-patterns. For each sub-pattern a linear and a rotary axis position the tube and the sub-patterns are machined successively by a two-axis galvanometric scanner. The whole area of each sub-patterns is ablated layer by layer until the tube wall is cut through (Schmid 2015, Schmid and Gillen 2016).

The laser beam hits the surface of the tube perpendicular only on one line on top along the tube axis. The sub-patterns therefore have to be much smaller than the diameter of the tube, or the ablation efficiency will drop either due to the laser beam moving out of focus or due to the non-perpendicular incident angle of the laser beam. A given scan length corresponds to a fixed optimum scan speed that represents the shortest machining time and depends on the scanner properties like acceleration and maximum scan speed. Fig. 5 shows the cycle time as a function of the scan speed for different scan vector lengths (Schlüter 2016, Jäggi 2016). The minimum is clearly visible and changes with the length of the scan vector.

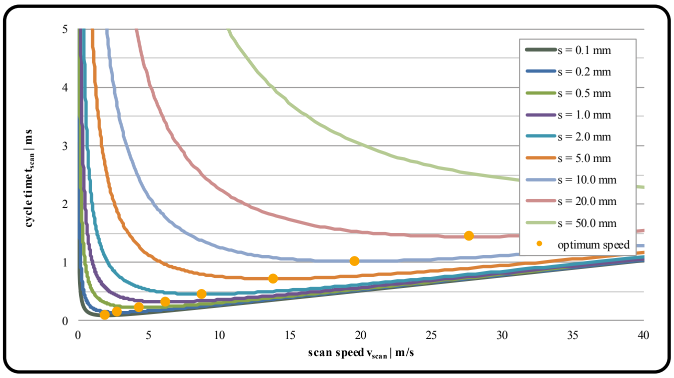

Fig. 5. Cycle time as a function of the scan speed for different scan vectors (Schlüter 2016, Jäggi 2016)

Considering this simple correlation, one should consider scanning longer vectors since they provide a higher potential for time saving. In addition, the number of vectors to be scanned increases with the number of sub-patterns, and thus it is obvious to reduce the number of sub-patterns. The positioning of the tube with the linear and rotary axis decreases the duty cycle because the laser is not processing during this time, such that the number of positioning steps should be minimized to reduce the overall cycle time.

2.2.3. Constant Rotation

The logical consequence is rotating the tube constantly and moving the laser beam across the axis of the tube over the entire length. Two ways are possible: either the hatch pattern, which represents the scan vectors for the major axis, is oriented along the axis of the tube or the geometry to be cut is converted into a bitmap to scan the tube raster-like. In both cases the “marking-on-the-fly” feature must be used to facilitate synchronization between the rotary axis and the galvanometric scanner’s minor axis (ACSYS 2018, SHT 2018). The rotational speed and scan speed need to be set such that the laser spot stays on the axis of the tube.

The rotational speed is relatively low, and the scanner cannot run at its highest speed because it has to be able to add the speed of the rotary axis, even if it’s only the minor axis.

Furthermore, the accuracy will decrease due to the required communication between scanner and rotary axis.

One should keep in mind that, as a consequence of the ablation process and the gaussian intensity distribution of the beam, the walls of the machined structures show a taper and are not orthogonal to the surface. This can partially be corrected by moving the beam slightly off the axis of the tube, which is referred to as off-axis cutting. Off-axis cutting can be used to adjust the taper of the cut structures actively, unfortunately only in the direction of the axis of the tube; the taper in radial direction will be defined by the process itself.

The structure is machined layer by layer and finally a cut is performed by ablating the entire tube wall. This can be seen as an advantage because additional features like pockets or surface modifications can be implemented into novel designs without a change in process.

2.3. Ablating with Polygon Scanners

As an alternative to galvanometric scanners polygon scanners can be used for higher scanning speeds up to several hundreds of meters per second (Loeschner 2015, Schneider 2017). In general, a polygon mirror can move the laser beam across a line of fixed length that is defined by the setup of the scanner and cannot be varied when processing. The duty cycle of a polygon scanner amounts to approx. 70% and thus is higher than that a of galvanometric scanner even if it is working bi-directional. For machining an area with a polygon scanner, a movement in cross-scan direction must be added, such as a linear axis or a galvanometric scanner.

In the case at hand, the cross-scan movement would be done by the rotary axis which would rotate at constant velocity. The polygon scanner needs to be mechanically aligned to the longitudinal axis of the tube, an angular adjustment by means of a virtual rotation in the software cannot not be added.

However, one can only benefit from the given advantages high scan speed and high duty cycle, if the full scan length is used. The duty cycle decreases linearly with the reduction of the effective scan length. Typical scan lengths are in the range of 100 mm to 300 mm. For the given samples the scan length varied between 20 mm and 50 mm.

For micro-structuring a printing drum, a polygon scanner LSE170STD with a scan length of 170 mm was used and synchronized to a rotary axis and an ultra-fast laser.

For reasons of flexibility, the galvanometric scanner was chosen for the given applications of cutting of metal tubes.

3. Principle and Experimental Set-up

3.1. Synchronization of Ultrafast Pulse Laser

The experimental setup is realized on a machine base consisting of a control from ACS-Control-System GmbH and three linear axes and one rotary axis from SCHNEEBERGER AG Lineartechnik. The rotary axis is equipped with a reduction gear to reduce the rotation speed. The ultrafast pulse laser that is used for the experiments is a modified version of a FUEGO from LUMENTUM Switzerland AG.

The linear polarized laser radiation is guided by two mirrors to a half waveplate and a rotatable thin film polarizer to adjust the average power externally. The polarization is set to circular using a quarter waveplate. The diameter of the laser beam is adjusted to the entrance aperture of an intelli*SCAN*$_{SE}$10 galvanometric scanner from SCANLAB AG by means of a Galilei telescope. Further mirrors are used to guide the laser radiation to the galvanometric scanner since it is mounted on the z-axes as shown in Fig. 6.

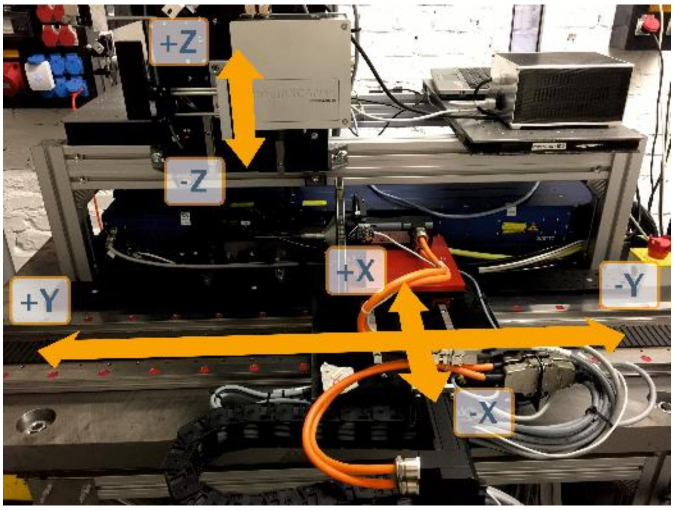

Fig. 6. Mechanical setup

The laser beam is focused to the workpiece with a F-Theta-objective with a focal length of $f_{foc} = 163\ mm$.

The galvanometric scanner is controlled by means of a specialized hardware based on a Zynq-SoM and a RTC5 controller card in a way that it can be synchronized to the ultrafast pulse laser (EP000003045257A3). In addition, the position and speed of a linear or a rotary axis can be controlled and synchronized to the ultrafast pulse laser as well. In contrast to currently used “Marking-on-the-fly” feature, in which the scanner adapts its speed according to the encoder signs of the linear or rotary axis, the presented setup controls the speed of the linear or rotary axis actively. The electrical setup is shown schematically in Fig. 7 and Fig. 8 shows a picture of the PCB.

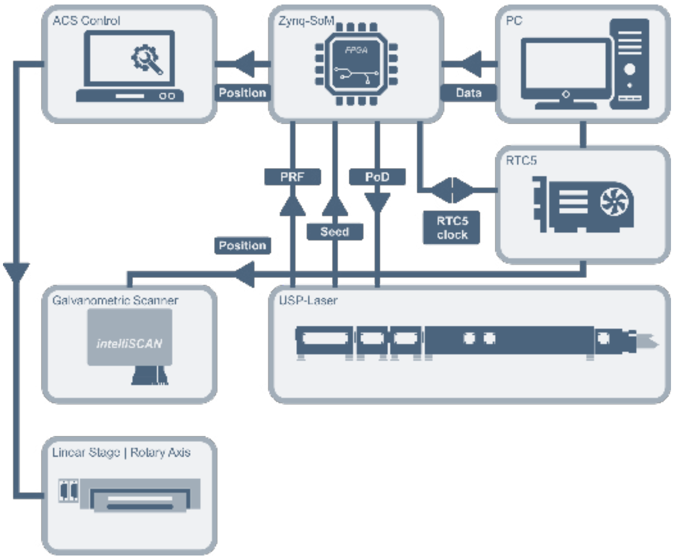

Fig. 7. Schematic drawing of electrical setup

Fig. 8. PCB with Zynq-SoM for synchronization of ultrafast laser to galvanometric scanner

Table 1. Specifications of modified FUEGO

Parameter	**Measurement**
Pulse repetition rate PRF	5 - 16 MHz
Pulse repetition rate PRF of PoD	single shot up to 16 MHz
Seed laser repetition rate	82.053 MHz
Average power @ 10 MHz	39.6 W
Average power stability	1.5 % peak - peak (0.21 % rms)
Pulse width (FWHM)	10.4 ps
Wavelength	$Nd:YVO_4$ (1064.5 nm)
Beam quality	TEM_{00}; $M^2 = 1.35$
Polarisation	Linear, vertical

The specifications of the modified FUEGO are listed in Table 1. The modifications on the FUEGO were necessary to guarantee a single pulse switching up to $f_{rep} = 16\ MHz$ with pre- and post-pulses below 10%. As a consequence of these modifications the beam shows a strong astigmatism with a non-neglectable difference in the positions for both focal planes. The effect of the astigmatism could be corrected by implementing two cylindrical lenses into the beam path. Fig. 9 shows two representative measurements of the beam.

The beam spot size is $2w_0 = 50\ \mu m$ at an average beam quality of $M^2 = 1.35$.

The laser spot was scanned across the tube in axial direction at a repetition rate of $f_{rep} = 5.12\ MHz$ and the lateral distance between two spots, the so-called pitch, was set to $p_x = 6.0\ \mu m$, resulting in a scan speed of $v_{scan} = 30.72\ m/s$.

The tubes are made of stainless steel AISI 304 (1.4301), with a length of $l = 20\ mm$ and have a diameter of $D = 1.8\ mm$ and a wall thickness of $b = 0.1\ mm$. The overall volume therefore amounts to $V_{tube} = 10.68\ mm^3$. Taking the optimum specific removal rate as $dV/(dt \cdot P_{ave}) = 0.14\ mm^3/(min \cdot W)$ at an average power of $P_{ave} = 18\ W$ the ablation time is $t(P_{ave} = 18\ W) = 255\ s$. Considering a duty cycle for mono-directional scanning of 50% the effective ablation time is $t_{eff} = 510\ s$. The circumference of the tube is $C_{tube} = 5.6\ mm$ and thus $N = 940$ lines have to be machined at a pitch of $p_y = 6.0\ \mu m$.

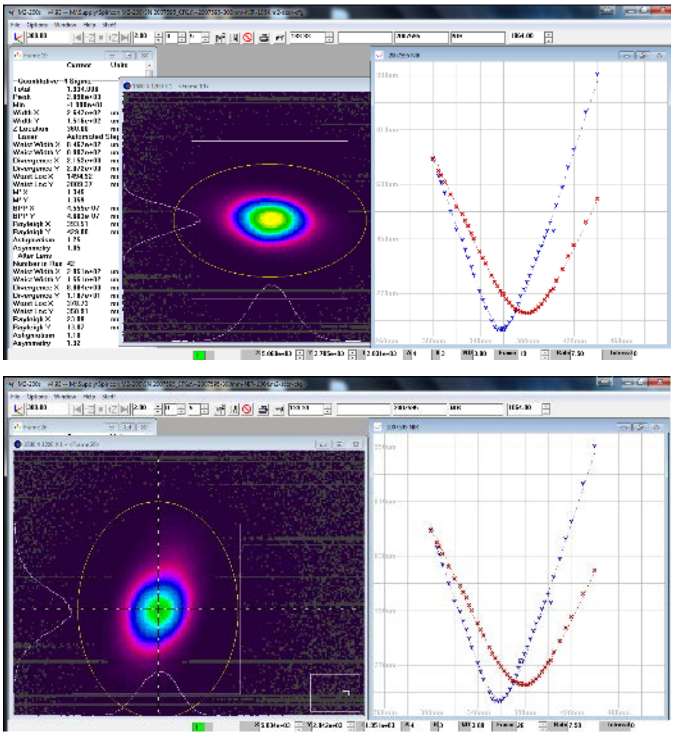

Fig. 9. Beam characteristics of modified FUEGO

The number of layers can be calculated according to equation (4)

$$N_L(P_{ave}) = \frac{b \cdot f_{rep} \cdot p_x \cdot p_y}{dV/(dt \cdot P_{ave})} \cdot \frac{1}{P_{ave}} \qquad (4)$$

and amounts to $N_L = 439$.

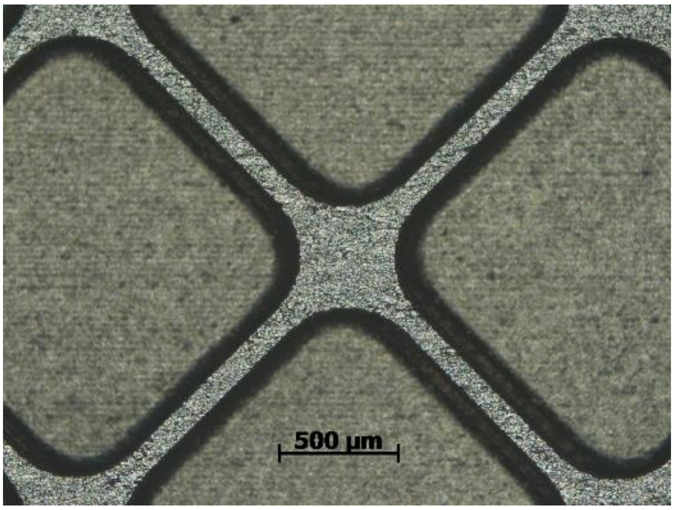

Fig. 10. Diamond test pattern machined on a stainless steel plate AISI 304 by means of a synchronized galvanometric scanner

First tests have been performed on stainless steel plates AISI 304 to demonstrate the fundamental principle of the synchronization of a high-end galvanometric scanner and a ultrafast pulse laser in MOPA design. Fig. 10 shows a diamond pattern that has been machined with a spot size of $2w_0 = 50\,\mu m$ (F-Theta objective $f_{foc} = 163\,mm$) and 500 layers, at a repetition rate of $f_{rep} = 2\,MHz$, a scan speed of $v_{scan} = 24\ m/s$ and an average power of $P_{ave} = 7\,W$.

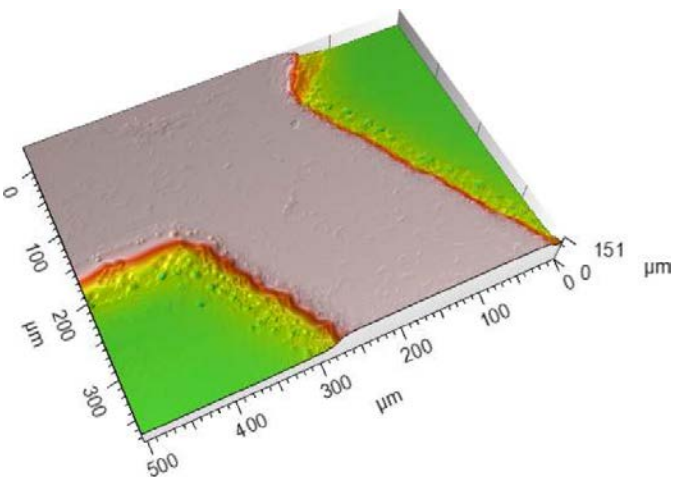

Fig. 11. White light interference image of test sample on stainless steel AISI 304

The edges are well defined and sharp and the machined surface is smooth and does not show any heat effects like coloration or CLPs as shown in Fig. 11.

4. Results and Discussion

The diamond test pattern has been machined on a stainless steel tube AISI 304 by means of a fully synchronized galvanometric scanner and rotary axis as shown in Fig. 12 with the laser and machine parameters mentioned above.

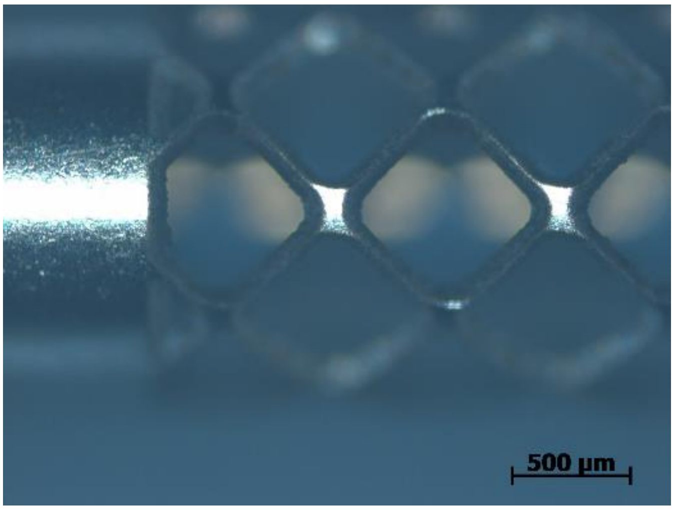

Fig. 12. Diamond pattern machined on a stainless steel tube AISI 304 by means of a synchronized galvanometric scanner and rotary axis

Due to the astigmatic beam and the elliptical spot the edges of the struts are rounded, and the taper is bigger than for the steel plate sample. For the same reason the number of ablated layers to cut through had to be increased to $N_L = 1000$. The pattern was setup with a phase shift to be able to see start and end of a single layer. Fig. 13 shows the interface for two successive layers. The edges in cross-scan direction show the same or even a slightly better quality and taper as a proof for the high accuracy of the system.

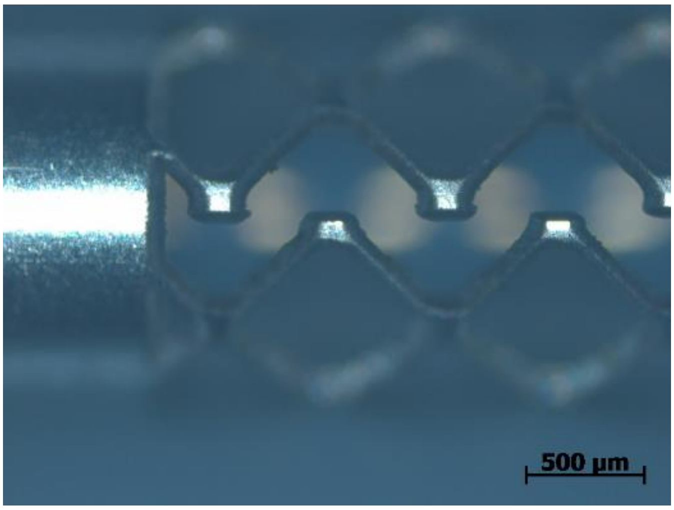

Fig. 13. Diamond pattern machined on a stainless steel tube AISI 304 by means of a synchronized galvanometric scanner and rotary axis

A honeycomb test pattern has also been machined on a stainless steel plate AISI 304 as well as on a stainless steel tube AISI 304 with a smaller size of the shapes and in a seamless manner as shown in Fig. 14 and Fig. 15, respectively. Laser and machine parameters were identical to those used for the diamond patterns.

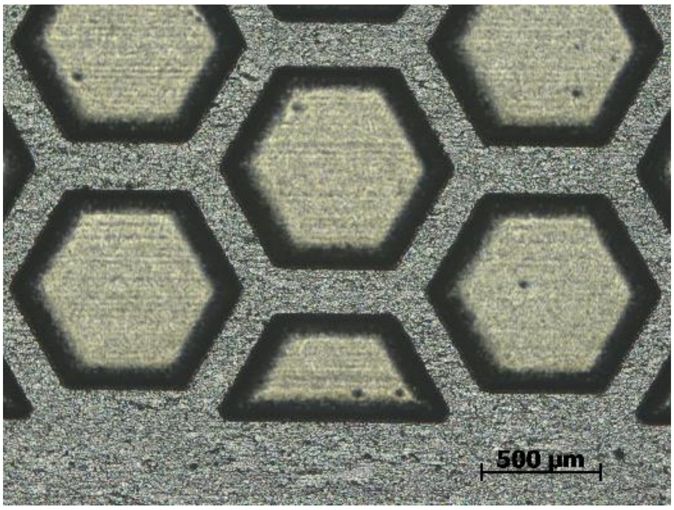

Fig. 14. Honeycomb pattern machined on a stainless steel plate AISI 304 by means of a synchronized galvanometric scanner

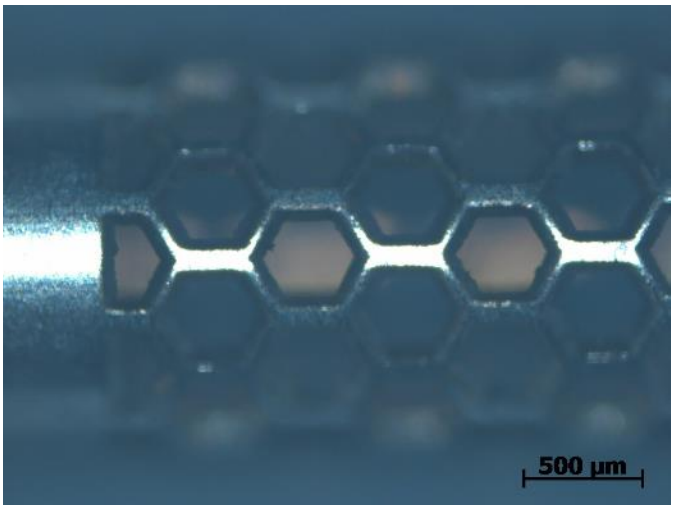

Fig. 15. Honeycomb pattern machined on a stainless steel tube AISI 304 by means of a synchronized galvanometric scanner and rotary axis

5. Summary and Outlook

Tube cutting by means of conventional laser contour cutting techniques reaches its technical limit because the process speed mainly is limited by the dynamics of the mechanical axes. The use of ultrafast pulse lasers with the conventional cutting technique does neither offer a technical advantage nor an economical benefit. New and innovation concepts are required to match the industrial demands and increase throughput.

Ultrafast pulse lasers reach their full potential at high repetition rates and high scanning speeds for micro machining. The present paper describes a technical solution to cut tubes by means of ultrafast pulsed laser radiation without the restrictions and limitations of the setup for conventional laser cutting by fully synchronizing an ultrafast pulse laser with a high-end galvanometric scanner and a rotary axis. The process presented does not utilize the “marking-on-the-fly” feature und thus is way more dynamic and it can be scaled up with the average power of the laser. Possibilities to realize new and innovative designs based on the nature of the ablation come for free with this setup.

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