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New concepts in ultra-short pulse laser ablation using digital tools

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Abstract

With the FlexibleBeamShaper (FBS), a flexible beam shaping system is available which allows to investigate new process approaches for high power laser micro processing using USP- lasers. The system is based on a combination of a spatial light modulator for flexible beam shaping using phase modulation and a galvanometer scanner for moving the shaped laser beam over the workpiece. The paper presented here summarizes the results of a study on two novel approaches for USP-ablation: Laser ablation by optical stamping with shaped laser radiation and scanning laser ablation with digital tool change. In the first approach, it can be shown that laser ablation with a dynamic sequence of point patterns allows higher average powers to be used in the process. The second approach transfers the approach of roughing and finishing established from mechanical milling to laser ablation. Digital tool change, i.e. combined machining with different tool diameters, allows the laser process to be significantly accelerated without loss of structure resolution or quality.

Keywords: Spatial light modulator; high power USP processing; process parallelization; beam shaping;digital laser tools

1. Introduction

The use of beam shaping in ultra-short pulsed laser processing has become an approved tool to optimize the efficiency of micro ablation, cutting and drilling processes. Beginning with top hat beam shaping to reduce thermal heat accumulation effects and to increase the maximum ablation efficiency per pulse (Nolte et al. (2016), Neuenschwander et al. (2010)) over beam splitting as an effective way to overcome process limitations in maximum laser power per beam (Kuang et al. (2009), Pulsar (2015)), up to focal beam elongation to enable a fast laser cutting of wide bandgap materials (Lopez et al. (2015), Trumpf (2015)), focal beam shaping has already entered industrial processes. Further experiments with shaped laser beams documented in scientific literature, such as using non-diffractive Bessel beams for high aspect ratio laser drilling of wide band gap materials (Froehly et al. (2014)), using radially polarized beams for a more efficient laser cutting (Weber et al. (2014)) or using doughnut shaped beam shapes for a laser trepanning in percussion mode (Kuang et al. (2011), Hamazaki et al. (2010)), demonstrate that there is even more potential for creating new efficient laser processes.

Most of these focal beam shaping transformations from a Gaussian intensity distribution to a process adapted focal intensity distribution can be performed by diffractive optical elements (DOEs). First industrial processing heads have occurred in the market, which combine focusing or scanning and diffractive beam-shaping for glass cutting or parallel processing (Pulsar (2015)). By combining a diffractive beam splitter and a galvanometric scanning system it is possible to generate a static configuration of multiple beams in the work plane of the focusing objective. Although this multi beam scanning approach is very efficient, one disadvantage of the DOE is that it provides only a static intensity distribution and that the DOE hence has to be changed if another spot configuration is required.

To bypass this drawback, spatial light modulators (SLM) can be used for dynamic beam shaping (Kuang (2010)). This electronically controlled module uses the orientation of liquid crystals and the resulting change in the optical path length to change the phase front of the incoming laser beam (Hamamatsu (2018)). Using a 2D chip, the phase of a laser beam can be shaped in three dimensions. The limit in accuracy of the beam shaping is given by the resolution of the SLM and hence through the number of pixels. This way the phase can be

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controlled digitally by a specific number of steps. After focusing of the modified laser beam, the sub beams with different phase delays interfere in the focal plane, so that a new beam shape is formed. This shape can be calculated and changed in a rate typically up to 180 Hz, depending on the SLM type. Due to the flexible configuration of the SLM, a variety of intensity distributions can be created which makes it a powerful tool for focal beam shaping. Within this short paper new process concepts for ultra-short pulse laser micromachining using a recently developed beam shaping system, based on a SLM and a galvanometric scanner, are presented. The basic idea is to use digital changeable photonics tools to combine different laser processes or to increase the average power in laser ablation using a beam shaping approach.

2. Experiments

2.1. Experimental setup

The experimental setup is a beam shaping system developed by Pulsar Photonics called FlexibleBeamShaper (FBS). The FBS consists of a phase only SLM-based beam shaping unit combined with a commercial galvanometric scanner to make the processing of larger areas possible and to allow precise positioning of the modified intensity distribution on the workpiece. An integrated cooling device with active cooling control allows to keep the temperature of the SLM-chip on a constant value and thus to work with higher laser powers of 100 W and more. A more detailed description can be found in our previous work (Klerks, Eifel (2016)). For laser ablation a high power ps-Laser system (Edgewave PX100, 532 nm, 10 ps, P_{max}=60 W) has been used.

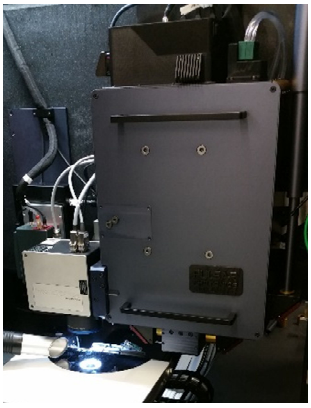

Fig. 1. FlexibleBeamShaper integrated in a laser machine configuration with a femtosecond laser system

2.2. Design of optical tools

For the generation of the desired intensity distributions in the focal plane of the FBS, a phase distribution or computer generated hologram (CGH) has to be calculated and displayed on the SLM. The method for generating the phase distributions is based on the Gerchberg-Saxton-Algorithm (Gerchberg, Saxton (1972)) which is located in the group of Iterative-Fourier-Transform-Algorithms (IFTA). The basic idea is to calculate a phase modulation for the incoming light to generate a target amplitude distribution (optical tool) through calculated diffraction. A more detailed description of the concept can be found in our previous work (Klerks, Eifel (2016)). Since the last report the IFTA was improved and expanded to obtain better results with respect to the quality of the generated focal intensity distributions.

The goal of the beam shaping in this paper is to distribute the available laser power on a larger area which allows to increase the average laser power in the process and hence reduces the process time. Two types of beam shaping can be distinguished, beam shaping of connected shapes like a top hat distribution and beam shaping of separated shapes like a multispot pattern. Creating a top hat distribution with an IFTA is still a subject of interest in research. There are successful approaches in generating top hats without any spatial masks but it is often a balance between quality and diffraction efficiency (Zhang et al. (2016), Guillon et al. (2017)). Instead of generating top hat distributions, within this work multispot patterns (MSP) are investigated in experiments as a substitute. Multispot patterns are easier to optimize for an interference free design with high spot homogeneity, high diffraction efficiency and high depth of field in the focal area.

2.3. Optical stamping with multispot patterns

In order to utilize the maximum available power while maintaining USP laser advantages, the FBS is used to generate multispot patterns. For this purpose, an algorithm has been developed to separate a given geometry in a number of MSPs, each having the same number of laser spots in order to keep the fluence constant. After calculating the CGH for each of the MSP, the CGHs are being displayed as a video with 50 frames

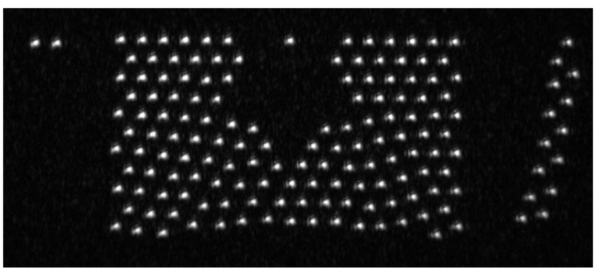

Fig. 2. Example for a multispot pattern with 140 spots generated in the focal plane for laser ablation.

per second on the SLM, each leading to a laser ablation of a thin gold film which was coated on a glass substrate. The sum of the ablation using the displayed MSP as an optical stamp results in the initial target geometry (cf. Fig. 3). Dependent of the power in the workpiece plane, the separation algorithm considers maximum number of points per image to ensure that the ablation threshold of the material is reached. The algorithm also regards distances between points, so interference effects do not occur.

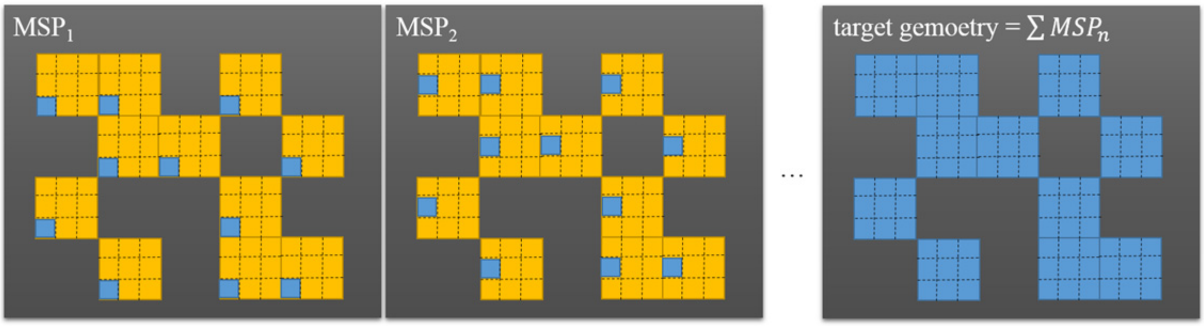

Fig. 3. The concept of optical stamping with multispot patterns is to divide the target geometry into several multispot patterns, which will be displayed consecutively after each other. The sum of the MSPs results in the initial target geometry. This strategy allows to overcome limitations in the available maximum pulse energy.

2.4. Roughing and finishing using compact multispot configurations

In traditional machining like milling it is common to use different tools for specific tasks while working on a workpiece. While roughing is the operation of removing large amounts of material rapidly to come close to the desired shape, finishing follows for slow and precise operations to reach the final geometry. If both strategies are combined the milling process can be significantly accelerated while the accuracy of the process remains high.

The FlexibleBeamShaper is used to transfer this roughing and finishing concept to laser micromachining by providing digitally configurable photonic tools. Since in reality it is difficult to create both a stable and interference free top hat in the workpiece plane over long process times, a compact multispot pattern with 18 laser spots is used for roughing to reduce process time (cf. Figure 4). The pattern has a maximum diameter of 148 µm and was configured so that the projected intensity of the tool in one axis is nearly constant. In the center of the distribution, no spot is deliberately placed to thermally optimize the laser processing, i.e. reduce thermal heat accumulation in the laser process. The roughing tool is used for the hatching of a test structure to be ablated, i.e. the filling of the spaces between the outer contour with scanning vectors (cf. Figure 5a). The native single spot is used in the end for finishing or contouring to produce sharp edges and finish up the result (Fig. 5b).

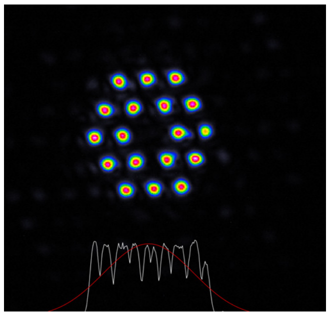

Fig. 4. Compact multispot distribution with 18 laser spots used for laser roughing. The projection of the intensity distribution on the x-axis leads to a nearly constant intensity over the diameter of the tool. Also, the configuration was thermally optimized by leaving out the spot in the center.

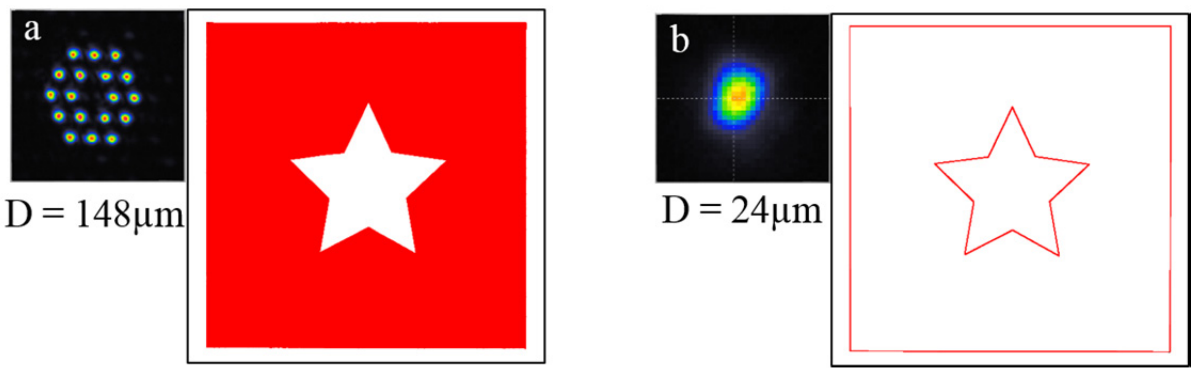

Fig. 5. The roughing or hatching of large areas is processed with a big spot pattern (a) while the finishing of fine structures and contouring is processed by a small spot (b).

Dependent on the SLM model, changing the photonic tool takes about 20ms – 30ms, so the FBS provides a highly dynamic tool changing system for photonic tools.

3. Results

3.1. Thin film ablation

Thin film ablation requires precise power management to not damage the substrate material. In this experiment a sapphire glass plate was used as substrate, coated with a 300nm thin film of gold. Good results were achieved with 200 mW for a single spot.

First optical stamping with multispot patterns has been investigated. Since the setup delivers about 28W on the workpiece in the 1^{st} diffraction order, it is possible to execute optical stamping with 140 spots simultaneously. The target geometry is split into 595 different MSP segments. The experiment is executed like described in section 2.3, so the process time is 10 s. No mechanical moving parts were used in this experiment, while achieving a maximum working plane of 10 mm. Due to limited resolution of the spatial light modulator the ablated result does not have sharp edges as shown in Fig. 6a.

For roughing and finishing first a benchmark was done by conventional methods. The target geometry with an outer diameter of 25mm was ablated with a single focused spot and an x-y-scanner. The process time of the benchmark is 206 seconds with a hatching distance of 10µm and scanner speed of 1000mm/s. The result shows

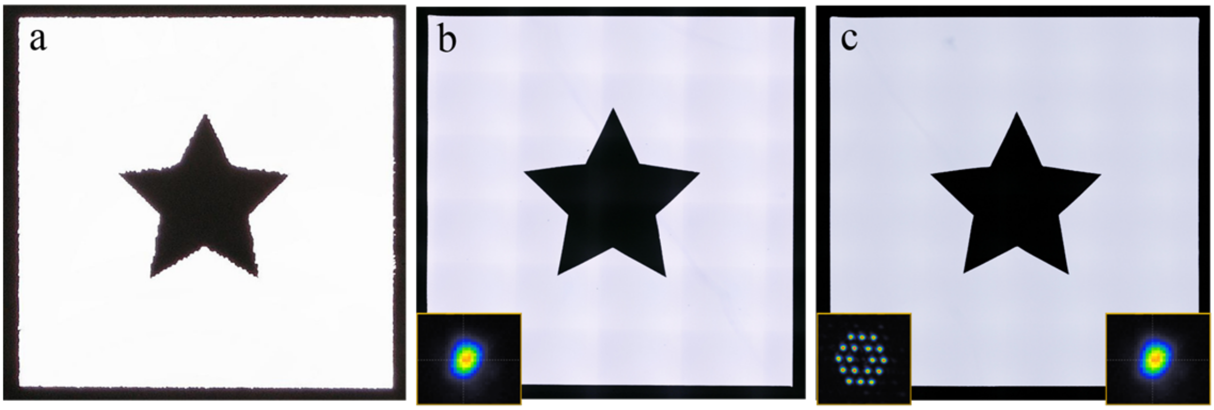

Fig. 6. (a) Ablated geometry on thin film through optical stamping with MSPs. (b) Ablated geometry on thin film with conventional method of single spot and scanner. (c) Ablated geometry on thin film through roughing (D=148µm) and finishing (D=24µm). In comparison to (b) the process time in (c) could be reduced by a factor of 4 through applying the strategy of roughing and finishing.

sharp edges and clean ablation (Fig. 6b). Then the roughing and finishing strategy was investigated. The roughing was done with a multispot pattern with a diameter of 148µm while the finishing was done by a single spot with the diameter of 24µm. With a hatching distance of 50µm and scanner speed of 1000mm/s the process time is 50 seconds. Applying the roughing and finishing strategy reduced the process time by a factor of 4 while the resulting quality is well comparable to the results of single spot ablation as shown in Fig. 6c.

3.2. 2.5D Steel ablation

The strategy of roughing and finishing was investigated on steel as well. Steel has a higher energy threshold for ablation and is also more sensible to thermal effects. The FBS can be used to design any wanted spot pattern to optimize thermal management. For this experiment a multispot pattern arranged as a ring formation was designed to achieve a more homogenous thermal profile on the workpiece.

In order to reach an ablation depth of 80µm with a conventional single spot of 24µm diameter, a process time of 1h 13m is needed. 4.5 W laser power were used for this process. In order to reduce the process time the strategy of roughing and finishing was applied with a multispot pattern of 6 spots with each spot having 4.66 W (total power = 28 W). After a process time of 19m 13s an ablation depth of 90 µm was reached. Applying the roughing and finishing strategy the process time was reduced by a factor of 3.84.

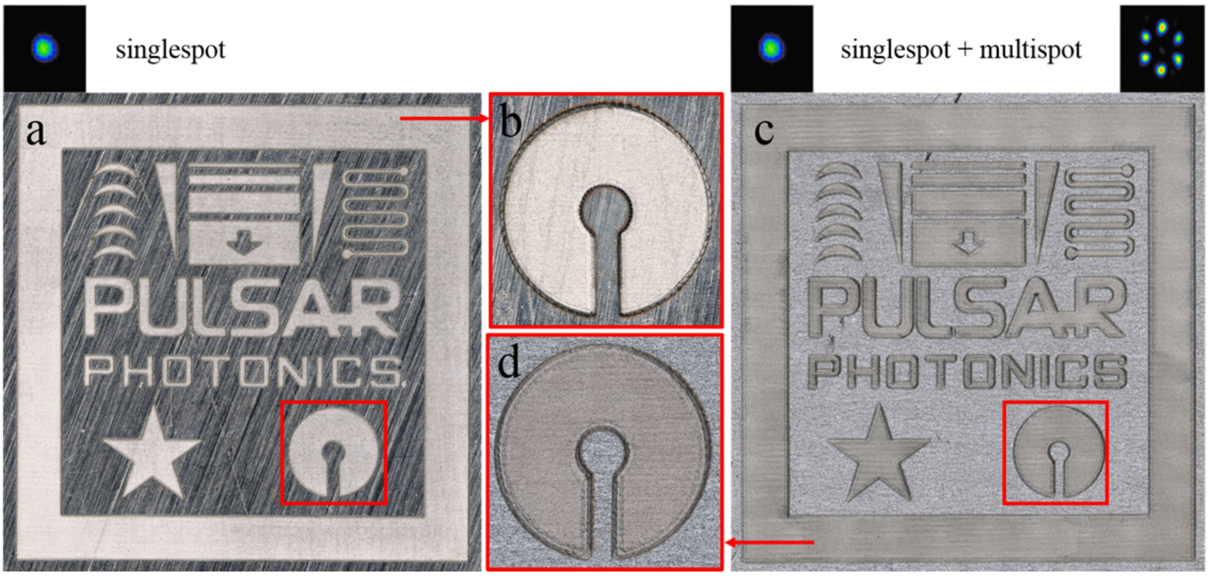

Fig. 7. (a) Ablation on steel with single spot. The process time for 80µm ablation depth is 1h 13m.Using roughing and finishing (c) the process time is reduced by a factor of 3.84 to 19m 13s while achieving an ablation depth of 90µm. (b) and (d) are zoomed in details of (a) and (c) respectively.

Fig. 7 shows the results for both, single spot benchmark and roughing and finishing combination. After roughing process the surface roughness is R_a = 1 µm, R_z = 6.5µm and average waviness W_a = 2.2µm. In comparison the roughness of the processed area with single spot is slightly lower: R_a = 0.37µm, R_z = 2.51µm, W_a = 1.37µm. The graphs of roughness and waviness are shown in Fig. 8.

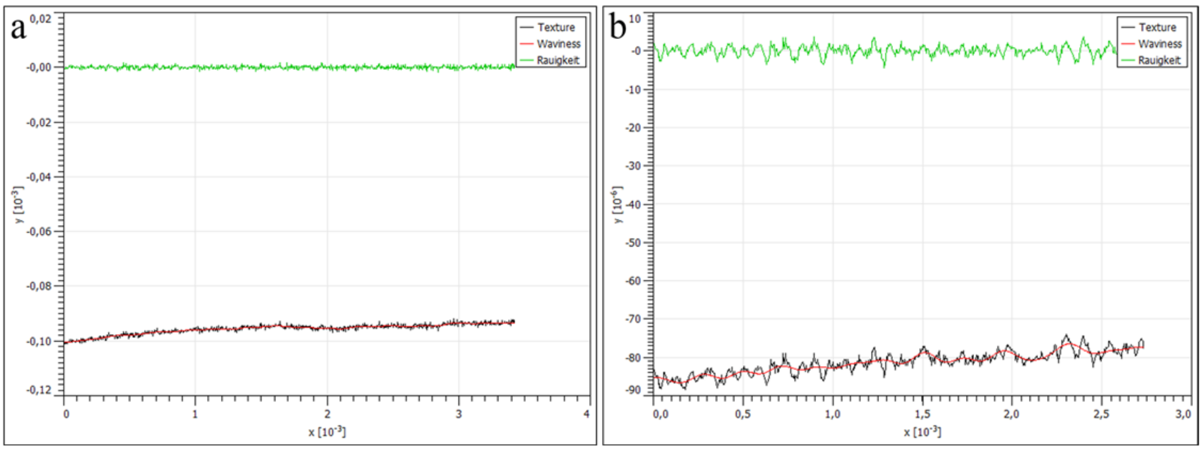

Fig. 8. Waviness and Roughness of processed area by single spot (a) and multispot pattern (b) plotted as graphs.

4. Conclusion

Two novel approaches for material ablation with USP laser were investigated. The first approach, optical stamping, does not need any mechanical moving parts in order to work in a 2D plane of about 10x10mm². Due to limited resolution of the spatial light modulator the edges of laser ablated structures were not sharp. This effect is especially visible on thin film ablation. Optical stamping could be used in marking applications, where a very fast and dynamic system is needed.

The second approach is to use the FBS as a dynamic photonic tool repository and adapt the concept of roughing and finishing. In comparison to the conventional method of using a galvanometric scanner and working with one spot, roughing and finishing led to a reduction in process time by a factor of 3.8 – 4 while achieving comparable surface qualities. With the FBS new concepts of laser micromachining with changeable photonic tools could be shown. In future other laser processes will be demonstrated with the FBS, like the combination of laser cutting and laser ablation in two subsequent laser processes, each process using an optimized digital photonic tool. Another interesting approach to be addressed is the laser form milling, i.e. using an optimized intensity distribution that generates defined depth profiles in the work piece.

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