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Ultrafast stamping by combination of synchronized galvanometer scanning with DOE's or SLM

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Abstract

The up-scaling of laser micromachining processes with ultrashort pulses is limited due to heat accumulation and shielding effects. Multi beam scanning represents one of the strategies to overcome this drawback. It is in general realized by combining a diffractive beam splitter with a galvanometer scanner. A full synchronization with the laser repetition rate offers new possibilities with minimum thermal impact. We will demonstrate this by means of a multipulse-drilling on the fly process with a regular 5x5 spot pattern having a spot to spot spacing of 160µm. At a repetition rate of 100 kHz and an average power of 16 W we were able to drill more than 2'300 holes/s in a 10µm thick steel foil. We have further extended this technology with a special light modulator for different periodic spot patterns and more complex intensity distributions.

Keywords: Laser micromachining; multi beam scanning; spatial light modulator; ultra-short laser pulses; drilling on the fly

1. Introduction

Machining thin foils using laser machining is a difficult application. There exist two main processing strategies:

First, high speed percussion drilling was demonstrated in 2008 [1]. For this application, the laser beam was positioned at all locations where a hole should get drilled. After positioning the beam to one of these locations, the laser emits a defined number of pulses and drills the hole through the material. This method is affected by heat accumulation effects i.e. due to the fact that a high power is applied to a small area during the whole drilling time, coloring and deformation of the foil can get observed. This can in principle be reduced by decreasing the applied laser power and/or the used repetition rate of the laser system, but this would increase the drilling time.

Second, percussion drilling on the fly has been presented in 2013 [2, p. 324]. This strategy demands a hard-synchronized scan system meaning, the clock of the scan system and the pulsed laser system are coupled, so that the laser pulses can be applied with a precision of approximately 1 µm. The scan system constantly moves the laser focus over all positions where the holes should get drilled but in contrast to the percussion drilling method only one pulse gets emitted at the location of each hole and the hole is machined by repeating this movement several times. Because only one pulse per movement gets applied for each hole, the thermal power is applied to a bigger area and the thermal stress gets reduced. To drive this process with highest possible average power each pulse should be used to machine the holes. Thus, the scan-system has to be fast enough to move the distance between two holes within two consecutive pulses with the repetition frequency (PRF).

As quality and heat accumulation effects will also limit the applicable peak-fluence for drilling the foil a further scale up of the drilling-rate can be achieved by increasing the PRF. But, the PRF is limited by the velocity of the scan-system and the spot-to-spot distance due to the mechanical limitations of a galvo-scanner, which may reach up to 25 m/s using a 100 mm

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optic. In principle it is possible to increase the marking velocity using polygon-scanner [4–6]. Marking speeds up to 800 m/s have been demonstrated but for many applications the usage of a polygon-scanners is not applicable due to limited flexibility and other possibilities must be found to increase the drilling rate. Multi spot drilling on the fly represents a method to increase drilling rates up to several 1000 holes per second for a thin foil.

The multi spot drilling on the fly method is illustrated in Figure 1. The light gray circles represent the scanner positions for each generated laser pulse during full motion of the scanner mirror with constant marking speed. Due to the full synchronization these positions are located exactly one below the other will be identical for each repetition within a precision of 1 µm [2] even for bi-directional mode [3]. During the motion of the mirror an *nxm* spot pattern (5x5 in Figure 1 a – e) the pattern is moved by only one horizontal spot-to-spot distance between two pulses which are assumed as infinitely short. At the turning point the pattern is shifted in cross-scan direction by one vertical spot-to-spot distance and the pattern is marked in opposite direction (Figure 1 f and g). Each hole of the machined area will be drilled with $n \cdot m \cdot N$ Pulses (with *N* the number of repetitions) except *n*-1 holes on the left and the right as well as *m*-1 on top and bottom as illustrated in Figure 1 h. This method is not limited to squared spot patterns only, many other patterns can be used in principle. Also more complex pattern can be applied as it will be shown in the stamping application.

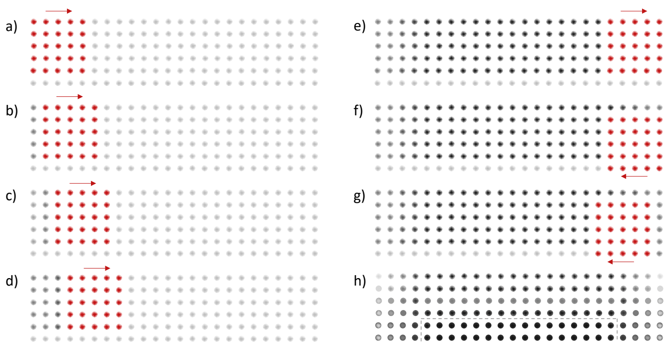

Fig. 1. Sketch of the multi spot drilling on the fly method with an *nxm* spot pattern moving forward (a – e) and backward (f and g) in synchronized mode. Holes at the edges (outside the dashed line in h) will not be drilled with the full number of pulses.

2. Experimental Set – Up

First experiments were performed using a FUEGO 10 ps laser system from Time Bandwidth Products (now Lumentum) emitting a linear polarized laser beam at 1064 nm wavelength with a beam quality factor of $M^2 < 1.3$. The average power was adjusted by using the internal attenuator called autoNLO consistsing of a polarizer and a rotating λ/2 wave plate. Having linear polarization with a constant polarization angle is important when using a Spatial light modulator (SLM). The beam was enlarged to a diameter of 5 mm with a 2-lens telescope and guided into the Beam Shaper from Pulsar Photonics as illustrated in Figure 2. Internally the beam gets shaped using a SLM from Hamamatsu (HighRes, SXGA with 1280 x 1024 pixel). At the exit of the beam shaper unit, an excelliSCAN14 from SCANLAB was mounted. The beam was focused with a telecentric 100 mm objective to remain a small beam or structure size. The maximal power on the workpiece amounted 20 W going with a pulse energy of 100 µJ at the used PRF of 200 kHz. Due to its flexibility this set-up was used to find well suited spot patterns and to test even more complex shapes.

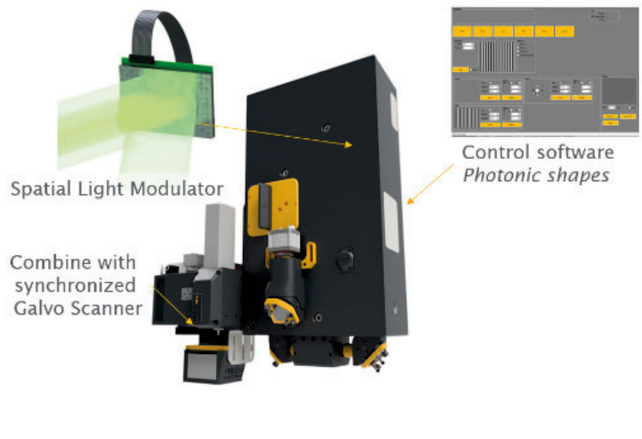

Fig. 2. Sketch of the setup from with the "Flexible Beam Shaper FBS-G3" from Pulsar Photonics [8] containing a common SLM and all required optical elements.

The desired beam shape can be generated in higher quality by a corresponding Diffractive Optical Element (DOE) due to its higher resolution. Additionally, shorter pulses would lead to higher removal rates [9]. To evaluate this, a PHAROS PH1-20 laser source from Light Conversion emitting 230 fs pulses at a wavelength of 1028 nm with a beam quality of $M^2 < 1.35$ and a PRF between 1 kHz and 1 MHz was used. The system worked at its maximum average power of about 20 W and at a PRF of 100 kHz resulting in a pulse energy of about 200 µJ. The effective power i.e. the pulse energy was adjusted externally by turning a λ/2 wave plate in front of a thin film polarizer. After this attenuation unit the beam was guided through a telescope enlarging the beam diameter to 10 mm to the scanning system. Instead of using the SLM the beam pattern was now generated by a DOE placed in the beam path just in front of the scanner as shown in Figure 3. As scan systems again the excelliSCAN14 was used.

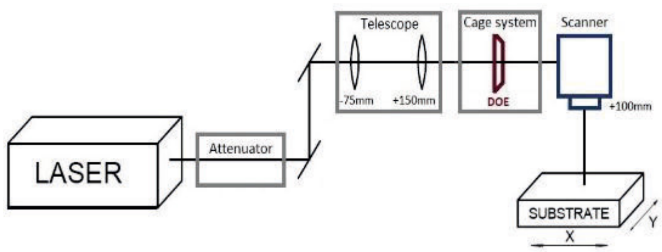

Fig. 3. System setup to achieve beam forming using a DOE.

For both set-up a thin steel foil out of stainless steel (1.4301/ ANSI301) with a thickness of 10 µm was placed in the focal plane of the objective. After the processing, the foils were cleaned in an ultrasonic bath with isopropanol and analyzed using an optical microscope.

3. Experimental Results

3.1. Realized Multi Spot Pattern with flexible beam shaper

Using the Iterative Fourier Transform IFTA-algorithm of the control software, multi spot pattern with 3x3, 4x4 and 5x5 equidistant spots per side have been realized. Highest drilling rates with good quality were achieved with the multi-spot pattern containing 5x5 spots having a spot-to-spot distance of 90 µm as shown in Figure 4 by a picture, taken with the internal camera of the beam shaping module and showing the far field distribution as it should appear at the focal point of the scanner objective. The small deviations (ellipticity ≈ 0.95, $M^2 < 1.3$) of the input beam from an ideal Gaussian one are responsible for the slightly elliptical shapes of the spots in Figure 4. By decreasing the spot-to-spot distance, the single spots start to interfere with each other, and the quality of the holes decreased. On the other hand further increasing the spot-to-spot distance would demand marking speeds which cannot be achieved with the used galvo-scanner (which was one of the fastest available today). Thus, only every second or third pulse could be used for machining reducing the usable average power by a factor of two or three.

As illustrated in Figure 1 the multi-spot pattern was only shifted by the spot-to-spot distance of 90 µm between two laser pulses and not by the whole pattern-size. Using the maximum laser power of 20 W, the 10µm steel foil was drilled within 100 layers resulting in 2500 laser pulses on every position due to the fact that a 5x5 multi-spot pattern consists of 25 spots. For 3x3 and 4x4 spots the average power was adjusted accordingly.

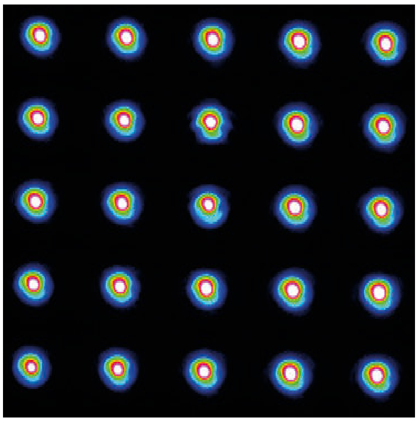

Fig. 4. Realized multi spot pattern with a spot-to-spot distances of 90 µm. It can be shown that the structure is pretty regular.

3.2. Realized Multi Spot Pattern using DOE

With the knowledge of the previous results, a DOE generating the 5x5 spot pattern was ordered. With this DOE, the findings of the experiments with the beam shaping unit should be confirmed with a fs laser offering higher specific removal rates in steel [7] As the DOE-setup showed a much lower power loss than the SLM set up, an average power of 16 W was available on the target for the used PRF of 100 kHz. Due to the better shaping quality, the higher energy per spot and the higher efficiency of the fs pulses the number of layers for drilling through was reduced from 100 to 17 i.e. each hole was machined with 675 pulses.

3.3. Machined hole patterns

The resulting holes of both multi spot patterns are shown in Figure 5 and Figure 6. The pictures are composed of different micrographs taken with an optical microscope (MF B-Series from Mitutoya) at high magnifications and stitched together. As mentioned above, the distance between two holes is 90 µm for the experiments with the SLM and 160 µm for the experiments with the DOE. For both experiments the exit side of the holes is round and sharp with a higher diameter in case of the SLM. On the entrance side black coloring is observed which is more pronounced for the holes generated with the SLM. This could be explained by the higher beam quality using the DOE. Additionally, for the holes generated by the SLM a slight ellipticity is visible whereas for the DOE it value is below 10%.

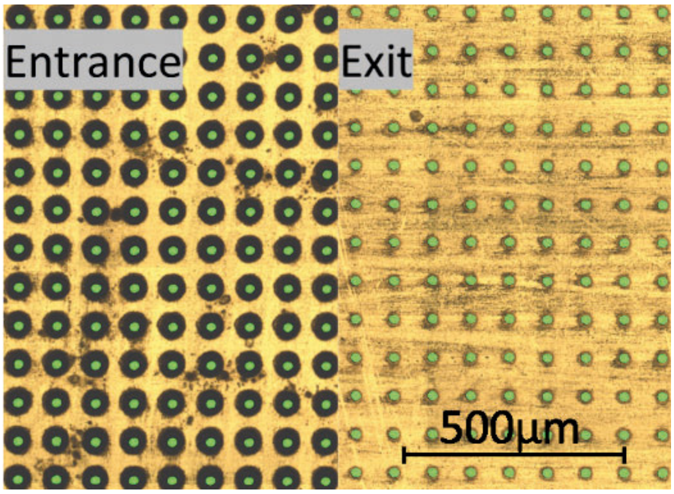

Fig. 5. Micrographs of the entrance and exit of the holes drilled with 5x5 spot pattern generated by the SLM. The green area shows the holes due to back light. The entrance-diameter is around 40 µm and the output diameter is 21 µm.

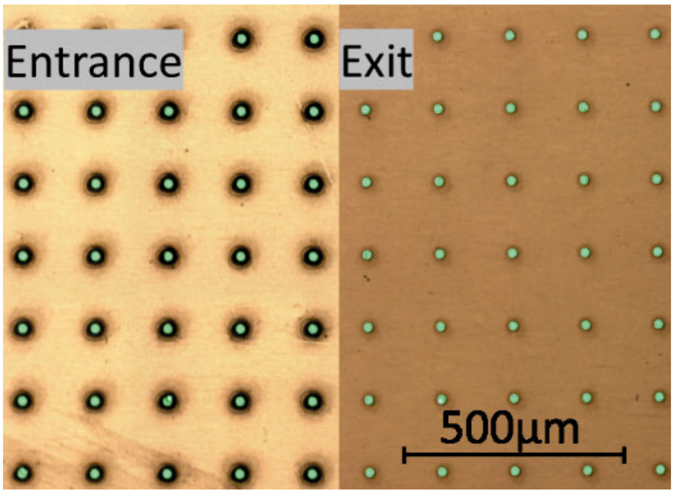

Fig. 6. Micrographs of the entrance and exit of the holes drilled with 5x5 spot pattern generated by the DOE. The green area shows the holes due to back light. The entrance-diameter is around 33 µm and the output diameter is 18 µm. For the SLM experiments the entrance and output diameters amounting 40 µm

and 21 µm differs from the ones obtained by the DOE amounting 33 µm and 18 µm. This difference can again be explained with the higher beam quality of the DOE.

3.4. Stamping pattern using SLM

The synchronized machining process also allows a stamping process of more complex patterns. The implemented IFTA-algorithm is well suited to calculate point distributions but partially fails for plain area structures. Several publications deal with the performance of different algorithms to calculate the computer generated holograms CGH. An impressive work has been presented by Weiqi Zhou-Hanf in hers master thesis [10]. By comparing Figures 3.6 and 3.7 [9, p. 15] she showed, that the Gerchberg-Saxton (GS) algorithm, a typical IFTA, fails to generate filled area-distributions. The result will be several narrow single spots. The same behavior will also be observed when a single line should be generated. The narrow spots are always more or less at the same position and cannot get averaged using multiple CGH's. Therefore, currently other software would be required to generate CGH for area filled structures.

To realize a stamping process with the present setup an axicon-distribution with a dominant first circle and higher orders with low power generating a ring was used. The picture of the internal far field camera (mounted in the beam shaping module) is shown in Figure 7. The diameter of the corresponding ring in the focal point of the scanner objective amounted about 270 µm. By using the synchronized scanning system, it is in principle possible to mark every ring at the normal spot position with high precision. By blanking out the corresponding pulses with the acousto-optic modulator of the laser systems pulse on demand (PoD) option, three rings with a distance of 300 µm to each other in the first line and another two rings 150 µm below in the second line forms the well-known Olympia logo as illustrated in Figure 8. Each point corresponds to a laser pulse and the pattern is formed by selectively blanking out single pulses during forth and back movement of the beam. By repeating this pattern for each of the multiple machined layers the pattern is stamped into the steel foil.

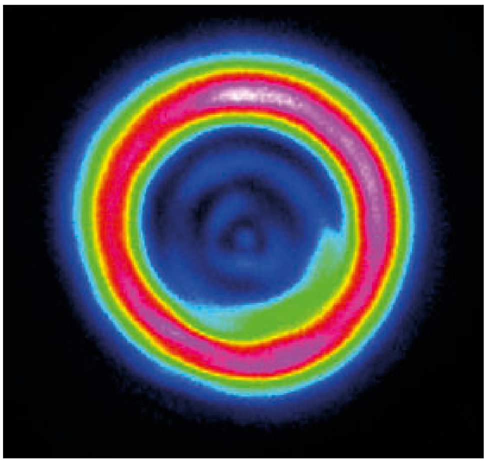

Fig. 7. beam profile of the realized axicon. Higher order rings could not be observed by the used camera. The diameter of the ring amounts 270 µm

Fig. 8. Alignment of the rings to get a structure, where the rings are arranged like on the Olympic logo. Each position (representing a pulse) is equidistant with a distance of 150 µm in X- and Y-axis. Selectively blanking out single pulses forth and back direction results in the desired structure.

Due to the large surface of the obtained ring and the limited pulse energy several tens of layers had to be machined for a clearly visible pattern on the foil. Figure 9 shows the obtained results for 50 machined layers. As for the holes no "smearing" of the rings is observed i.e. a very precise stamping process is achieved.

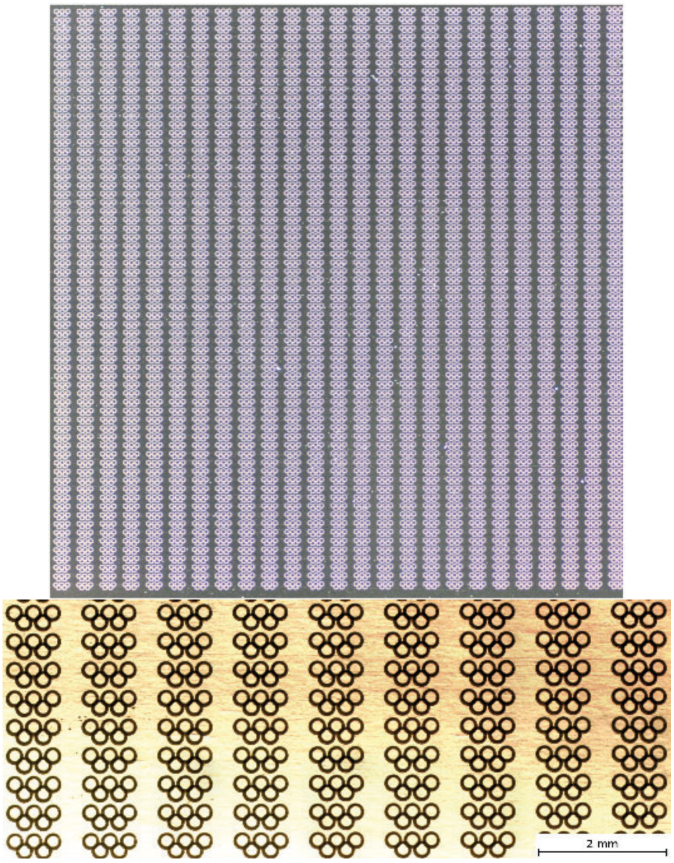

Fig. 9. Resulting stamped surface. On the top an overview of the 30x30 mm machined surface is shown. On the bottom a zoomed image demonstrates the high precision of this stamping process. The upper picture is taken by a common photo camera and a macro-objective whereas the lower picture is again composed of different micrographs stitched together.

4. Summary

It has been shown that the drill rate in the stainless-steel foil can be significantly increased by using a more dynamic scanner and spatial splitting the beam in multiple spots. In the presented experiments a multi spot pattern with 5x5 grid-oriented spots (totally 25 spots) has been used. Due to the fact, that every sub spot machines one hole and the pattern is shifted by only one spot-to-spot distance between two pulses, the demanded marking speed keeps low while a high average power could be used.

To generate these multi beam patterns two different techniques have been used, a beam shaping unit containing a Spatial light modulator (SLM) and a diffractive optical element (DOE). While the SLM offers high flexibility, the DOE offers a higher spatial resolution going with more precise pattern and further lower losses. The lower precision of the SLM is assumed to be responsible for the colored area around the holes machined with the SLM pattern compared to the ones machined with the DOE where almost no side effects could be observed.

Using a 5x5 multi shot pattern, the machining time for 10’000 holes was reduced from around 1 minute 45 seconds for single spots down to around 4.25 seconds resulting in a drilling rate >2300 holes/s while preserving the machining quality. The only drawback are the edges of the machined area where the first 4 holes are not or not properly drilled through because they got less pulses than the holes in the center as illustrated in Figure 1.

Additionally, optical stamping with a more complex pattern has been demonstrated with the beam shaping unit. In principle this optical stamping method can be extended to even more complex regular pattern for highest throughput surface structuring.

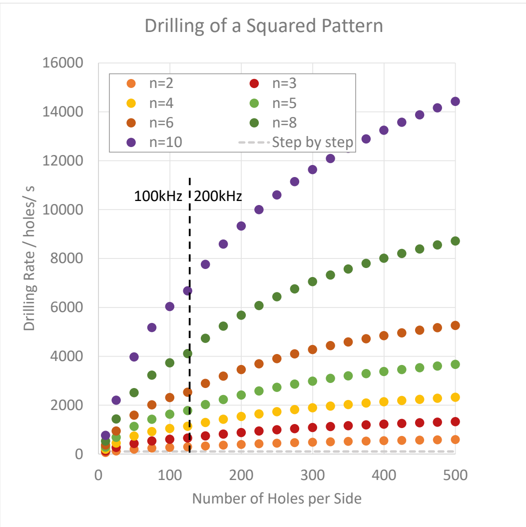

Fig. 10. Calculated drilling rates for squared gridded spot patterns as a function of the total numbers of holes per side and the number of spots per pattern. At a number of about 125 holes per side a PRF of 200 kHz would be more efficient.

5. Outlook

To increase the drilling rate, higher pulse energies and number of spots in the pattern are required. Figure 10 show a calculation based on the experiments presented for the DOE and the fs pulses. This calculation includes the down time at the edges of the pattern when the marking direction is changed and is therefore realistic. It shows that drilling rates exceeding 10’000 holes/s should easily be achievable with a 10x10 spot pattern corresponding to 4 times higher pulse energy and average power. Additional experiments with more powerful lasers and higher pulse energies are therefore demanded these drilling rates. Further the higher pulse energy would also allow to stamp regular patterns of high complexity for an efficient surface structuring process. Nevertheless, it has been shown, that it is possible to increase the drilling rate by splitting the beam in multiple sub spots.

Additionally, further studies are needed to determine the influence of small deviation from the focal plane i.e. it has to be clarified over which distance a shape can be kept and no influence onto the machined pattern can be observed.

As the current Gerchberg-Saxton algorithm used for the SLM cannot generate areas with a homogenous intensity distribution. New improved algorithms like the Offset-Mixed-Region-Amplitude-Freedom OMRAF algorithm must be tested for the generation of more complex patterns.

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