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High resolution pixel based direct laser patterning for surface functionalization

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Abstract

Micro patterning with ultrashort laser pulses allows the production of micro and nano sized surfaces patterns, which results in specific functional properties. For the generation of those functionalities on large surfaces a two step processing is necessary in which rotating cylinders are laser structured and those cylinders are used in micro embossing to achieve processing speeds up to 20 m²/min. In order to realize embossing cylinders with seamless embossing features, a moving ultra-short pulsed laser ablation process with multi beams is used. In this contribution direct processing of negative nano and micro features are completely realized by a digital work flow beginning from a digital data asset which is based on a pixel-to-pixel ablation in a fast surface scanning process (up to 40 m/s). Using high repetition rate ultrashort pulsed laser ablation, a high productivity can be achieved with features sizes from 2 µm to several 10 µm at areas of 2m² for adjustment of the surface properties. A newly developed high compact ps-laser with repetition rates of up to 1MHz and an average power of up to 500W was distributed into 16 independent modulated parallel beamlets by a diffractive optical element (DOE).

Keywords: usp-laser, diffractive optical element DOE, acuosto optical modulator AOM, multi spot, parallel micro processing, 3D micro structures, surface functionalization, metal sheet embossing, roll-to-roll micro embossing, nano imprint lithography (NIL), intaglio print

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1. State of the art

1.1 Large area micro structuring

Periodic surface topographies produced by process engineering like LIPPS or Laser Interference structuring are widely used for surface functionalization. Nevertheless, for several functions these technologies do not offer the right features as they do not provide the necessary degree of freedom. Therefore, micro structures with feature sizes of 2 – 20 µm realized through high resolutions of up to 25400 DPI pixel-based processing are of great interest for the applications “electronic printing” and “surface functionalization”. Realized in a direct laser process on metallic masters and replicated on plastic films in a R2R processing, a wide variety of products could be produces with new functions.

1.2 Tooling of embossing cylinders

The outstanding quality of ultrashort pulse lasers with an almost melt-free removal, due to the extremely short pulses, offers fine ablation geometries. With ablation dots down to 2 µm, near the ablation threshold, machining resolutions of 25400 DPI are possible. For achieving acceptable processing times with these fine resolutions, a high-speed scanning application as offered by cylinder micro machining systems is required to provide the necessary efficiency. In combination with high repetitive lasers, it is possible to serve this high-speed scanning application with pulse to pulse overlaps of 50 %. For example, to realize a 50 % pulse overlap with a spot size of 2 µm at 10 m/s, a pulse repetition rate of 10 MHz is necessary.

2. Ultra-high precision cylinder micro processing system

For a high precision micro machining application, a temperature stabilization is inevitable if a processing of m² is demanded. In a cylinder processing system, the workpiece is rotating with uniform speeds of 50 m/s which is possible due to a hydrostatic bearing of the cylinder (Fig. 1). Beside the control of the high velocity, the position stability of the rotating axis is in the sub µm range. The positioning of the laser head in a cylinder processing system is in the range of +/-200 nm for an engraving width of 5 m.

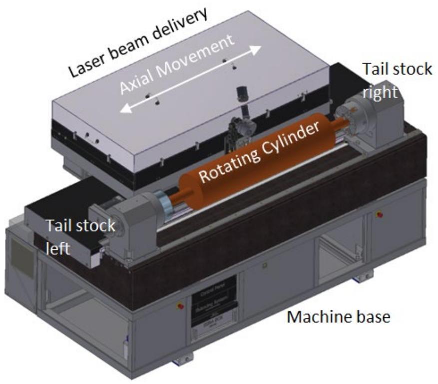

Fig. 1. Schematic of a cylinder processing system

2.1 Data handling

The fastest way of transferring a pixel-based image is realized in a cylinder processing system according to the image setter principle. This means that the laser is controlled pixel by pixel through a bit map data asset. In an 8-bit data asset the lateral resolution is given by the pixel size. Beside the lateral pixel dimension, the tone value defines the depth. The depth resolution is then defined by the ablation removal per layer. The material removal per layer is inversely proportional to the possible depth resolution and is dependent on the metal to be structured. In common printing and embossing applications feature sizes of 100 – 200 µm are processed with a resolution of 5 µm and spot sizes of 10 µm. For functional topographies with feature dimensions of approx. 25 µm, a pixel size of 1 µm combined with a spot size of 3 µm is necessary to transfer the correct image. For example, in Fig. 2 a typical hydrophobic structure, inspired by a predatory fish with an 1,5 µm vertical line and 4 µm diagonal lines, is resolved with a pixel size of 500 nm. If the pixel size was increased to 2 µm, the information and the function would be lost. The diagonal lines would no longer be symmetrical, and the vertical line would be sporadically lost in accordance with the resolution (Fig. 2 Right).

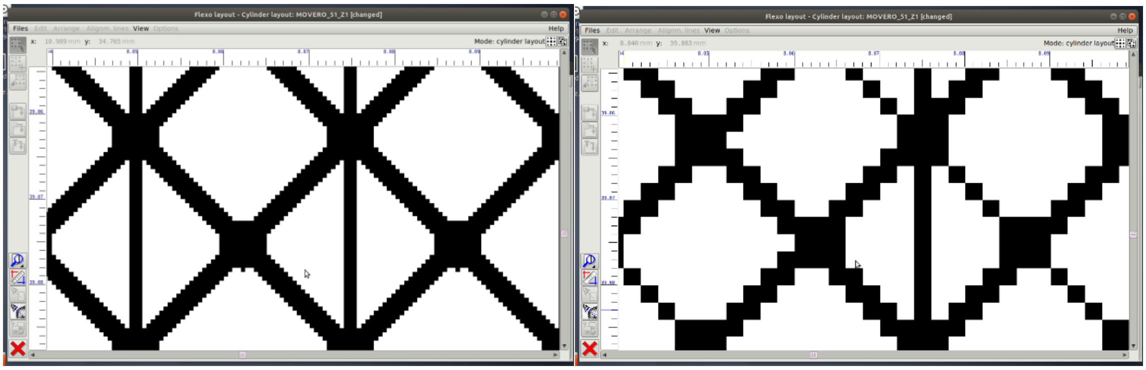

Fig. 2. Pixel based image of a hydrophobic structure. Left: Resolution: 50800DPI; Right Resolution: 12700DPI

3. Multi spot beam system

For a high precision micromachining, fluencies near the ablation threshold provide the highest depth resolution. In consideration of the small spot size and the resulting low pulse energies, one laser source is sufficient to serve several spots. The splitting of a high-power laser beam into a defined number of spots by a diffractive optical element (DOE) and a pulse picker for pulse modulation in the MHz regime based on acousto optic modulators, however, offers a compact processing system. Due to the principle, an adaption to different wavelengths is possible, so that it can be transmitted from 1064 nm to 532 nm and 355 nm.

For beam splitting a smooth diffractive surface DOE based on fused silica was used [8], providing a nine and alternatively a 17 channel even-separated beam splitter design. One of the diffraction orders was out-coupled and used for power reference leading to an eight and 16—channel beam delivery. The fine pulse energy adjustment of each beam could be achieved by modification of the acoustic field of the modulator, changing the diffraction efficiency of the Bragg grating of the acousto optical modulator.

To achieve high scanning speeds with simultaneous high repetition rates (up to 3MHz), a multi-channel acousto-optic modulator (AOM) offers some advantages. In a cylinder processing system, the multi beam modulation has only the task to distribute the laser power to several channels in order to minimize the thermal influences. The combination of a multi-spot array and a fast axis (cylinder rotation) is highly efficient. However, maximum scan speeds of *50 m/s* are possible by using this method. In the following chapters two multi spot setups will be discussed (Bruening et. al. 2017).

3.1 300W ps-Laser / 8 beamlets

In a first step a high power laser beam split into nine spots by a diffractive optical element (DOE) was realized. Each spot in the beam comb can be modulated separately by the AOM according to the grey levels of the engraving data as described in chapter 2.1.The experimental ablation rates have been evaluated by engraving areas of rotogravure cells (Fig. 3) of 150µm x 150µm. After synchronization of the 8 beams the setup was tested with 300W laser power and at 3MHz repetition rate and different fluencies (1.6, 3.2, 4.8, 6.4 and 7.9J/cm², adjusted by an external pulse picker engraving rotogravure cells with a diagonal size of 83µm and a wall width of 35µm at a resolution of 2000 l/cm in circumference direction (with a surface speed of 16 m/s) in axial direction. The achieved ablation depth/layer was 4 µm, respectively 24µm after 6 passes [Bruening et. al. 2017]. This equates to an ablation rate of 16.3 mm3/min in copper (approx. 2 mm3/min per beam) (Fig. 4).

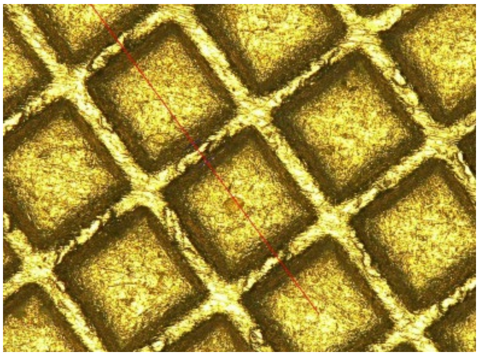

Fig. 3. Ablated rotogravure cell

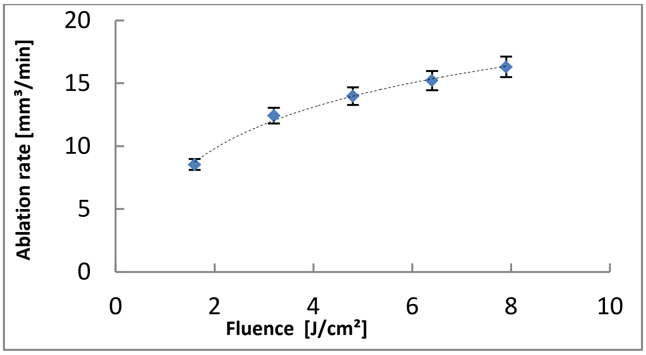

Fig. 4. Ablation rate of 8 parallel spots

3.2 500W ps-Laser / 16 beamlets

To provide the necessary pulse energy in a 16-spot system, the laser power was increased to 500W. Assuming, that the adequate fluence for engraving copper dies is approx. 5 J/cm², it can be estimated that the developed 500W slab-based ps-laser with a pulse repetition rate at 1MHz could be implemented into a processing head that generates 16 beamlets with similar efficiency. In Fig. 5 the beam delivery starts with the laser source SRC. The emitted beam was split by a DOE into 17 beam orders with defined propagation angles BS. A Fourier lens set FL1 and FL2 focusses and parallelizes the beams into two 8 channel acousto optical modulators AOM1 and AOM2. The multi spot intensity distribution at the ablation area is formed by a setup of three lenses Tl1, TL2 and TL3.

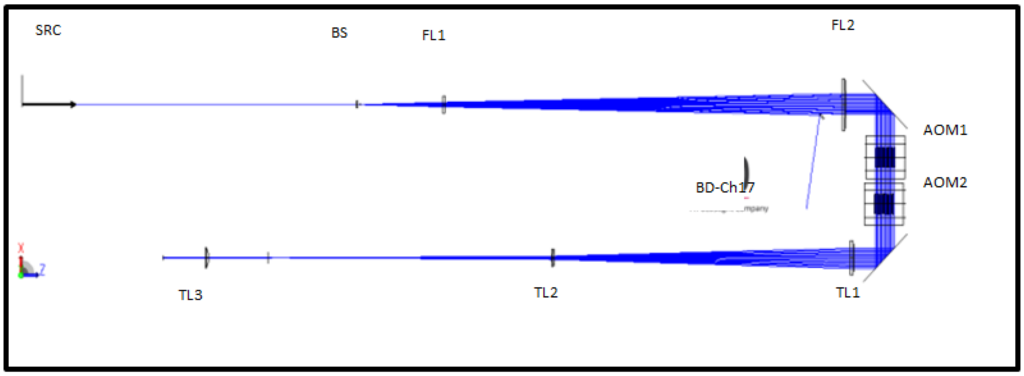

Fig. 5. Diffractive beam splitting of a 500W laser into 16 independent modulated beams, each about 20W +-1W at the focal plane.

Due to the spatially restricted acoustic field per beamlet, the interim range of the AOM crystal could be used for transferring every 2nd beamlet without significant influence. A sophisticated arrangement of two 8-channel AOMs, as it is shown in Fig. 6, provides a sequential switching of the beamlets, according to the propagation direction. Owing to the longitudinally separated switching planes in combination with only one mirror, providing the Bragg angle of the AOM, an acceptable small lateral shift of < 40µm of the beamlets, perpendicular to the beamlet comb axis, is achieved as shown in Fig. 7. This misalignment of the position can be compensated by a software synchronization adjustment.

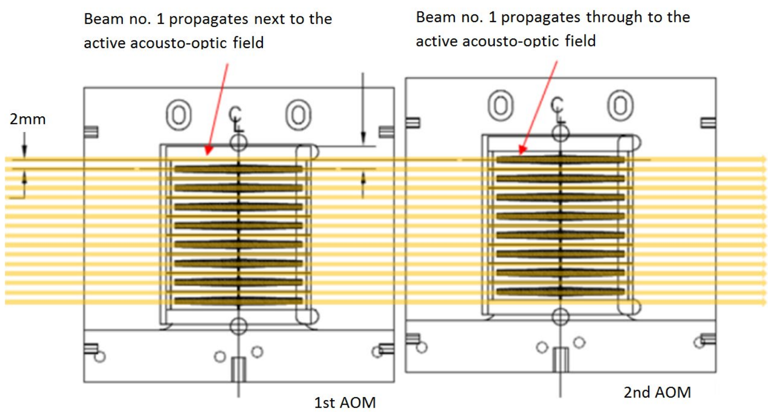

Fig. 6. Arrangement of two 8-channel AOM´s with a 2mm orthogonal Shift

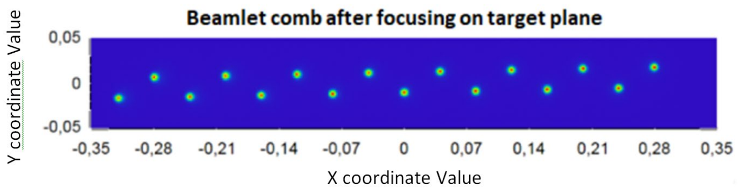

Fig. 7. Ray tracing simulation of the beamlet comb in the target plane

In Fig. 8 the distances of the 16 beams from Fig. 7 could be practically approved by engraving all beams parallel a triangle structure. The pictures shows two rows (distance 40µm) of each 8 triangles. The distance of the triangles in each row is 80µm.

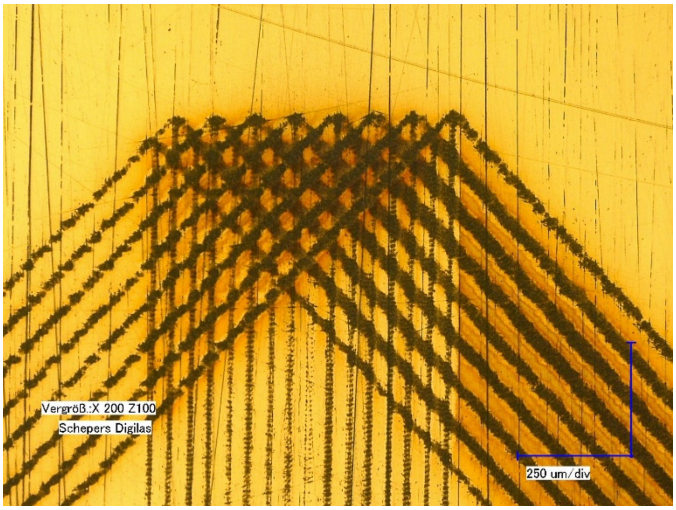

Fig. 8. Ablation of 16 parallel acting spots without synchronization

After synchronization of the 16 beams the setup was tested with 500W laser power and at 1MHz repetition rate and different fluencies (2.2, 4.1, 7.9, 10.9 and 13.2J/cm², adjusted by an external pulse picker) by the rotogravure cell from Fig. 3 with a surface speed of 10 m/s. The achieved ablation depth/layer was 8,5 µm, respectively 85 µm after 10 passes. This equates to an ablation rate of 27.09 mm^3/min in copper (approx. 1,7 mm^3/min per beam) (Fig. 9).

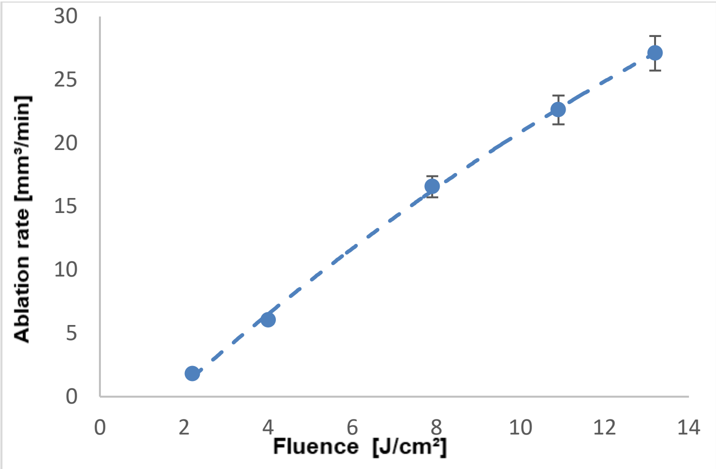

Fig. 9. Ablation rate of 16 parallel spots

But since each beam path has to be modulated externally by a separate modulator per spot, the maximum number of this multi spot approach can serve between 16 and 24 spots. Limitation in this case is not the laser power, since ultrashort pulsed lasers are available in the several 100W region. Using a 500W laser and single spot energies of less than 10 µJ more than 50 single beams could be realized. The limiting factors are the size of the modulator-crystal, beam delivery optics and focusing optics. Hence, the concept of laser beam splitting is limited, a further scaling up the multi spot arrays could overcome the limit.

4. Examples

Specific surface functionalities can be generated through topographic modifications of the surface. For bio medical and optical applications, the dimensions are in the nm up to µm range combined with a low surface roughness and high aspect ratios. The design of those topographies is mostly based on parameter criteria which are known for influencing the interface functions. For optical applications, several software tools are available to create functionalized pixel-based data, which could be used for laser processes. The following examples were processed with a 532 nm pulse duration 10 ps and 2 MHz pulse repetition rate.

4.1 Optical structures

Structuring of embossing dies with structure sizes of some 10 µm for the functionalization of surfaces for refractive-optical laser mass production tools will be covered by typical refractive-optical structures like micro lenses. These topographies can then be transferred to a film which can be used for targeted light guidance in flat screens. Furthermore, the creation of surface structures by laser texturing with ultra-short pulsed laser pulses has proven to be a useful technique for producing well-defined micro-scale surface textures like diffractive structures.

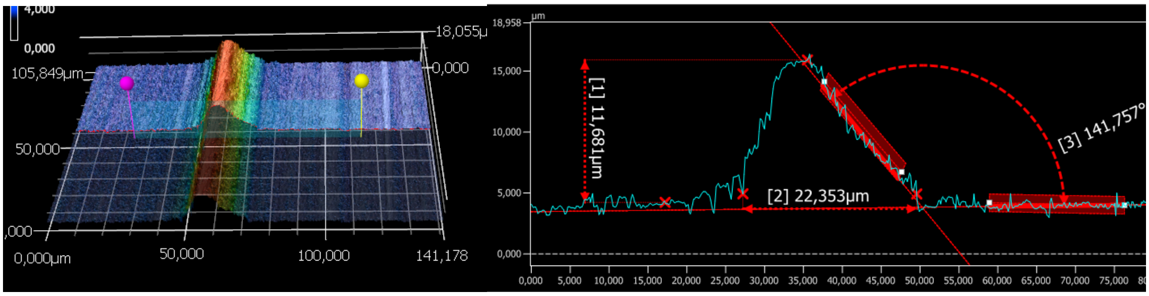

Fig. 10. Refractive 3D Micro Fresnel element, Left: 3D Element, Right: cross section view

Refractive µm-structure

For a light management application, optics in µm scale could be used for many products. Micro prisms with a base length of 22 µm were directly processed. In a first step, a continuous 3D structure was digitally generated in a pixel based 8-bit data asset (pixel size 500 nm). The data were transferred, pixel by pixel, onto a copper surface as shown in Fig. 10. The prism was engraved with a depth of approx. 10 µm in 20 passes (depth per pass 500 nm). The laser processed positive structure could be inverted into a negative structure on the final foil in an embossing / printing process.

Diffractive structure

Diffractive optical structures are used as security elements in the packaging industry to avoid product piracy. As food is mostly packed up in single use packages, these security elements must be manufactured in a low-cost roll-to-roll mass production. This means that diffractive structures must be laser processed on a cylinder that could be used as a mass production tool. In Fig. 11, a detail view of a micro structured diffractive element with a resolution of 4 µm is shown. The depth was adjusted by the grey value of the pixel and was processed during the micro structuring process by controlling the laser fluence. A cylinder tool with this structure could be reproduced on foils in a rotary UV-Nano Imprint process

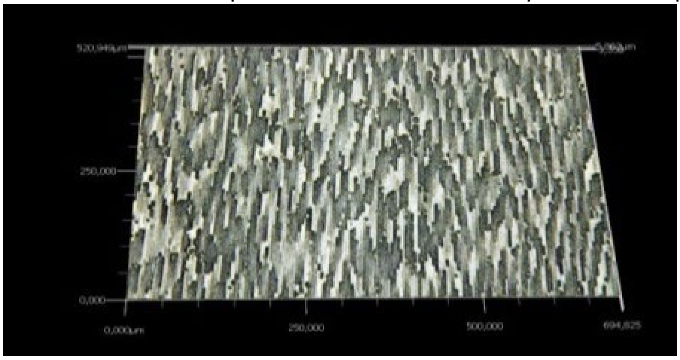

Fig. 11. In stainless steel engraved diffractive structure, pixel size: 4µm, depth 1,4µm, 30steps

4.2 Biological structures

Bio medical structures

Surface topographies designed by features with heights of 5 µm, arranged in an imaginary square with sizes of 10 by 10, 20 by 20 or 28 by 28 µm², lead to a significant cell growth. These features are built up by using microscale primitive scales like circles, isosceles triangles and thin rectangles. For the adjustment of the functionalities, computer based mathematical algorithms are used. The variety of cells and bacteria is high, and thus also the behavior of the organisms is different. This means that the micro structure has to be adjusted to the habits of living cells. Therefore, several thousands of distinct, randomly designed surface topographies are necessary to enable the desired functionality (Papenburg, 2009). For example, primitive shapes of pins with a diameter of 4 µm and circles with a diameter of 18 µm (Fig. 12, Left) are processed in one step by a usp-laser engraving process on a copper surface (Fig. 12, Middle), and reproduced (Fig. 12, Right)

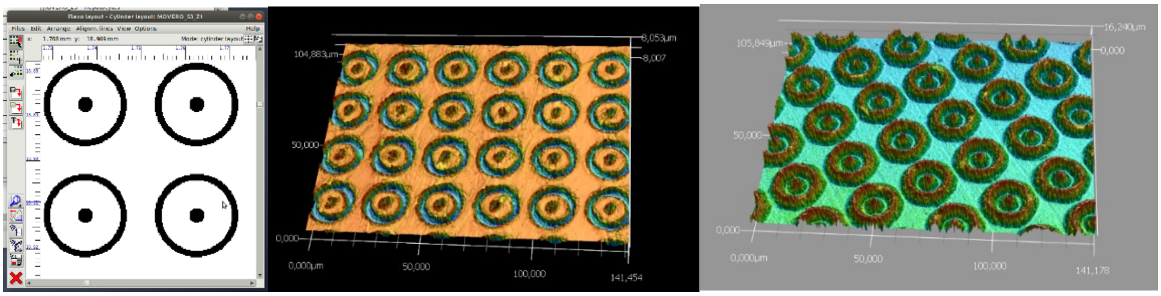

Fig. 12. Left: Data asset bio medical structure, Middle: laser engraved in copper, Right: Embossed sample

Antibacterial structures

Today antibacterial properties are usually achieved by chemical modifications of surfaces. These chemical processes are not always safe and therefore not approved for all applications. In this contribution, antibacterial surfaces are processed whose function is based only on the structuring of the surface. This eliminates questionable additives and this result can be transferred to a variety of other applications. The typical dimensions of antibacterial structures are in the range of 1-5 µm, as shown in fig 2. This pixel-based structure was engraved into a copper surface (Fig. 13, Left).

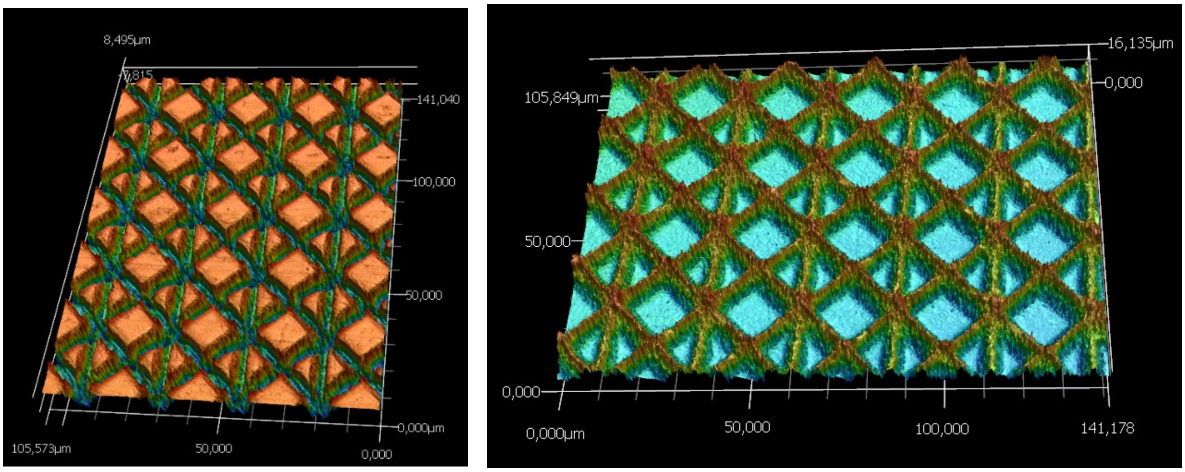

Fig. 13. Left: laser engraved hydrophobic structure in copper, Right: Embossed sample

The negative structure of the laser processed plate was embossed onto a plastic substrate (Fig. 13, Right). In this manner a regular triplet structure was achieved. This example demonstrates the freedom of this processing method compared to LIPPS or Laser interference patterning. At last a computer simulated antibacterial structure could be used in a mass production application.

Resume

A 16 spot approach for USP laser processing with high quality and high throughput have been described in this paper achieving high ablation rates. The ablation rate achieved with a 500W laser modulated into 16 beams with a spot diameter of 13 µm is around 27 mm^3/min. Tools for the roll-to-roll fabrication for the embossing of optical, optical-diffractive, antiseptic, cell-growth-promoting have been processed.

The properties of surfaces can be significantly influenced by applying specific functional microstructures. The size of these structures varies depending on the function. The size and complexity, in turn, define the necessary

Resolution and also the process technology. In this contribution the transition from a multi-step manufacturing method of embossing shims to a single-stage production process without the use of wet-chemical process steps has been shown.

Acknowledgements

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References

Bruening, S., Jarczynski, M., Du, K., Gillner, A., 2018, „Large Scale Ultrafast Laser Micro Texturing with Multi Beams", Proceedings of LPM 2018 – the 19th International Symposium on Laser Micro Fabrication, Edningborough, England

Bruening, S., Jarczynski, M., Mitra, T., Du, K., Fornaroli, C., Gillner, A., 2017, „Ultra-fast multi-spot-parallel processing of functional micro- and nano scale structures on embossing dies with ultrafast lasers", LiM Laser in manufacturing, Munich

Bruening, S., Hennig, G., Eifel, S., Gillner, A., 2011, " Ultra-fast scan techniques for 3D-micro structuring of metal surfaces with high repetitive ps-laser pulses", LiM, Laser in manufacturing, Munich

Papenburg, Bernke, 2009, "Design strategies for tissue engineering scaffolds", PhD thesis, University of Twente, Netherland