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World record in high speed laser surface microstructuring of polymer and steel using Direct Laser Interference Patterning

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ABSTRACT

Periodic surfaces structures with micrometer or submicrometer resolution produced on the surface of components can be used to improve their mechanical, biological or optical properties. In particular, these surfaces can control the tribological performance of parts, for instance in the automotive industry. In the recent years, substantial efforts have been made to develop new technologies capable to produce functionalized surfaces. One of these technologies is Direct Laser Interference Patterning (DLIP), which permits to combine high fabrication speed with high resolution even in the sub-micrometer range. In DLIP, a laser beam is split into two or more coherent beams which are guided to interfere on the work piece surface. This causes modulated laser intensities over the component's surface, enabling the direct fabrication of a periodic pattern based on selective laser ablation or melting. Depending on the angle between the laser beams and the wavelength of the laser, the pattern's spatial period can be perfectly controlled. In this study, we introduce new modular DLIP processing heads, developed at the Fraunhofer IWS and the Technische Universität Dresden for high speed surface laser patterning of polymers and metals. For the first time it is shown that effective patterning speeds of up to 0.90 m^2/min and 0.36 m^2/min are possible on polymer and metals, respectively. Line- and dot-like surface architectures with spatial periods between 7 µm and 22 µm are shown.

Keywords: Surface functionalization, Direct Laser Interference Patterning, high speed fabrication

1. INTRODUCTION

Today researchers worldwide are investigating various technologies to modify materials and surfaces on a micro- and nanometer scale. By using either stochastic (non-periodic) or determistic (periodic) structures beneficial new or improved material or surface properties can be achieved. These functionalizations are highly relevant for a huge spectrum of topics like implants in medicine techniques, piston rings in the automotive industry, optoelectronic devices like light emitting diodes or thin film photovoltaics [1-4]. Recently, it has been shown that deterministic surface patterns can reduce the coefficient of friction between 20 – 50 % on various materials like metals, hard coatings or polymers, for instance [2, 5-7]. These investigations were also confirmed by simulations depicting that periodic topographic features can be advantageous for designing improved hydrodynamic surface properties [5]. Further on, with micro patterns the efficiency of organic light emitting diodes (OLEDs) and organic solar cells could be increased by 35 % and 21 % respectively [3,8].

On the other hand, conventional micromachining technologies like optical lithographic based methods, conventional direct laser writing or micro-milling can attain only processing speeds between 0.01 and 200 cm^2/min [9,10]. Furthermore, the fabrication speed is typically decreasing with the structure size. Additionally lithographic technologies are generally not applicable to 3D part geometries. This means in general, that conventional methods are either too slow, too expensive, or cannot either be used to treat 3D parts, nor achieve the structure sizes required to obtain a

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functionalized surface. In consequence, the application of these technologies for the direct functionalization of surfaces is still challenging.

In this context, the aim of this study is to develop a laser based technology capable of producing surface patterns with submicrometer and micrometer resolutions on two dimensional and three dimensional parts with high production speeds (up to 0.9 m^2/min) accompanied with low production costs (~ 1.2 USD/m^2). A promising way to make the micro patterning process significantly faster, while reducing processing and equipment costs and preserving high resolutions is the direct laser interference patterning technology. We are introducing new modular DLIP processing heads, for high-speed laser structuring of polymers and metals. The fabrication of line- and dot-like surface architectures on these materials is evaluated.

2. DLIP – ULTRAFAST SURFACE PATTERING METHOD

2.1 Interference principle

In DLIP, a coherent laser beam is split into two, three or more partial beams, which are guided to interfere on a sample. Line-like interference patterns can be generated by using two laser beams. The spatial intensity distribution *I* depends on the number of laser beams as well as their geometrical arrangement. Assuming two monochromatic plane waves the intensity distribution is given by:

$$I = 4c\varepsilon_0 E_0^2 \cdot \cos^2\left(ky \cdot \sin(\alpha/2)\right), \quad (1)$$

where E_0 is the amplitude of the individual laser beams, ε_0 is the dielectric constant in vacuum, α is the angle between the laser beams and *c* is the speed of light. The expression $cos2(ky{\cdot}sin(\alpha/2))$ is 1 if $ky{\cdot}sin(\alpha/2) = 0,\pm\pi,\pm2\pi,\ldots$ and 0 if $ky{\cdot}sin(\alpha/2) = \pm\pi/2,\pm3\pi/2,\ldots$. This shows that the interference pattern for a two-beam configuration follows a trigonometric sinus-like shape. Additionally, it can be observed that the laser intensity at the interference maxima positions is four times the laser intensity of each individual beam or two times the intensity of both interfering beams together. The periodicity Λ is controlled by the angle α between the laser beams and the wavelength λ:

$$\Lambda = \frac{\lambda}{2 \cdot \sin(\alpha/2)}. \quad (2)$$

Thus, increasing or decreasing the angle between the partial beams permits to reduce or increase the spatial period, respectively.

2.2 Structuring procedure

For the laser experiments a q-switched high power Nd:YAG Laser emitting 1064 nm wavelength in pulses of 8 ns duration (Edgewave) was used. The average power of the laser is 180 W at 10 kHz and 155 W at 5 kHz repetition rate. The typical intensity distribution of the output beam is top-hat in one direction and Gaussian in the other one. The initial beam geometry is rectangular with an edge length of ~5.0 mm (see Figure 1).

With a telescope, the beam diameter can be controlled (see element (2) in Figure 1). Using a DLIP processing head (Fraunhofer IWS), the shaped laser beam is split into two beams which are overlapped and focussed with a cylindrical lens on the work piece. The grating period (the angle between the laser beams, see Eq. (2)) can automatically adjusted with the DLIP processing head.

In our experiments, the patterning process of both materials (steel and polycarbonate) was performed with a single laser pulse, under atmospheric pressure and room temperature. The laser power was measured with FieldMaxII-TO Laser Power Meter (Coherent). The processed samples were placed on XY cross table with mechanical-bearing supported direct-drive linear stages with a length of 500 x 500 mm and a maximum speed of 1 m/s.

Both materials, a polycarbonate substrate doped with an IR absorber and steel foils, were used as received.

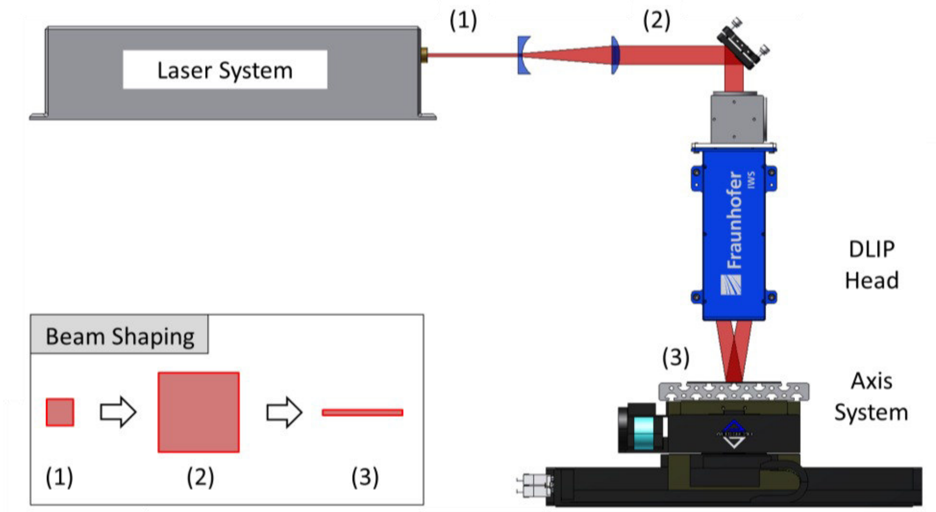

Fig. 1 Schematic drawing of the two beam laser interference setup for high speed laser pattering [11].

3. RESULTS AND DISCUSSION

3.1 High speed direct laser interference patterning of polycarbonate

Polycarbonate (PC) foils doped with a black IR absorber were used for high speed DLIP processing. Three different speeds for the translational stage were used: v = 0.25, 0.50 and 1.00 m/s. The pulse frequency was set to f_p = 5 kHz, resulting in a pulse energy of 31 mJ at 155 W power.

As mentioned in the previous section, these patterns were generated with two line-shaped laser beams arranged in the same plane of incident as shown in Figure 2d. The angle between the laser beams was set to α = 2.73° obtaining a spatial period of Λ = 22.2 µm in accordance to Eq. 2. Due to the strategy utilized to shape the beams, a long stretched spot (~15 mm by 10-20 µm) containing the interference pattern is obtained.

The sample movement was set to be perpendicular to the line-shaped beams (see Figure 2d). Thus, the pattern periodicity is on the one hand determined by the DLIP spatial period Λ and on the other direction by the distance between to laser pulses (Λ_M) which is defined by the axis speed (v) and the pulse frequency (f_p):

$$\Lambda_M = v \cdot f_p^{-1} . \tag{3}$$

In consequence, differently from DLIP patterns shown previously in the literature, the pattern period/density is not only controlled by angle between the laser beams and the laser wavelength but also by the conditions used during the processing of the material. Furthermore, this characteristic can be used to produce two dimensional patterns using only two interfering laser beams.

Confocal microscopic images of the treated polycarbonate material are shown in Figure 2a-c. According to the used axis speed (1.00 m/s, 0.50 m/s and 0.25 m/s), spatial spacing (Λ_M) between the laser spots of 200 µm, 100 µm and 50 µm were obtained. In the case of the used polycarbonate foils doped with a black IR absorber, it was found that local swelling of the irradiated material took place at the interference maxima positions . For the used laser conditions (laser fluence: 1.2 J/cm²), the structure height was approximately 4 µm.

In Figure2, the pattern height is decreasing from the right to the left side. We suggest that this is due to a tilt of the sample as well as non-proper focusing of the beams over the surface leading to a decrease of the laser energy density. Corresponding to the length l = 15 mm of the DLIP irradiated area (see Figure 2d) and the axis speed v, fabrication speeds of 0.9 m^2/min, 0.45 m^2/min and 0.25 m^2/min were achieved.

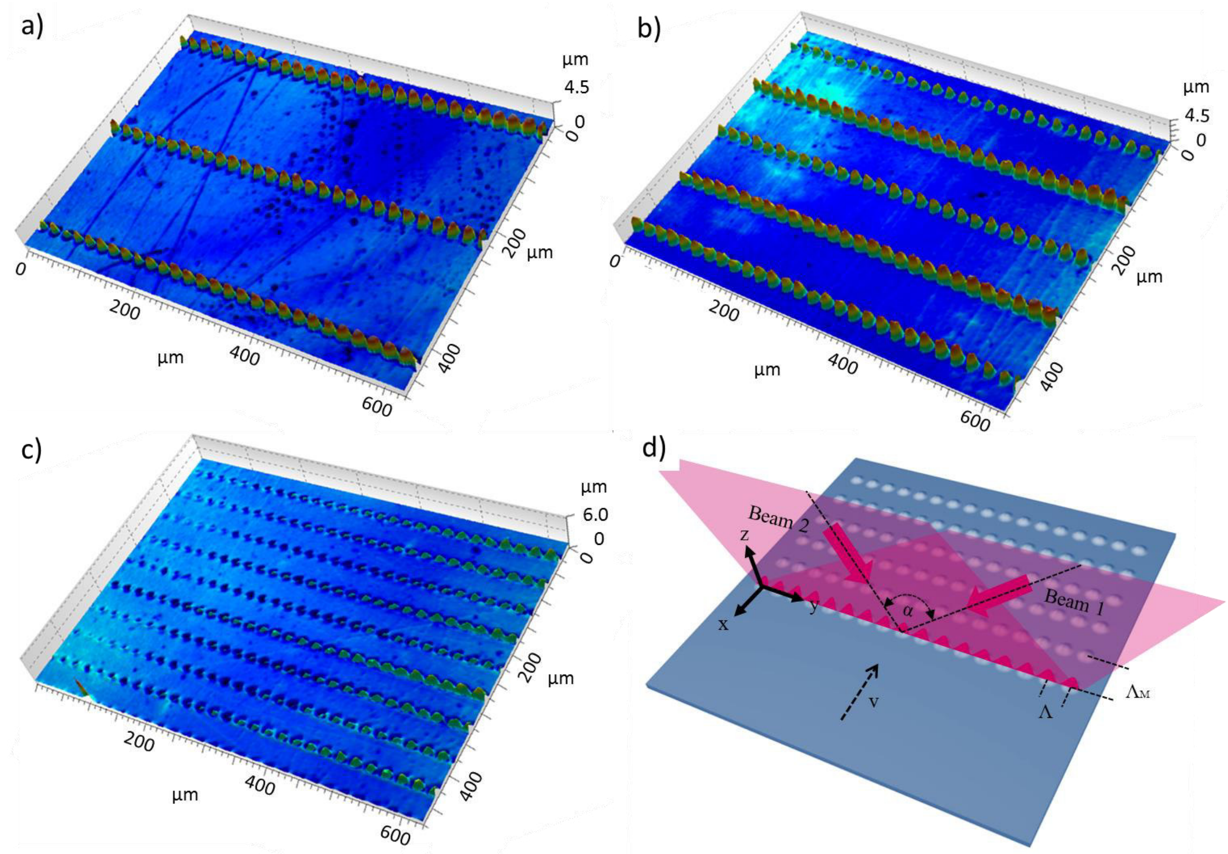

Fig. 2 DLIP patterned PC with various axis speed v: a) v = 1.00 m/s, b) v = 0.50 m/s and c) v = 0.25 m/s. The pulse frequency was 5 kHz and the laser fluence was Φ = 1.2 J/cm^2. d) Schematic representation of the line-shaped overlapping beams on the material surface.

In addition to 3D confocal images of the treated PC surfaces, a scanning electron microscope (SEM) image of the treated material is shown. Again the pattern period is Λ = 22.2 µm and a laser fluence of Φ = 1.2 J/cm^2 was used. The pattern formation is homogeneous and no variations in the lateral pattern dimensions are visible. However, in this case it can be observed that the patterned areas are elliptical, which is indicating that the focus diameter is larger than the DLIP period. In addition, it can be observed that the pattern orientation has a tilt of β = 32° to the direction of movement (v). This angle depends on the parallelism of the interfering laser beams (see Figure 2d) and can be controlled by the optics within the DLIP processing head.

Cross sections of the DLIP patterned black PC at different laser fluences are depicted in Figure 3b-d. The cross sections were realized using a dual SEM- and ion beam system, which could ablate the material locally and with high accuracy at the regions of interest. The SEM images were taken at an angle of 36° to the normal direction of the sample.

The analysis first shows that the laser radiation at the interference maxima positions produces a certain amount of pores into the PC material (see Figure 3b). Therefore, a local swelling of the PC is produced. This development of pores is indicating the zones where the IR absorbing pigment interacts with the laser radiation. We assume that the energy is later transmitted in form of heat to the PC matrix, and at this positions the evaporation temperature of polycarbonate is reached.

The maximum width W (at the PC surface) of this zone is increasing with the laser fluence from W_1 = 9.1 µm, W_2 = 17.7 µm to W_3 = 22.1 µm (corresponding to 0.8 J/cm², 1.4 J/cm² and 1.6 J/cm² laser fluences, respectively).

Differently to the width *W*, the maximal structure depth is not achieved for the highest used laser energy density. In our experiments, the maximal swelling height was h_2 = 4.7 µm, corresponding to a laser fluence of Φ = 1.4 J/cm^2 (see Figure 3c). The reason to explain this phenomenon is because at relatively high laser fluences (at least higher than Φ = 1.4 J/cm^2) the material is also affected at the minima positions and thus the relative height of the structures is reduced.

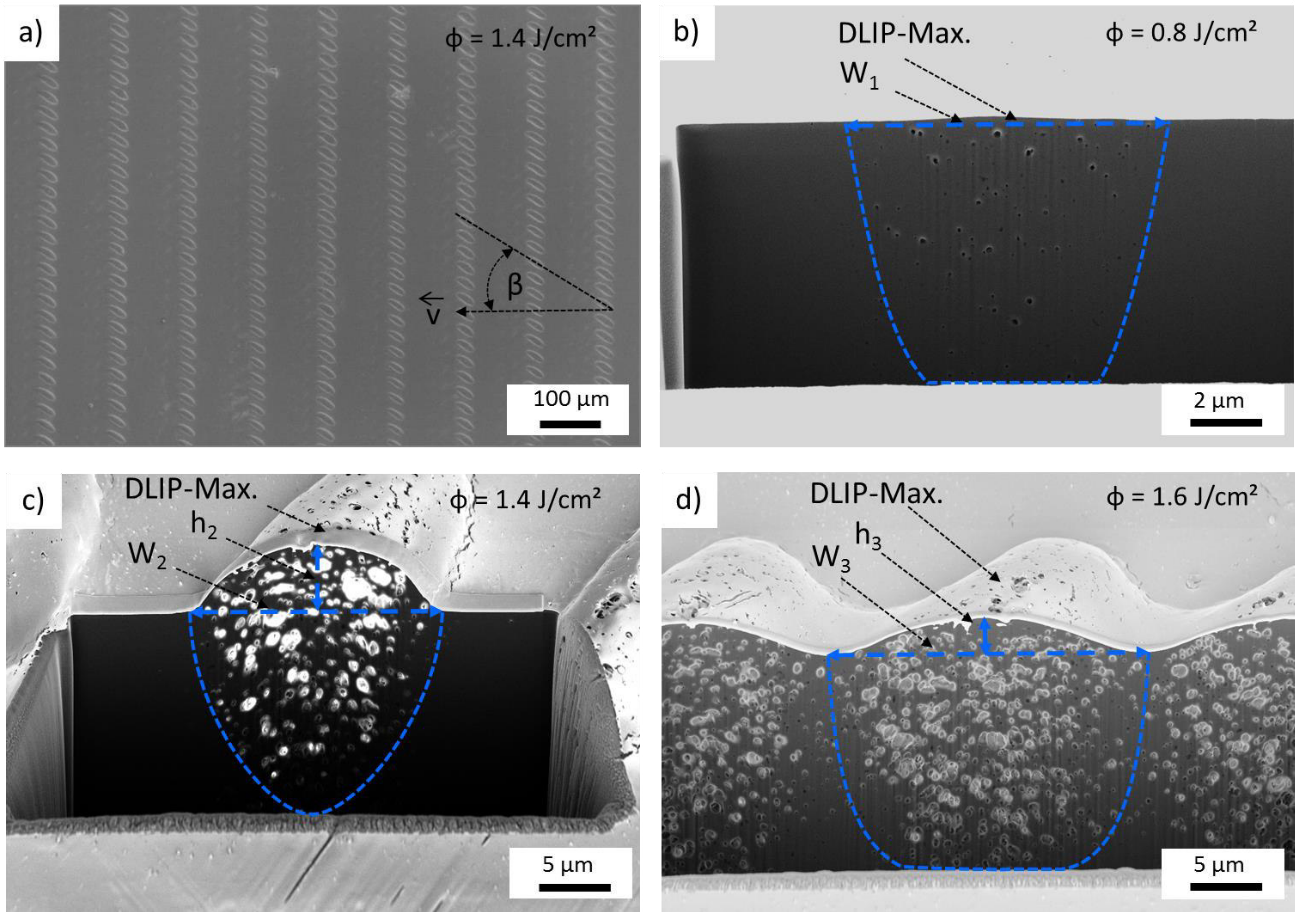

Fig. 3 Examples of DLIP patterned PC with various laser fluences as indicated in the images. The axis speed was v = 1 m/s and the pulse frequency is 10 kHz and the pulse energy 18 mJ [11].

3.2 High speed DLIP of steel

In addition to the PC foil, this method was also used to treat a metallic foil. Figure 4 shows confocal microscopic- and SEM images of treated (a, c) and non-treated (b, d) steel foils. In contrast to the patterned PC samples these structures are more inhomogeneous due to the high initial roughness of the used steel foils (R_a = 0.10 µm and R_z = 1.34 µm).

On the reference images (Figure 4b and d) a significant number of rolling marks (cylindrical grooves) can be observed, which result from the manufacturing process of the foils. Differently, the DLIP treated foils not only shown the produced line-like structure, but also a reduction of the initial roughness due to the photo-thermal interaction process of the laser beam with the material.

The spatial period of the pattern was $\Lambda = 7.2$ µm and the laser fluence was set to $\Phi = 2.8$ J/cm^2. The confocal microscope analysis permitted to measure a structure depth of approximately ~0.4 µm at the above mentioned conditions. The size of the patterned area per pulse was 6 mm by 200 µm, the pulse frequency 5 kHz and the axis speed 1 m/s. In consequence a fabrication speed of 0.36 m^2/min was achieved. Similarly to the patterns in PC, the axis speed can be varied bringing an additional characteristic length to the structure (Λ_M).

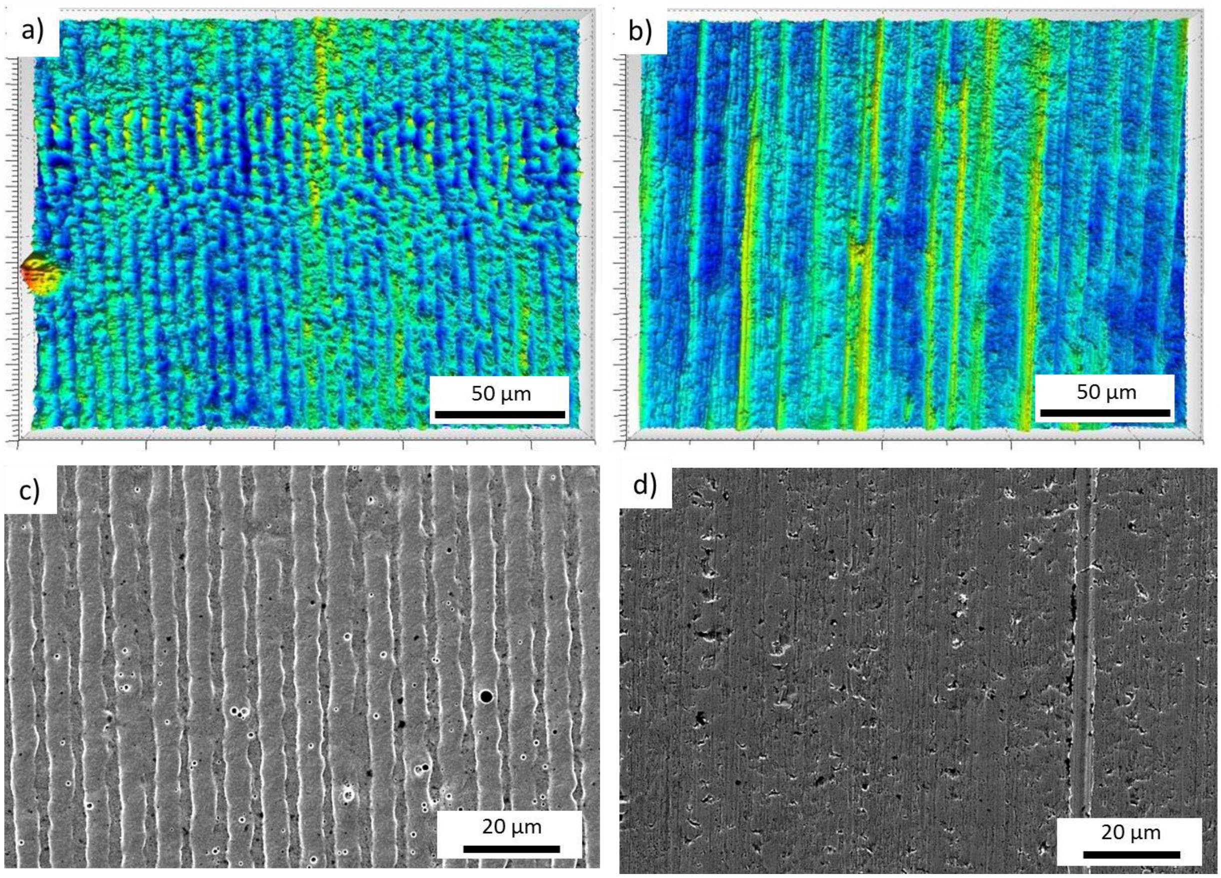

Fig. 4 (a,b) Confocal microscopic and (c,d) scanning electron microscopic images of treated and non-treated steel foil. The untreated material is shown in images b) and d). The processing conditions for a) and c) were v = 0.9 m/s, $\Phi = 2.8$ J/cm^2, $f_P = 5$ kHz and $\Lambda = 7.2$ µm.

The homogeneity of the produced line-like geometry over the whole treated area is shown in Figure 5. In the SEM image the line-like patterns are oriented perpendicular to the DLIP patterned area per pulse. The spatial period is $\Lambda = 7.2$ µm (similar to Figure 4) but the distance between two laser pulses is $\Lambda_M = 180$ µm, corresponding to a pulse frequency of $f_P = 5$ kHz and an axis speed of 0.9 m/s. Due to the fact that we used a multi-mode laser for high speed patterning there are minor deviations in the width of the patterned regions. A possibility to avoid these deviations and to attain even more homogenous patterns is to use beam shaping optics. The enlarged view of the region between two patterned areas depicts that overlapping DLIP patterns can result in a complete surface melting and in consequence an extinction of surface patterns. However, we found that this can be avoided by reducing the laser fluence (not shown in this publication). Thus even line-like features without interruptions can be processed on large areas by decreasing the laser fluence and increasing pulse-to-pulse overlap.

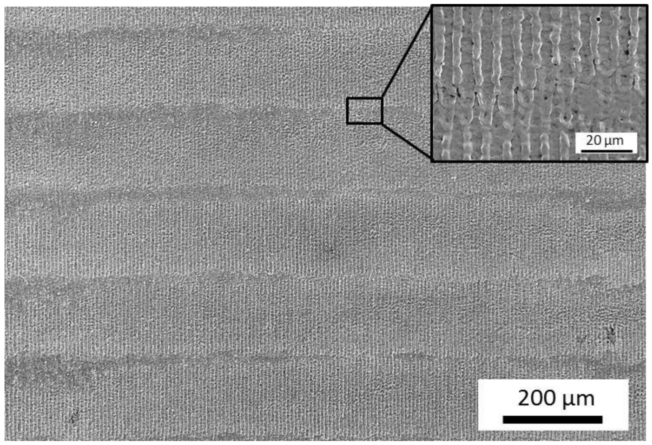

Fig. 5 Scanning electron microscope image of a DLIP treated steel foil. The processing conditions were v = 0.9 m/s, Φ = 2.8 J/cm^2, f_P = 5 kHz and Λ = 7.2 µm.

CONCLUSIONS

The reported results demonstrate the capabilities of the Direct Laser Interference Patterning method to produce periodic surface patterns at record fabrication speeds of 0.36 m²/min and 0.9 m²/min on metal and polymers, respectively. These fabrication speeds were produced by developing advanced DLIP processing heads which are used not only to produce the interference patterns by overlapping two laser beams but also by shaping the individual beams with special geometries which are necessary according to the structuring strategy for high speed patterning. These process speeds were demonstrated with periods between 7 µm and 22 µm.

By using more powerful laser systems in the future, it will be possible to further increase the here reported speeds to several m²/min. This makes new solutions in optical, mechanical or medical applications both feasible and affordable.

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