WLT LiM 2017

Wissenschaftliche
Gesellschaft
Lasertechnik e.V.

Lasers in Manufacturing Conference 2017

Ultra-fast multi-spot-parallel processing of functional micro- and nano scale structures on embossing dies with ultrafast lasers

Stephan Bruening[a,*], Manfred Jarczynski[b], Thomas Mitra[b], Keming Du[c] Christian Fornaroli[d], Arnold Gillner[d]

[a] Fa. Schepers GmbH & CO KG,
[b] Fa. LIMO GmbH,
[c] Fa. EdgeWave GmbH,
[d] Fraunhofer ILT, Aachen

Abstract

Functionalization of surfaces is of major interest for several applications, e.g. tooling industry, printing industry and for consumer products. In suitable mass production applications, like injection molding or roll-to-roll processing for diverse markets, the final product could be equipped with new features, like hydrophilic behavior, adjustable gloss level, soft-touch behavior, light management properties and so on. For the generation of functionalities at reasonable costs, dies and molds can be complemented with an additional structure in micro/nano scale using laser ablation technologies. Through the availability of USP-lasers, features sizes down to the diffraction limit could be transferred in a digital way (pixel by pixel / voxel by voxel) to a tool, like a cylinder for a roll-to-roll mass production. In recognition of an industrial implementation, an ultra-high resolved direct digital transfer is a limiting factor. Shorter processing times by further increasing the spot- or workpiece-movements are limited. By keeping the achieved state-of-the-art performance, scaling-up individual modulated lasers/laser-spots enable a less challenging way of increasing the productivity. In this work, the parallel process of individual modulated multi laser sources is compared with a laser source split by Diffractive Optical Elements (DOE) for applications in a cylinder micro structuring system. With spot sizes down to approx. 2 µm and depth resolution of 50 nm per pulse, diffractive elements are processed on a metal plate (e.g. stainless steel plate, shim). This shim could be used as an embossing die for mass production roll-to-roll processes.

Keywords: ultrashort laser pulse; 3D µm machining; ablation; Soft-Touch-Structures; hydrophobic surfaces; antibacterial surfaces; diffractive optical elements (DOE); ultra-short pulsed lasers; functional surfaces; light management; micro prisms; Fresnel lenses; lenticular lenses; micro processing; roll-to-roll production; embossing dies; shim

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[*] *E-mail address:* s.bruening@schepers-digilas.de .

1. Motivation / State of the Art

Due to an increasing demand for functional requirements for consumer products such as reduced friction, extended life, improved soft touch or antibacterial effect etc., a targeted adjustment of the surface layer properties is becoming increasingly important for industrial applications. The solution to this requirement is not only to provide the right functionality, but also to adjust the service life of the product. In many cases, the various types of coating technologies do not provide the required lifetime. However, laser processing methods can provide a solution to this problem. Using laser micro-structuring of cylinder surfaces as a replication tool and replicate the structures on foils in roll-to-roll processes, proper functional surface properties with the required lifetime could be produced. In addition to the function requirement, the production costs and environmental pollution can also be reduced compared to the costly coating technologies.

This is the base for a synthetic generation of nano/micro structures on a mass fabrication tool like an embossing cylinder which is used for high precision, large scale, high speed micro processes. Micro-structuring of the embossing die with ultra-short laser pulses offers many benefits compared to alternative processes. The ultra-short pulses and the high pulse power allow extremely high intensities which offer a material-independent ablation with minor melt effects [2]; (Fig. 1). Newest high power ultrashort pulsed laser sources ($P_{average}$=300W) boost 3D micro-structuring of large scale metal surfaces for embossing and printing applications with ps-lasers by a significant reduction of the processing time. Although the advantages of ultrashort laser pulses are well known in the industrial micro material processing with regard to lateral and depth resolution, there is still a lack of productivity compared to competing procedures especially for applications where large ablation volumes are required.

In several papers it was shown that a moderate fluence is necessary to achieve very high ablation qualities. A very well balanced algorithm to generate an ablation process is necessary, which on the one hand allows smooth processing surfaces and on the other hand at the same time prevents the accumulation of heat and melt residues [1]. With an available pulse repetition rate of Ultrafast -lasers in the MHz range and the high speed of common cylinder scan devices in the range of 20-30 m/s, the necessary low overlap can be managed. A further increase of the scanning speed presupposes an improvement of several components like data processing, modulation velocity and rotation / beam deflection velocity. A much more convenient and efficient approach to get optimized processing conditions at higher power levels is possible by a multi spot application. To preserve a split in multiple paths, the fluencies of each single spot must be kept moderately. A central question in a multi spot application is the interaction between the acting spots and the resulting thermal accumulation on the metal surface.

2. Ultra-fast micro processing approaches

For realizing a higher productivity, an energy level per pulse between 1 µJ and 60 µJ enables a maximum ablation rate with the well-known quality level of ultrafast lasers. With common fast moving work pieces (e.g. cylinder engraving system) or fast distributing beam deflection systems [1] (e.g. Polygon scanners) maximum pulse frequencies of up to 5 MHz will also allow the proven quality. Both systems are in principle limited at approx. 100 m/s. An increase would mean a very high effort in mechanical, optical and electronical components. Applying parallel acting laser spots will raise the ablation rate of an existing application without reaching the limit of these components. In this paper, results of two different parallel principles of parallel acting laser spots are shown and discussed. This study includes the analysis of structured areas from spot size dimensions of 2 µm up to several 10 microns on two- and three-dimensional geometries.

Combining several lasers is a known principle to increase the processing performance (chapter 2.1). On the other hand, distributing power of one laser into several spots is necessary if the laser source provides enough power to serve several spots (chapter 2.2).

2.1. Combining Multi Laser sources

In micro structuring applications, where the lateral resolution is secondary and where the advantages of melt-free removal are desired, spot diameters of approx.. 50 µm can be used in some cases. In order to be able to produce the necessary fluence with these relatively large ablation diameters, the entire pulse energy of a single beam source must be used. A possibility to reduce the processing time in this cases is the scaling up of laser sources. As long as high power ps-laser radiation could not be transferred by fibers, a compact setup is a challenge. A beam delivery with one focusing lens allows a compact system set up. The requirement for high compactness limits the maximum number of combinable lasers. In Fig. 2.1 the merging of four lasers is schematically shown. Due to this arrangement, the spots can be placed at a distance of some 10 µm in the focal level on the substrate which allows a very compact machining head. Through a defined beam propagation angle to each other, a tele-centric setup could be realized. The pulse frequencies of the individual lasers could be synchronized to each other in order to influence the plasma created by the single pulses.

2.2. Splitting one laser beam in several spots

If smaller spot sizes are obtained and the pulse energy of one laser can serve multi laser spots (> 8), the division of a laser beam out of one single beam source will be most efficient. The approach used for the investigation shown in chapter 2.2 is based on a diffractive optical element which splits the beam in a defined number of spots. The beam size and divergence angle have to be adjusted before the laser source is split into several beam orders. The beam orders will spread in defined angles before a Fourier lens collimates all beams to generate the correct beam propagation into a multi-channel acousto-optical modulator. In our approach, the beam comb after the modulator will be spatially compressed by a pair of prisms to allow a beam delivery with smaller optics. The ablation area is formed by a setup of two lenses [3].

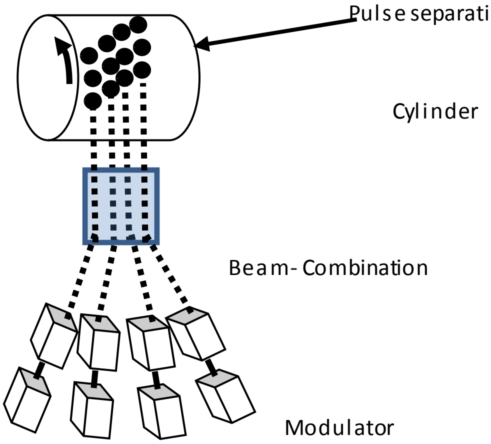

Fig. 2.1. Combination of several Laser sources

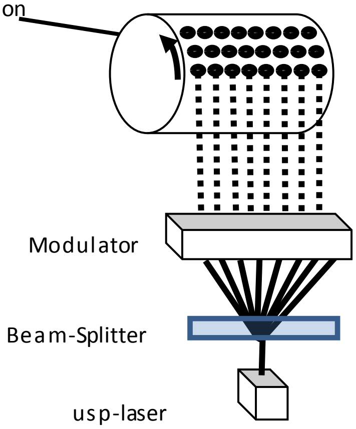

Fig. 2.2. Splitting of one laser source

The principle of applying multi laser spots by splitting one laser in several beam paths or combining several lasers to a multi spot system is defined by the desired resolution, and respectively by the size of the ablating spot.

3. Results with a 300W ps-Laser system

3.1. *Ablation rate and quality aspects with a 300W ps-laser*

For the experiments a newly developed ps-laser (pulse duration 12ps) with repetition rates of up to 8 MHz and an average power of 300 W was used. By means of a fast rotating work piece (cylinder) for pulse separation, the maximum usable laser power and thereby the maximum ablation rate was investigated at an adapted ablation diameter of 50 µm to achieve moderate fluencies. The experimental ablation rates were evaluated by engraving 150 µm² cells as shown in Fig. 2.4 These cells were ablated with different fluencies (2.5, 3,4, 4,6, 4,9 and 5,1 J/cm², adjusted by an external pulse picker) and machined with a scanning speed of 25 m/s with a machining resolution of 2540dpi. The results of this investigation are shown in Fig. 2.3. Three different materials, steel X1.4310, copper and brass were investigated.

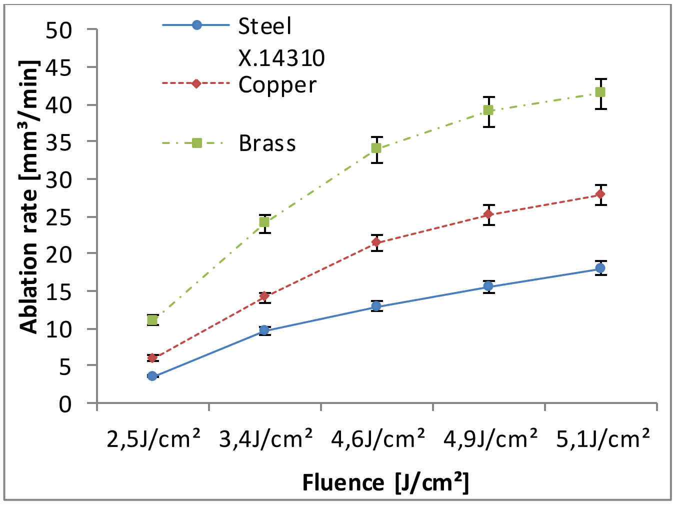

Fig. 2.3. Ablation rate, ablation diameter: 50µm, 300W ps-laser

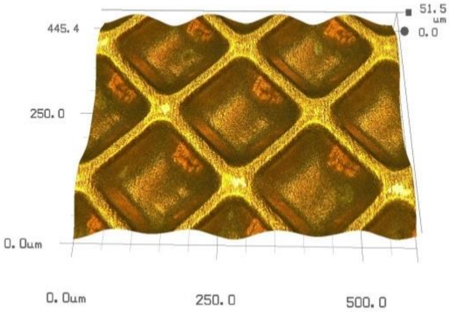

Fig. 2.4. Gravure cell, copper, size 150µm², depth: 50µm

The maximum ablation rate of 42mm³/min was achieved with the material brass. The ablation rate in copper was nearly 25 mm³/min and in steel 17 mm³/min. Besides the ablation rate, the contour accuracy between the digital image data and the produced geometries are of major interest when comparing the characteristics of the picosecond approach with the nanosecond processes. Contour and geometry accuracy is also influenced by larger spot diameters, even if the pixel accuracy of the machine in the range of 10 µm. Therefore an optimum has to be found between machine resolution and achievable ablation rate. Generally the ablation behavior with respect to ablation depth per pulse, surface roughness, residue and burr is similar to smaller spot sizes with a low power laser (P average < 100 W) and comparable fluencies. Independent to the resolution or structure size with 300 W average power, the contour accuracy could be achieved, as shown in Fig. 2.4

Depending on the micro structure size to be achieved, an adequate spot size has to be adjusted. In consideration of a machining fluence of approx. 5 mJ/cm² , the average power has to be decreased for higher resolutions. With a smaller spot size and a lower average power, the ablation rate is decreasing in the same manner (Fig. 2.5).

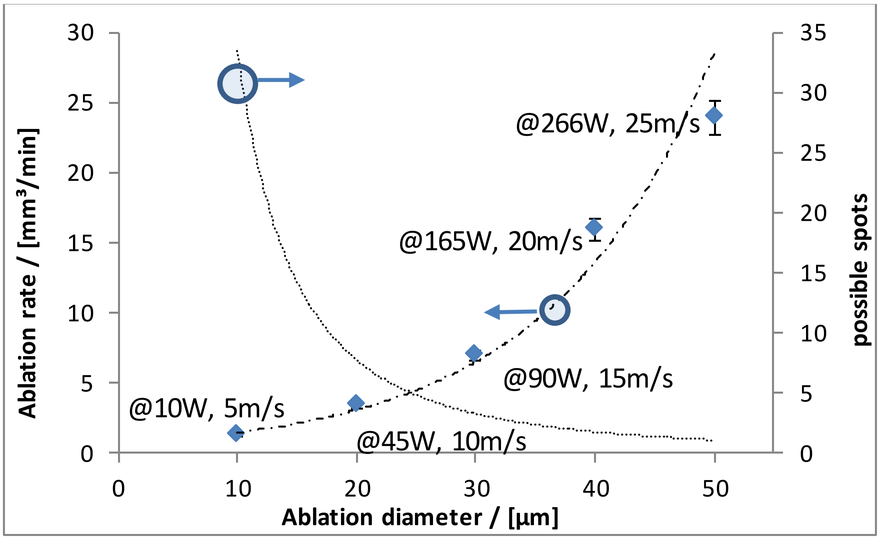

Fig. 2.5. laser power and corresponding ablation diameter vs. ablation rate

By means of the investigated 300 W ps-laser and a preset pulse energy of 150 µJ at 2 MHz, the maximum ablation rate of 27 mm³/min with a fluence of 5,1J/cm² in copper was achieved. For a further reduction of the processing time, a coupling of several laser sources is inevitable to realize a multi spot application as described in chapter 2.1. For example, with a combination of four laser sources with an overall average power of 1200 W an ablation rate of 108 mm³/min in copper is expected. If higher resolutions are obtained, the spot size and accordingly the pulse energy will decrease. This means that the laser power has to be reduced. Nevertheless, to transfer the laser power into a maximized ablation rate, the laser has to be split into multi spots.

3.2. Ablation rate and quality aspects in multi-spot application

For a multi beam setup the pitch precision, the spot uniformity and the efficiency of the integrated DOE in combination with an acousto-optical modulator are the important factors. For the 8 spot set up, used in this work Fig. 3.1 shows the beam intensity distribution. The average pitch in the target plane is *20µm and the spot diameter is 10µm* which is in the tolerance of the measurement setup. Each spot in the comb is separately modulated by an acousto optical modulator per channel and according to a grey level bitmap file. The non-uniformity between the maxima is below *8%,* and the efficiency is larger than *78%* in the target plane. A modulation frequency of 4 MHz allows scanning speeds of up to 50 m/s (pulse to pulse distance 10 µm). An optical setup with 8 modulated beams increases the modulation rate to 32 MHz, and thus the ablation rate up to values, which can be achieved with a single beam at a scan speed of 400 m/s . As surface speeds of cylinder engraving systems are limited to 50 m/s, the combination of a multi-spot array and a fast turning cylinder scanner is highly efficient.

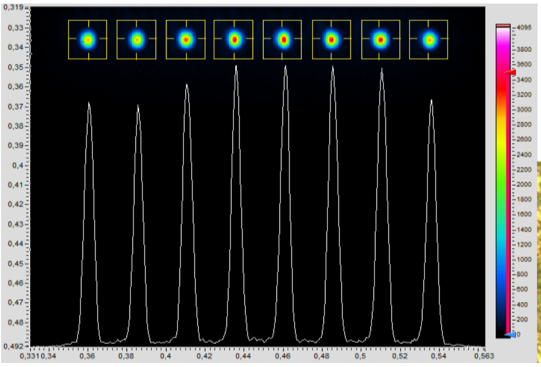

Fig. 3.1. Loboratory results in the target plane, pitch: 20µm

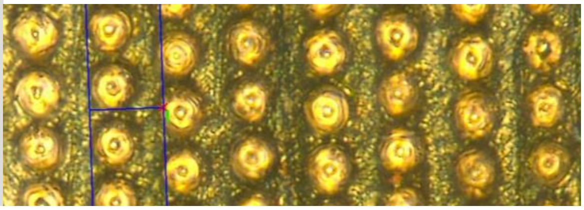

Fig. 3.2. Engraving result, spot diameter: 10µm of each beam

The spot-to-spot contrast and the efficiency are as expected as shown in Fig. 3.2. All beamlets show a focus diameter of 10µm and the ablation diameter per beamlet is 10µm.

4. Thermal interaction between multi spots on steel and copper

In a multi-spot application, of course, a minimum spot distance is desired to keep the process time as short as possible. However, in order to keep the thermal interaction between the laser pulses as low as possible, a minimal distance is required. The following section will investigate the thermal influence of the lateral spot distance on the ablation behavior of steel with respect to the line width for steel and copper. Ablation experiments are conducted at repetition rate of 400 kHz, a laser wavelength of 532 nm and an average power of 2.1 W and 1.6 respectively. With this power levels three spot distances of 130 µm, 220 µm and 300 µm are compared at three different pulse overlaps of 95.8 %, 98.3 % and 99.2 %. Fig. 4 shows the result of these ablation experiments for steel on the left side with respect to top views of the ablation crater, documented with a digital light microscope. On the right side of the figure the line width is plotted in a diagram in dependence of the pulse overlap for different spot distances. The line width almost consistently increases with decreasing spot distance. For example for an average power of 2.1 W and a pulse overlap of 95.8 % the line width amounts 28 µm at a spot distance of 220 µm and rises to 33 µm at a spot distance of 130 µm, which refers to a relative increase of 18 %.

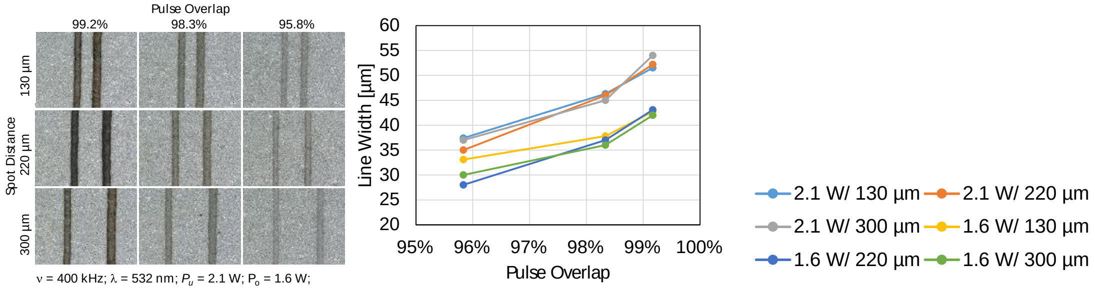

Fig. 4. Thermal Influence on the ablation behaviour of steel with respect to the line width in dependence of the lateral spot distance

A similar behaviour can be observed for an average power of 1.6 W and the same pulse overlap. For higher pulse overlaps the clear impact of the spot distance on the line width disappears. This can be explained with the increased thermal pulse interaction in movement direction. The same experiments are also conducted with copper as the target material. Here the correlation between spot distance and line width is much smaller due to the higher thermal conductivity of copper in comparison to steel. At an average power of 2.1W, a pulse overlap of 95.8 % and a spot distance of 300 µm a line width of 31 µm results. A reduction of the spot distance at constant average power and pulse overlap leads to line width of 34 µm, which means a relative increase of 9 %. Future investigations at lower pulse overlaps and smaller spot distances will enable further knowledge about reasonable spot distances and the resulting thermal influence on the ablation behaviour.

5. Embossing dies for surface functionalization

5.1. Structural sizes> 50µm (micro machining resolution: 1000dpi)

Structuring of embossing dies with structure sizes > 50 µm are used , for example, for technical decorative and optically refractive structures. Using ultrafast laser ablation three-dimensional structuring in "delicate" materials is conceivable. The manufacturing process is independent from the kind of material and a post-treatment is not necessary. Depending on the size of the structure and the material, the process times can be considerably shortened in comparison to established processes. The production of tools for embossing metal sheets is typical application. 3D structures with depths of 200 µm can be transferred, nearly 1: 1 in aluminium surfaces. As a tool for hot-forming applications, for example, microstructures can be multiplied very efficiently in a roll-to-roll process. In the decorative sector, these are leather structures, wood decorations or synthetic structures. Here, the transition is smooth to optically refractive structures. On the one hand, these structures can complement the actual motif by means of specifically adjusted reflective properties in combination with decorative elements. However, on the other hand, functional refractive elements can also be produced for technical applications. In this work a 300W ps-laser (pulse duration 12ps) source with pulse repetition rates of 2MHz and a spot size of 50µm was used in a single spot application for processing parabolic surfaces in copper (Fig. 5.1).

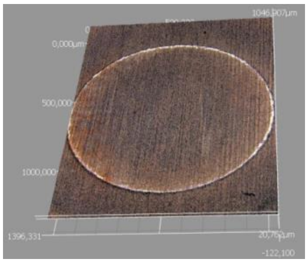

Fig. 5.1. Parabolic surface diameter: 1000mm, depth: 50µm

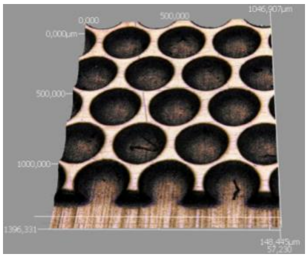

Fig. 5.2. Concave lens array: diameter: 170µm, depth: 50µm

Through the large spot diameter of 50µm the applied fluence could be kept moderate at approx.. 7,6J/cm² and allows a micro structuring process in copper at surface speeds of 15m/s with an acceptable quality (Fig. 5.2). If even smaller feature sizes are necessary the spot size has to be reduced to 20µm as described in the next chapter.

5.2. Structural sizes 20µm - 50µm (micro machining resolution: 2540dpi)

For the functionalization of surfaces for soft-touch-, refractive-optical or icephobic-structures [5] smaller features sizes are required. As shown in chapter 5.1, laser mass production tools will cover typical refractive-optical structures like micro lenses. These structures can then be transferred to a film which can be used for targeted light guidance in flat screens. Fresnel or lenticular lenses are also possible as decoders. Skin rubbing on plastic surfaces can be adjusted by defined microstructures, and thus the haptics. By means of these soft-touch structures, the friction values can also be defined in a direction-dependent manner.

Fabrication of surface structures by laser texturing using picosecond laser pulses has proven to be a useful technique for producing well-defined micro-scale surface textures. The frictional behaviour of these micro-scale textures is determined by the properties of the stratum corneum. Considering the stratum corneum has a high elastic modulus optimisation of textures produced by laser texturing is expected to bring forth surfaces having very low friction [4]. Four different kind of textures have been micro processed in a stainless steel plate, by scaling the pillar density. The pillar diameter of 30µm and the depth of 10µm was kept constant and the pitch was scaled in distances of 40, 60, 80 and 100µm (Fig. 5.3)

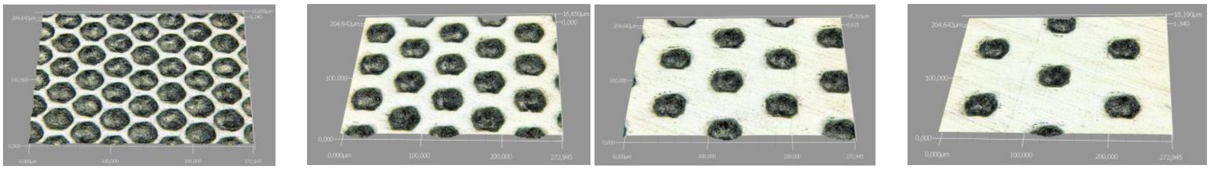

Fig. 5.3. “soft touch “embossing die, stainless steel, pillar diameter 30µm, depth 10µm, pitch from left to right: 100µm, 80µm, 60µm, 40µm, The die with the soft touch structures shown in Fig. 5.4 was reproduced in Silikone to demonstrate the forming process

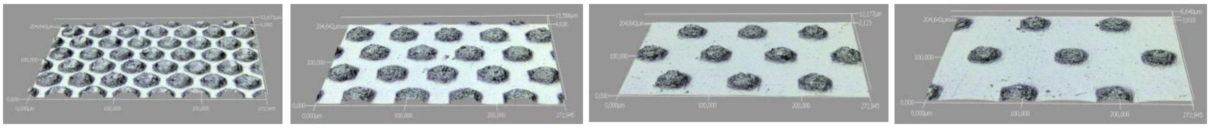

Fig.5.4. “soft touch “replica of Fig. 5.3

5.3. Structural sizes 5µm - 20µm (micro machining resolution: 5080dpi - 12700dpi)

Light-scattering, antibacterial, hydrophobic and biomedical structures have sizes typically in the range of 5µm to 20µm. Workpieces and surfaces with these structural sizes can be embossed on plastic films in a hot-embossing process. Films produced in this way can be used as light-diffusing films, for example, for increasing the efficiency of solar cells. Antibacterial or hydrophobic structures could be used, for example, in the food container for yoghurt covers and packaging. Biomedical structures are in turn used for targeted growth of cells in the field of tissue engineering e.g. Line structures with 4µm width and 10µm depth (Fig. 5.6).

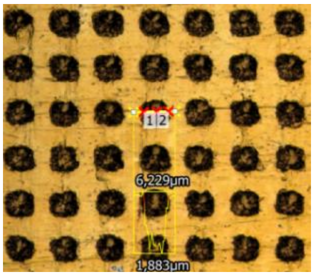

Fig. 5.5. Squared Screen with a size of 6µm² in coppers

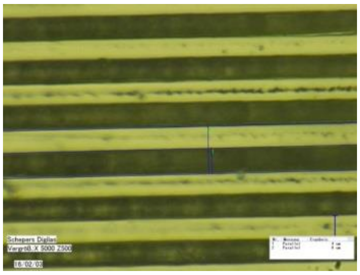

Fig. 5.6. Line width: 4µm, depth 10µm in stainless steel

5.4. *Structural sizes of 2µm – 5µm (25400dpi – 50800dpi)*

In addition to the structures listed in chapter 5.3, diffractive optical structures are in the range of 1µm to 5µm. Cylinder surfaces with these structure dimensions can be reproduced on foils in a rotary annealing process. For example, diffractive structures are implemented as safety elements in a mass production processes. In Fig. 5.7 a detail view of a data asset with a resolution von 4µm is shown with a depth resolution of 255 grey levels. The grey value of the pixel defines the laser power in the micro structuring process. The name DIGILAS was transformed to a digital diffractive data asset with 4µm pixel in 255 grey levels. This data asset was micro structured with a 515nm fs-laser (pulse duration 900fs) to a stainless steel plate (Fig. 5.8).

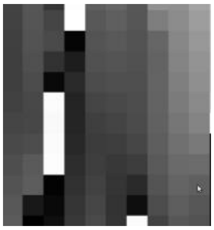

Fig. 5.7. Detail view data asset, 4µm pixel

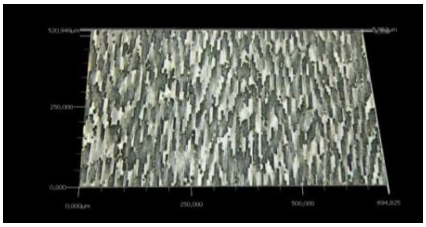

Fig. 5.8. Diffractive structure, pixel size: 4µm, depth 1,4µm, 30steps

According to the final application the micro structure was prepared in two different depths. For a reflective diffractive structure a depth of 350nm was realized and for a transmissive element a depth of 1,4µm was used as embossing die.

5.5. *Structural sizes of <1µm (micro machining resolution <1270dpi)*

In the previous chapters, micro structuring procedures with structure sizes larger than 2µm were achieved. If even smaller structure sizes are required, a pixel by pixel transfer direct in metal surfaces is challenging. Actually there are only lithographical applications useful for structures smaller than 2µm. To generate micro line structures directly in the sub-µm range two principles are state of the art. The laser interference structuring and the generation of laser induced periodical surface structures (LIPSS) [6]. In the case of laser interference structuring the angle of the two interfering beams define the line period. The line periods of LIPSS are given by the laser parameters and the orientation is defined by the polarization angle. In this work the generation of LIPSS was performed by a 532nm ps-laser (pulse duration: 10ps) with a spot diameter of 30µm and a fluence of 0,87J/cm² on a cylinder with a high reflective chromium surface (Fig. 5.9).

Fig. 5.9. Micro processed Logo with LIPSS structures

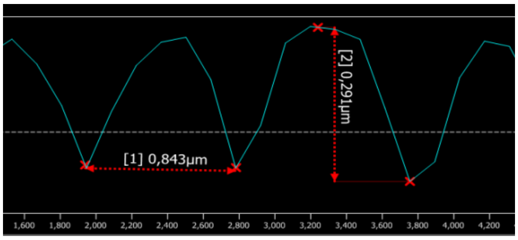

Fig. 5.10. LIPSS dimensions of the surface

The relative large spot size and machining resolution of 1270dpi allow a fast surface processing of large areas. This principle is useful as long as repetitive micro structure in dimensions of the wavelength are desired (Fig. 5.10) and when processing areas (given by the laser spot) of a few 10 µm are sufficient. Thus, the lateral extension of the structures always comprises several line periods. Large surfaces can only be created with preset line structure parameters. Also, changes in the line spacing, structuring depths and line widths are not possible dynamically from laser pulse to laser pulse. As a result, free-form surfaces such as, for example, diffractive structures described in chapter 5.4 with these methods are not possible. A digital transfer from pixel to pixel is indispensable for generating free-form surfaces.

6. Conclusions

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 work, two strategies for shortening process times will be presented.

At low resolutions < 1200 dpi and spot sizes of approximately 50 µm, the scaling of laser sources is unavoidable since the pulse energy of the laser must be fully utilized to achieve the processing fluence. The ablation rates of four combined 70 W lasers have been investigated. At higher resolutions and smaller spot diameters, the pulse energy can be divided into several spots and a division of a laser beam source on many spots is useful. A beam delivery with a 300 W ps-Laser and 8 parallel spots has been presented. In both parallel-acting principles, the distance or the heat influence from adjacent spot show a noticeable increase in the removal rate, but does not lead to a reduction in quality. By means of these two process technologies, tools for the roll to roll fabrication for the embossing of optical, haptic, antiseptic, cell-growth-promoting and optical-diffractive structures have been produced. With a minimum ablation diameter of 2 µm, variable diffractive structures could be directly transferred into a high reflective stainless steel substrate. Thus, embossing shims could be produced in a single-stage production process, without the use of wet-chemical process steps.

Acknowledgements

This work was partly funded by the BMBF within the project MULTISURF.

MultiSurf

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