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Automated polarization control for the precise alignment of laser-induced self-organized nanostructures

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ABSTRACT

Laser-induced periodic surface structures (LIPSS) found in particular applications in the fields of surface functionalization have been investigated since many years. The direction of these ripple structures with a periodicity in the nanoscale can be manipulated by changing the laser polarization. For industrial use, it is useful to manipulate the direction of these structures automatically and to obtain smooth changes of their orientation without any visible inhomogeneity. However, currently no system solution exists that is able to control the polarization direction completely automated in one software solution so far. In this paper, a system solution is presented that includes a liquid crystal polarizer to control the polarization direction. It is synchronized with a scanner, a dynamic beam expander and a five axis-system. It provides fast switching times and small step sizes.

First results of fabricated structures are also presented. In a systematic study, the conjunction of LIPSS with different orientation in two parallel line scans has been investigated.

1. Introduction

Laser-induced self-organized nanostructures (LIPSS) have been investigated intensively both in theory and experimentally since many years. Their utilization can be found in various fields of surface functionalization as for instance anti-reflection [1–3], anti-counterfeiting [4,5], tribology [6,7], wetting [8–10] and the control of cellular responses [11].

Periodic ripple structures can be fabricated using linearly polarized laser radiation. In a self-organized way, two different ripple types develop at different parameter regimes: Depending on the laser fluence and the effective number of pulses per surface area, either low spatial frequency LIPSS with a periodicity close to the laser wavelength or high spatial frequency LIPSS with a periodicity much smaller than the laser wavelength develop.

Large areas of homogenously aligned nanostructures were already fabricated by various groups [12–14] arranging parallel line scans at a suitable distance. The connection of the LIPSS of two parallel line scans has been investigated in detail by several groups [14,15]: Having the same polarization in two adjacent line scans, the LIPSS connect coherently, if the distance between the line scans is suitable. The coherent linking of the LIPSS is attributed to the influence of the initially produced LIPSS on the plasma density wave of the LIPSS, which are produced afterwards [15].

The orientation of the LIPSS depends on the polarization of the laser radiation. Whereas low spatial frequency LIPSS align perpendicular to the polarization direction on metals, high spatial frequency LIPSS align parallel to the polarization direction. For other materials like dielectrics, the orientations of the different types can be reversed [16]. However, in one material their alignment always occurs in the same orientation with respect to the polarization direction.

Several research groups have exploited this property to manipulate the structure orientation. For instance, Dusser et al. [4] fabricated large areas of low spatial frequency LIPSS with different orientations that change the optical reflection properties in a defined way. In this approach, they were able to paint images on two-dimensional surfaces. Gräf et al. [17] controlled the polarization direction of linear polarized laser radiation dynamically with a motorized polarizer and studied the resulting nanostructures in detail. With large rotation speeds, they could produce similar structures as for circularly polarized laser radiation.

For industrial applications, it is moreover necessary to create arbitrary patterns of nanostructures with different orientations on free-form surfaces. The challenge is to merge the nanostructures smoothly and without any visible steps to create a homogeneous surface. For an effi-

Abbreviations: LIPPS, Laser-induced self-organized nanostructures; SEM, Scanning electron microscope.

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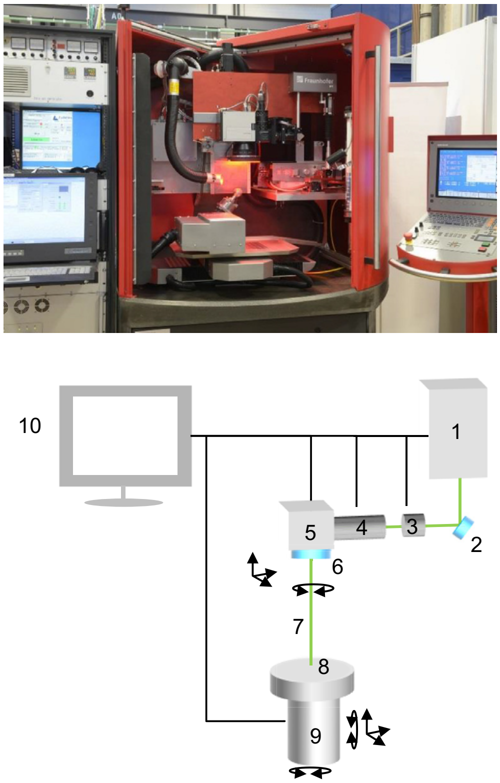

Fig. 1. Photograph (top) and schematic diagram of the system solution. 1 laser, 2 mirror system, 3 half-wave plate and liquid crystal polarization rotator, 4 dynamic beam expander, 5 laser scanner, 6 telecentric F-Theta lens, 7 laser beam, 8 sample, 9 5-axis handling system, 10 computer with control software solution.

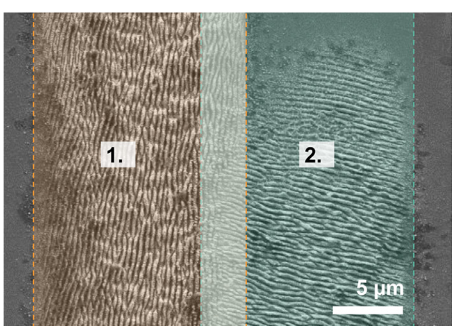

Fig. 2. Conjunction behavior: The first line scan was processed with an initial polarization direction. In a second step, a second line scan was performed with a different polarization direction and a certain line overlap.

cient process, a completely automated setup that can change the polarization direction fast and in small increments is indispensable.

To control the polarization direction of the laser radiation, various approaches have been realized. One way to manipulate the direction of the polarization is to use a spatial light modulator [18]. In most scientific publications on the fabrication of LIPSS the polarization direction was controlled manually by static optical elements like wave plates or polarizers (see for example [19,20]). Some approaches also combined wave plates with a at least partially automated rotation stage [17]. In the area of laser drilling, an approach exists for the partially automated control of the polarization, using a liquid crystal polarization rotator [21]. To improve the production quality of laser-drilled holes, the polarization direction was switched between two states synchronized with a laser. Despite this approach already shows a distinct degree of automation, it only takes into account two polarization states and does not consider the 3-dimensional processing.

Fig. 3. Free-form part that demonstrates the functionality of the developed system solution.

Similar to this scientific approach, one commercial system is already available on the market for controlling the polarization electronically during the laser structuring process. The polarization control switches between linear and elliptical polarization [22].

None of the presented approaches is sufficient to manufacture patterns that contain a large amount of different orientations efficiently and to transfer them on three-dimensional free-form surfaces.

So far, no system solution exists that is able to control the polarization direction completely automated in one software solution. In the following, a system solution with a liquid crystal polarizer that is synchronized by using a CAM software with a scanner, a dynamic beam expander and a five axis-system is presented that provides fast switching times and small step sizes. In addition, first results of fabricated structures are presented. In a systematic study, the conjunction of LIPSS with different orientation in two parallel line scans has been investigated.

2. Materials and methods

2.1. Experimental setup

The developed system solution enables an automated alignment and fabrication of LIPSS on free-form surfaces. The setup is shown in Fig. 1.

The workpiece was clamped in the 5-axis handling system (Kern Microtechnik GmbH, Eschenlohe, Germany). A linearly polarized laser beam was emitted by a picosecond laser (Super Rapid, Lumera Laser GmbH, Kaiserslautern, Germany). The laser had a pulse duration of $\tau = 9$ ps and a wavelength of $\lambda = 532$ nm. As the polarization direction of the laser beam needed to be well adjusted with respect to the polarization rotator, a static half-wave plate (Castech Inc., Fuzhou, Fujian, China) aligned it prior to the liquid crystal device. Subsequently, the laser beam entered the liquid crystal polarization rotator (Meadowlark Optics, Frederick, Colorado, United States) that controlled the polarization direction according to a voltage signal. Afterwards, a mirror system directed the laser beam with the rotated polarization direction