Lasers in Manufacturing Conference 2017

Direct laser interference patterning: from fundamentals to industrial applications

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Abstract

Direct Laser Interference Patterning (DLIP) is a method that implements physical phenomena of interference to produce periodic structures on surfaces by transferring the shape of the pattern directly to the material by selective laser ablation. Recent developments of the DLIP method will be presented in this talk. The structuring of thin metallic films and bulk materials using nano- and picosecond laser systems will be introduced by going through different optical setups and industrial systems which have been recently developed. Several technological applications including tribology, biological interfaces, thin film organic solar cells and electrodes as well as decorative elements and safety features will be discussed and summarized in this presentation.

Keywords: Selective Laser Ablation; Direct Laser Interference Patterning; Surface Functionalization; High-Speed Structuring

1. Introduction

Surfaces with deterministic topographies can show superior surface properties in comparison to surfaces with a "random" roughness as reported by Favret et al., 2011. Such topographies can be utilized to functionalize surfaces and adjust their properties to the specific requirements for a certain application. In the past, several studies have shown at laboratory scale that micro- and nano structured surface can impact tribology, light management, wettability, bacteria adhesion or biocompatibility of materials (such as implants). However, in order to unlock the great potential of these functionalities on technological surfaces, industrial-scalable and economic processes for the fabrication of tailored surface structures are required.

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A promising technology for the fabrication of period surface patterns is Direct Laser Interference Patterning (DLIP). In DLIP, laser systems must show sufficient high pulse energies in order to process materials directly without the need of special atmospheric conditions such as clean room or inert atmospheres. Typically, the periodic patterns generated during DLIP processing exhibit a well-defined long-range order on the micrometer scale given by the interference periodicity leading to precise topographies in metals (Mücklich, 2009), ceramic materials (Soldera, 2016) or polymers (Yu, 2005). Since the interference pattern is generated within the intersection area of overlapping beams, the DLIP technology can produce structures with feature sizes bellow the diffraction limit (typically 5 to 15 µm) of conventional laser writing systems.

2. Results and Discussion

2.1. Direct Laser Interference Patterning

In general, interference patterns can be obtained by splitting a coherent laser beam (e.g. by using beam splitters) into two or more sub-beams which are later overlapped at the workpiece using several mirrors. Figure 1 exemplifies the resulting two and three-beam configuration which results on the sample surface.

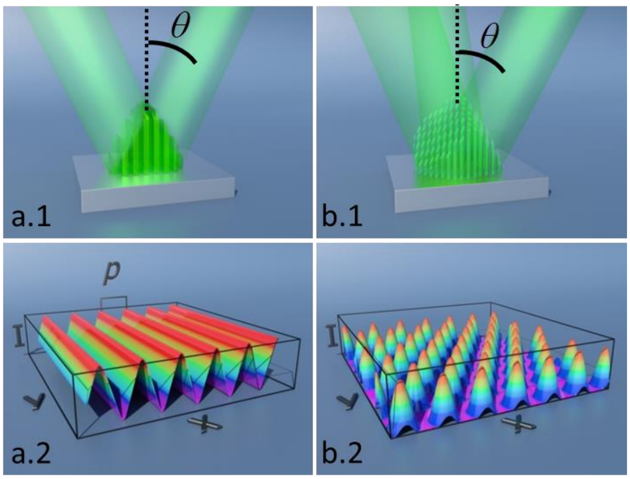

Fig. 1. Calculated intensity distribution for (a) two-beam interference and (b) three-beam interference assuming symmetrical configuration.

The interference of two and three laser beams (see Figure 1a.1 and Figure 1b.1, respectively) leads to an effective modulation of the laser intensity profile (line-like: Figure 1a.2; dot-like: Figure 1b.2). The patterns can be directly transferred to any material which absorbs the energy of the laser at the selected wavelength. The structuring process is based on photothermal, photophysical, or photochemical mechanisms, depending on the type of material. In general, polymers and ceramics are processed with UV laser radiation, whereas green or IR lasers are applied to treat metals and coatings.

In the case of metals, the DLIP process is dominated by the photothermal interaction that involves local melting and/or selective ablation at the interference maxima positions. For nanosecond laser pulses, the primary material removal mechanism is ablation but also substantial melting occurs. The minimum achievable spatial period is therefore limited by the thermal diffusion length (e.g. 1 µm for stainless steel and titanium for 10 ns pulses). By using ultra-short pulsed lasers (ps and fs laser systems), minor thermal damage is observed and spatial periods below 1 µm are feasible. Figure 2 exemplifies line-like periodic surface patterns of 5.0 µm (ns-DLIP) and 0.5 µm (ps-DLIP) on stainless steel.

Although optical configurations such as beam splitters and optical tables are acceptable for research purposes, an industrial application of the DLIP technology will only be possible if compact (and integrable) optical-head solutions and systems are available.

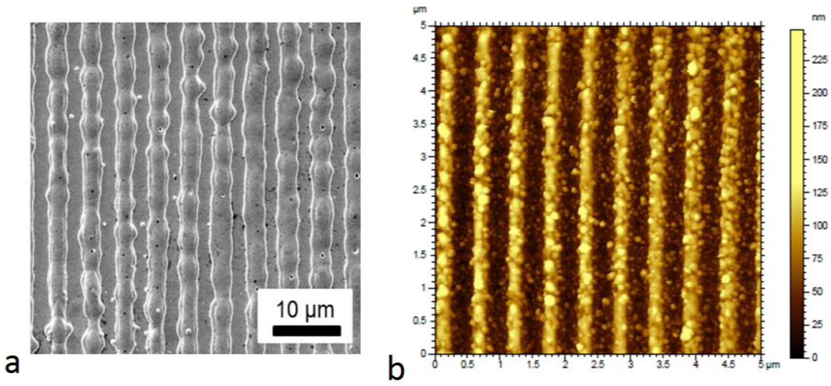

Fig. 2. DLIP of stainless steel with a spatial period of (a) 5.0 µm with ns-pulses and (b) 0.5 µm with ps-pulses.

2.2 Industrial concepts of Direct Laser Interference Patterning

In recent years, various interference patterning optical modules and systems have been developed at Fraunhofer IWS as part of the DLIP-µFab concept (see Figure 3). The DLIP-µFab systems (see Figure 3c) offer the possibility not only to process planar surfaces but also complex three dimensional parts. Two general designs, have been developed. The first one is optimized for the high-throughput structuring of surfaces (Figure 3a) while the second concept allows a fully-automatic fabrication of surface patterns with flexible structure geometry and size. Using the high-throughput (or high-speed) DLIP optical head, Lang et al, 2016 achieved processing speeds of up to nearly 0.4 m²/min on metals and 1 m²/min on polymers. The second concept (DLIP high-flexibility) enables an individualized control of structure properties depending on the surface area and in this way, decorative (holographic) elements, as shown in Figure 4a can be fabricated.

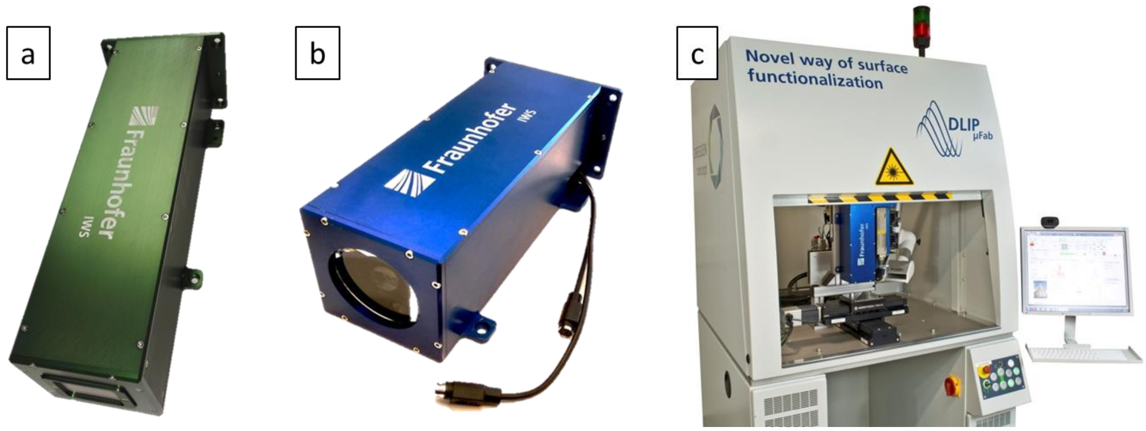

Fig. 3. Industrial DLIP-µFab concepts for the fabrication of deterministic surface structures. (a) DLIP high-speed module, (b) DLIP module for the fabrication of surface structures with flexible structure geometry and size and (c) DLIP-µFab system.

In addition to two-dimensional parts, DLIP can be also utilized for the treatment of three-dimensional surfaces as demonstrated by Bieda et al., 2013. For example, if rotation symmetrical parts have to be treated, the DLIP-µFAB system can be equipped with a rotational axis. As example, the processing of a PET bottle is shown (Figure 4b). Using this system, the bottle was fixed to the rotational axis and was translated with a linear stage and rotated to produce three decorative elements (LMO, Fraunhofer IWS and DLIP-µFAB logos) directly on its surface. Due to the high accuracy of the used translational stages and rotation axis, the accuracy between the treated area (holographic pixel) per laser pulse was better than 1 µm (~ 0.5 µm).

For the case that larger parts must be treated, a special DLIP system (developed at the TU-Dresden) can be used as shown in Figure 4c. This system permits to treat cylindrical parts up to 600 mm in length and 300 mm in diameter as shown by Lang et al., 2017. The system is equipped with both ns and ps- laser systems. Similarly like in the DLIP-µFAB system, different optical heads can be utilized. Preliminarily results of a treated Ni-sleeve (300 mm length and 300 mm in diameter) are shown in Figure 4d.

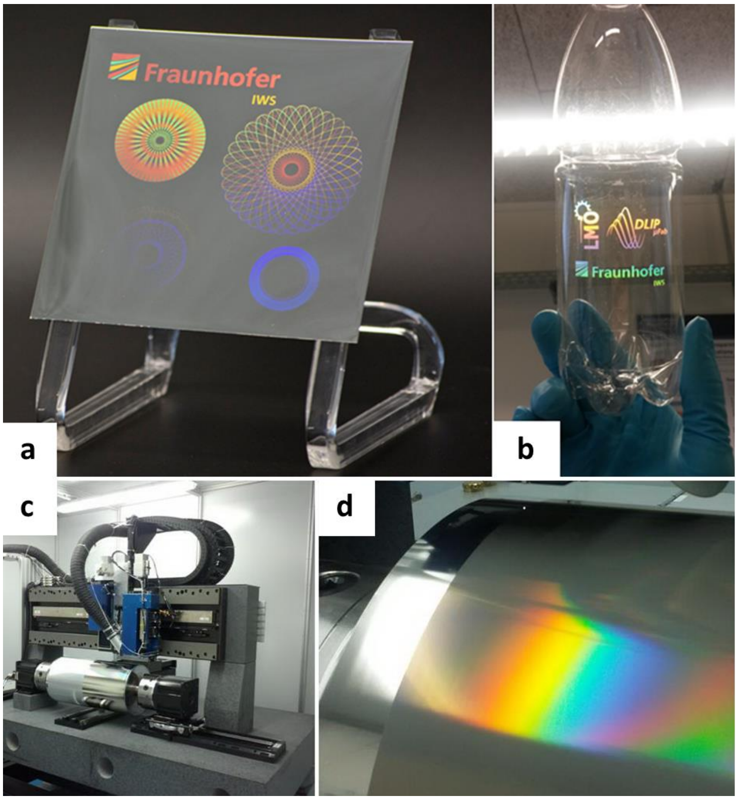

Fig. 4. Decorative motives on (a) nickel surface (three different spatial periods) and (b) PET bottle fabricated using the flexible DLIP-µFab system. (c) Large area DLIP System for cylindrical parts (e.g. sleeves) and (d) ps-DLIP treated Ni-sleeve.

3. Conclusions

These results here reported demonstrate the capabilities of the DLIP method for the production of periodic surface patterns on 2D and 3D parts. Resolutions down to the submicrometer range could be reached. In addition, our results indicate the high maturity level of the technology and highlight its potential for integration into industrial applications.

Acknowledgements

The work of AFL is supported by the German Research Foundation (DFG) under Excellence Initiative program by the German federal and state governments to promote top-level research at German universities. This research was also partially funded by the German Federal Ministry of Economics and Energy (BMWi) within the Promotion of Joint Industrial Research Program (IGF) due to a decision of the German Bundestag. It was part of the research project 18359BR by the Association for Research in Precision Mechanics, Optics and Medical Technology (F.O.M.) under the auspices of the German Federation of Industrial Research Associations (AiF).

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