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Tool mastering by ultrashort pulsed laser for roll-to-roll processes

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Abstract

Ultra-short pulsed lasers are becoming increasingly popular in industrial applications for tool mastering in high-precision mass-manufacturing. In order to be able to produce large surfaces in the shortest possible time, cylinder tools structured with USP lasers are often used in roll-to-roll (R2R) processes. Surface features / functions in R2R processes can be created by ink transfer in flexographic, gravure or screen printing processes or applied by embossing or nanoimprint processes. Printed electronics, optical films, light-conducting structures, antibacterial and biomedical properties and the adjustment of friction properties are further examples of functional topographies. UV lasers up to IR lasers are used for the surface functionalisation of cylinder tools. With Bessel beam configurations, ablation diameters of up to one µm are possible here. Multi-laser, -scan and -beam configurations are possible to accelerate the process.

Keywords: Ultrashort pulsed lasers, functional surfaces, mass production

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1. State of the Art

1.1 Roll-to-roll production

The surface functionalization of plastic films and paper webs through roll-to-roll (R2R) processing, as well as metal sheets with thicknesses of up to 2 mm through roll-to-plate (R2P) processing, is of great interest for a variety of products. However, directly structuring these substrates with structure depths of, for example, 200 µm remains a challenge due to insufficient throughput rates in direct laser processing. For instance, the throughput rate for plastic foils is approximately 1 m²/h (using cw-Yb fiber laser or CO_2 laser), or 1 m² in days for steel (using ultrashort pulsed lasers). This indicates, that the throughput rate falls significantly below the industrial demand. Nevertheless, microstructures can be transferred to various substrates through an R2R/R2P embossing process. Transferring the topography using a tool in a mass production process with high throughput rates up to 250 m²/min for paper, around 10 m²/min for plastics, 4 m²/min for aluminum sheets enables the required duplication speed. Furthermore, R2R UV nanoimprinting processes have recently been employed, even achieving (e.g. holographic structures) for large-area surfaces at throughput rates of 10 m²/min [1].

1.2 Tooling embossing rolls

One major advantage of roll-to-roll processing is the use of a cylinder-based embossing tool as the master, allowing for the production "endless" substrates with microstructures without a seam. To micro structure embossing roll surfaces, a manufacturing system can be employed, which involves a fast rotating cylinder and slow transversal moving optical box, based on a rotationally symmetrical embossing tool. This system enables the application of a highly uniform circumferential speed. By utilizing resolutions of 5080 dpi (with a pixel size of 5 µm) and an ultrashort pulsed laser with an average power of 44 W in a single beam, along with a surface speed of 10 m/s, an ablation rate of 4 mm³/min for steel can be achieved in a cylinder engraving system. By employing four laser sources, this ablation rate can be increased to 16 mm³/min. Consequently, a steel surface with a depth of 220 µm covering an area of 1 m² can be processed in approximately 10 days [2]. In the BMBF project MULTISURF, an additional process acceleration was pursued by increasing the number of laser spots. The objective of the project was to distribute the powerful ultrashort pulsed laser source among up to 100 individually modulated spots. This contribution shows the application of micro processing cylinder surfaces, the generation and modulation of numerous individually parallel ablating spots, as well as some representative applications.

2. Ultra-precise cylinder micromachining system

Thanks to the consistent rotation of a cylinder at a speed of up to 4000 RPM, surface velocities of up to 50 m/s can be achieved in a cylinder micro machining system like the Digilas (Fig. 1), enabling rapid structuring [3]. This method allows for the placement of ultrashort laser pulses with a repetition rate of 2 MHz and a spot diameter of 12 µm in the circumferential direction without any pulse-to-pulse interaction. The multi spot beam comb on the cylinder surface is guided axially along the fast rotating cylinder. The control system adjusts the intensity of each individual spot based on a digital database. The spot comb can be actively positioned with an accuracy of +/-200 nm within a 5 µm engraving width. When laser spot and pixel sizes smaller than 1 µm are required, lithographic processes become unsuitable, and the importance of ultrashort pulsed lasers processes increases. However, a challenge has been the ability to focus the ultrashort pulse laser to 1 µm and smaller diameters while maintaining a suitable depth of field for material processing. Bessel beams offer a significant advantage over Gaussian beams, as they can achieve very fine focusing and provide a large focal depth. This enables the engraving of structures smaller than 1 µm with high precision in an ultra-precise processing machine.

Fig. 1. Cylinder micro processing system, Digilas 7000 for cylinder lengths up to 5m and diameter up to 650mm

3. High-power ultrashort pulsed laser

To scale up the power and energy of a laser system, oscillator and amplifier systems (MOPA) such as INNOSLAB systems are generally used [4]. The high-power slab laser includes an Nd:YVO_4 mode locked oscillator that generates 50 MHz, 10 ps pulse trains, known as pulse bursts, with an adjustable number of pulses within a burst and an average power of 1.7 W, a pulse picker, and an amplifier was adopted for the first stage, and a single-pass amplifier for the second stage. The output power of the first stage is 300 W, and the second stage amplifier is designed for an average power of 500 W with a Gaussian beam profile and $M^2<1.3$.

4. Multi spot beam delivery

One approach to reduce the processing time is to scale up the number of laser sources that can simultaneously and parallelly process a workpiece. However, the available space limits the maximum number of lasers that can be combined. When smaller spot sizes (5 µm – 15 µm) are desired for high resolution applications, the available pulse energy of a single laser source can serve multiple laser spots to maintain the fluence close to the optimum level. Splitting a single high-power laser beam into a defined number offer the possibility of a compact processing system.

4.1 Diffractive Beam splitter

Research on beam-splitting components has shown that diffractive optical elements (DOEs) are sometimes less efficient than refractive, polarization, of thin-film beam splitters [5]. One aspect of DOE´s is that they typically consists of discrete binary or multistage components. An alternative method is the direct transfer of the continuous phase function. In this work a continuous diffractive structure on fused silica was used for beam splitting [5]. However, it is difficult to generate an even number of uniformly distributed points, and the results are often overlaid by a strong zero order. For these reasons a seventeen-channel. Odd-numbered beam splitter design was combined with two eight-channel acousto-optical modulators (AOM´s). In the application, this optical setup offers an increase in the removal rate similar to serial processing in an application with a polygon mirror at a scanning speed of 800 m/s.

4.2 High power / Multispot system

An investigation was carried out using a 16-spot setup combined with a 500 W ultrashort pulsed laser [6]. The overall concept is presented and described in detail in [6]. A laser beam with 500 W power at a wavelength of 1064 nm and 10 ps pulse duration (adjusted for size and divergence angle) is divided into 17 beam orders with defined propagation angles using a diffractive optical element (DOE). A set of two Fourier lenses is used to focus and parallelize the beams, ensuring proper coupling into two 8-channel acousto-optical modulators (Fig. 2). The multi-spot intensity distribution in the ablation area is achieved by a setup consisting of three lenses. Key factors for the multi-beam arrangement include the precision of the pitch, the uniformity of the spots and the efficiency of the beam splitting by DOE in conjunction with the AOM´s. The pitch on the work piece is 20 µm+-0.5 µm and the spot diameter (1/e²) measures 8 µm. The total power non-uniformity between the maxima is less than 16 % and the overall efficiency on the work piece is approximately78 %.

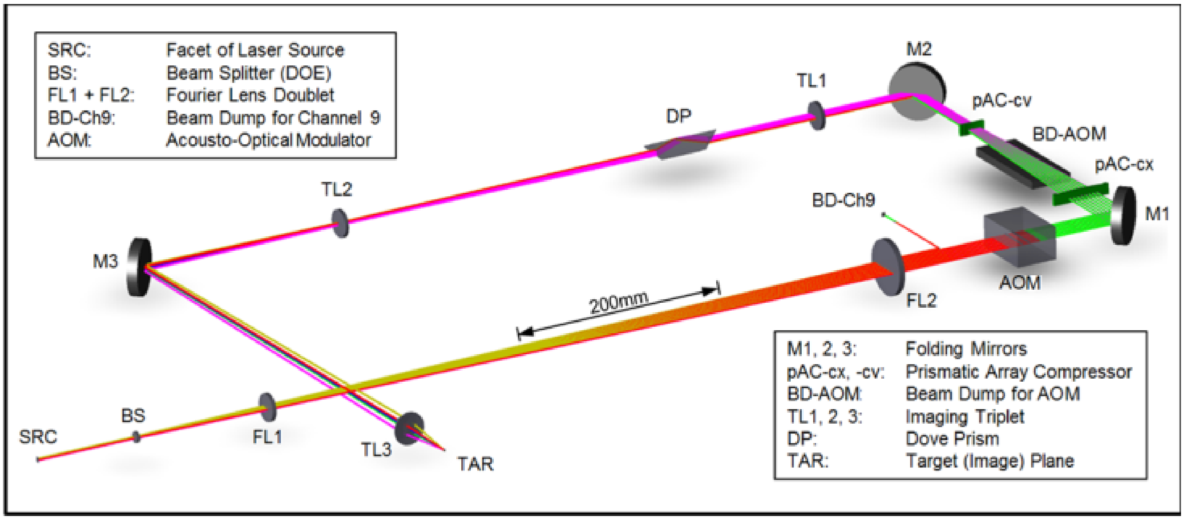

Fig. 2. Diffractive beam splitting of a 300W laser into 8 independently modulated beams, each about 29 ± 1 W at focus.

5. In-process topography measurement system

In the BMBF project LARA, Schepers has integrated a new type of laser measurement process into the cylinder micro structuring system, that allows precise in-process quality control of the cylinder topography. The engraving can thus be controlled during the machining process by copying back the measurement data obtained without manual intervention or measurement with separate devices. The measurement takes place coaxially in the machining head. The basis of the measuring system is a specialized laser with resonator-internal frequency shift [7]. An other advantage of this method over established approaches is the resulting insensitivity to external interference. The measurand (distance) is obtained by measuring a frequency and not an intensity. Thus, a measurement resolution <1 µm can be achieved with a measurement time of 1 ms. The system is insensitive to external disturbance such as extraneous light and is largely independent of the surface roughness and the angle between the measuring surface and the measuring beam.

6. Applications

Different functional surface geometries were implemented on an embossing roll to serve as a master for replicating the structures in roll-to-roll processes. The aim is to create structured embossing dies with geometries in the range of 10 µm, enabling the functionalization of surfaces for refractive-optical laser mass production tools [8] (Fig. 3). These structures include features such as friction reduction, improved soft touch and light guiding elements. By transferring these topographies onto a polymer film, targeted light guidance in flat screens can be achieved. Additionally, the technique of laser texturing using ultrashort pulsed lasers has been proven effective in creating well defined micro -scale surface textures, including diffractive structures.

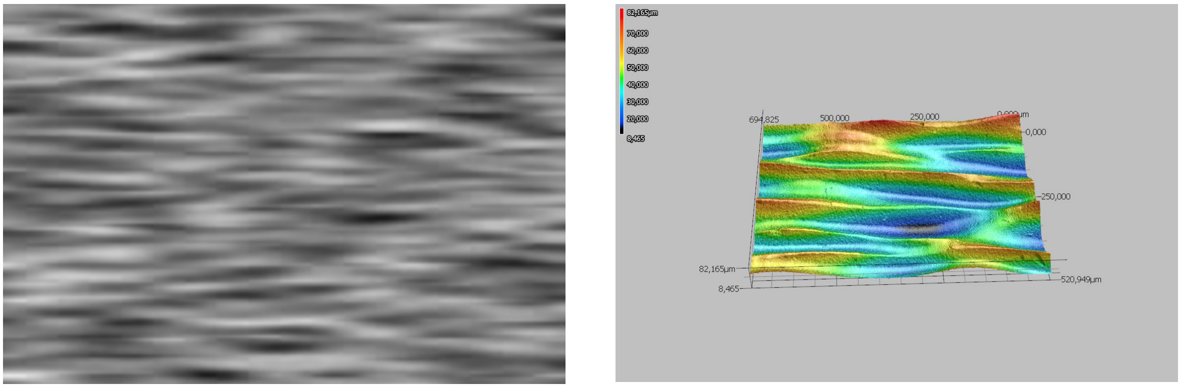

Fig. 3. Left: 3D data asset of a refractive structure; Right: micro structured cylinder surface

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