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Erstveröffentlichung in / First published in:

SPIE LASE. San Francisco, 2018. Bellingham: SPIE, Vol. 10520 {Zugriff am: 02.05.2019}.

DOI: <https://doi.org/10.1117/12.2290320>

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Valentin Lang, Tim Hoffmann, Andrés Fabián Lasagni, "Optimization for high speed surface processing of metallic surfaces utilizing direct laser interference patterning," Proc. SPIE 10520, Laser-based Micro- and Nanoprocessing XII, 105200K (19 February 2018); doi: 10.1117/12.2290320

SPIE.

Event: SPIE LASE, 2018, San Francisco, California, United States

Optimization for high speed surface processing of metallic surfaces utilizing direct laser interference patterning.

Valentin Lang^{a,b}, Tim Hoffmann^b, Andrés Fabián Lasagni^{a,b}

^aInstitute for Manufacturing Technology, Technische Universität Dresden, George-Baehr-Str. 3c, 01069 Dresden, Germany; ^bFraunhofer Institute for Werkstoff- und Strahltechnik IWS, Winterbergstrasse 28, 01277 Dresden, Germany

ABSTRACT

Direct Laser Interference Structuring (DLIP) is a manufacturing technology capable to functionalize large areas with high-precision periodic patterns. However, for industrial use of this emerging technology, solutions must be developed for specific requirements. With the objective of optimizing Direct Laser Interference Patterning in terms of process speed, an advanced optical module was developed that permits to superimpose two laser beams obtaining the interference pattern within an elongated area (linear spot) to meet the requirements of high-speed processing. After that, the influence of the process parameters on the quality of the surface patterns produced with the developed optical assembly was determined. It could be shown that the pulse overlap, in contrast to the applied average fluence, has a significant influence on the resulting structure heights of the produced patterns. Furthermore, it became apparent that during the course of the process, the underlying physical process dynamics seem to change, which was indicated by the resulting structure heights variations over the process. The gained findings will make a contribution to improving the quality of surface patterns produced with DLIP and to enabling reliable manufacturing qualities in the future.

Keywords: Surface Functionalization, Direct Laser Interference Patterning, High Speed Fabrication

1 INTRODUCTION

Surfaces constitute the interfaces between different components or with the surrounding environment. Hence, they play a key role in the function of structural parts. In addition, they have also a decisive influence on the service life of components. The main task of surface engineering is to adapt surface properties to the existing operating conditions [1,2]. While conventional approaches follow chemical changes of the surfaces or the application of additional functional layers or coatings in order to achieve certain properties, texturing technologies can also provide new surface functions inspired by extraordinary examples from nature showing surface topographies with defined periodic microstructures. Prominent examples from nature are the hydrodynamic optimized skin of sharks, the superhydrophobic cuticle of the lotus plant or the antibacterial cuticle of the collembola [3-5].

In principle, various manufacturing processes are capable to improve surface properties by fabricating periodic micro patterns on technical components [6-8]. Within these methods, Direct Laser Interference Patterning (DLIP) is characterized to provide both high resolution and throughput rates [9]. The DLIP method allows the fabrication of microstructures with dimensions of a few micrometers or even below in a one-step process using high power lasers [10]. This technology uses the periodic modulation of the laser intensity distribution that occurs when two or more coherent laser beams are superimposed. Depending on the pulse energy of the used laser systems, large areas can be irradiated using a single pulse, which may contain thousands or even millions of periodic microelements (corresponding to the interference maxima positions). This high number of periodic microelements can be formed on the components surface with a single laser pulse, which enables outstanding surface processing rates. DLIP permits to process every kind of material absorbing the laser radiation. For example, metallic substrates can be treated using either infrared or visible radiation, while for polymers ultraviolet wavelengths are necessary [11]. In contrast to competing machining processes with resolutions also in the sub-micrometer scale, DLIP does not require vacuum, hence does better suit system investments and machinable part dimensions. Although the possibilities of surface functionalization and basic advantages of DLIP have already been proven in scientific investigations on a laboratory scale, large-scale industrial use still requires development work at the level of technological readiness. For industrial applications, modular solutions must be found that can be easily integrated into the industrial environment and guarantee a high degree of robustness and process reliability.

In this study, we present an approach of Direct Laser Interference Patterning with particular development priority on maximum process speeds. The effects of different optical beam shaping concepts and other process parameters such as used laser fluence and number of laser pulses are investigated. The characterization of the fabricated surface topographies is carried out using scanning electron microscopy (SEM) and confocal microscopy (CM).

2 DEVELOPMENT OF HIGH THROUGHPUT DLIP PROCESSING MODULE

If two or more coherent laser beams interfere, a periodic modulation of the amplitude of the laser intensity occurs. The resulting interference pattern is suitable for well-defined processing of materials creating structural elements at the positions corresponding to the interference maxima. For instance, Line-like shaped interference patterns can be generated by using two laser beams. Assuming two monochromatic plane waves the intensity distribution is given by:

$$I = 4c\epsilon_0 E_0^2 \cdot \cos^2(ky \cdot \sin(\alpha/2)) \quad (1)$$

where E_0 is the amplitude of the electric field of the individual laser beams, ϵ_0 is the dielectric constant in vacuum, α is the angle between the laser beams, c is the speed of light and k is wavenumber ($k = 2\pi/\lambda$). The expression $\cos^2(ky \cdot \sin(\alpha/2))$ is 1 if $ky \cdot \sin(\alpha/2) = 0, \pm\pi, \pm2\pi, \dots$ and 0 for $ky \cdot \sin(\alpha/2) = \pm\pi/2, \pm3\pi/2, \dots$. Thus, the interference pattern for a two-beam configuration follows a 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. In addition, the spatial period Λ , defined as the lateral distance between two interference maxima or minima, depends in on the laser wavelength of the radiation λ and the angle at which the beams intersect α following:

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

Therefore, the spatial period Λ can be tuned up to the submicrometer range, depending on the angle of incidence.

In order to meet particular requirements of industrial environments, a modular device has been developed for laser interference processing, permitting to achieve high throughputs. The module consists of a cylindrical telescope to expand the laser beam, followed by an arrangement of two bi-prisms for beam splitting and alignment (patented by Fraunhofer IWS, Dresden, Germany). After that, a cylindrical lens is used for compressing the laser sub-beams in one dimension (see Figure 1).

Fig. 1 Schematic drawing of the two beam laser interference setup for high speed laser patterning.

In this way, the module realizes beam forming to a long drawn line in the focused area, which for functional reasons also corresponds to the area of the beam overlap. Forming the interfering beams into the shape of long lines has advantages in achieving maximum process speeds. For this purpose, the laser energy must be distributed over the largest possible area achieving an appropriate laser fluence (energy density). In order to realize the relative movement between the laser focus and the substrate surface, which is necessary for the process, as well as reaching laser fluences over 1 J/cm², the laser beam has to be focused at least in the direction perpendicular to the relative movement. The dimensions of the line-like focused laser spot, the width w and the length l , can be varied by moving the optical components of the cylindrical telescope and the final cylindrical lens (for example 10 mm x 100 μ m). The interference pitch Λ is determined by the angles of the two beam splitting prisms (see Fig. 1). In principle, a change in the interference period is made possible by exchanging one of the two prisms. In our experiments, the angle between the laser beams was set to $\alpha = 3.39^\circ$ and $\alpha = 7.64^\circ$ obtaining spatial periods of $\Lambda = 18 \mu\text{m}$ and $\Lambda = 8 \mu\text{m}$, respectively, in accordance to Eq. 2.

The used laser source was a Q-switched slab-type solid-state laser (EDGEWAVE InnoSlab 400) emitting at its fundamental wavelength ($\lambda = 1064 \text{ nm}$) with pulses of pulse duration $\tau = 10 \text{ ns}$, operating in a range from 1 Hz up to 10 kHz and performing a maximum average power of 150 W. The initial beam geometry is rectangular with an edge length of $\sim 5.0 \text{ mm}$ showing a Gaussian intensity distribution in one direction and top-hat in the perpendicular one. The relative movement between the interference spot and the substrate required to process a certain area is realized by linear stages (AEROTECH PRO225LM) which translate the substrate. The sample movement was set to be perpendicular to the line-shaped laser spots (see Figure 1).

The DLIP experiments were carried out on stainless steel (X5CrNi18-10, 1.4301). The characterization of the produced surface structures was carried out by scanning electron microscopy (Philips XL30 ESTEM FEG) and confocal microscopy (Leica DCM 3D).

The pulse repetition frequency f_{rep} was set to $f_{\text{rep}} = 2 \text{ kHz}$, resulting in an average power $P_{\text{av}} = 78 \text{ W}$, corresponding to a pulse energy $E_p = 39 \text{ mJ}$.

Different speeds for the translational stage were used, corresponding to different overlap of pulses. The pulse-to-pulse (p2p) overlap $\cap_{p2p}$ is derived from the relation of pulse-to-pulse feed d_{p2p} and the width of the focused line-like laser spot w :

$$\cap_{p2p} = \frac{w - d_{p2p}}{w} = 1 - \frac{d_{p2p}}{w} \quad (3)$$

The pulse-to-pulse feed d_{p2p} results from pulse repetition frequency f_{rep} and feed rate of the axis v_{feed} :

$$d_{p2p} = \frac{v_{\text{feed}}}{f_{\text{rep}}} \quad (4)$$

3 RESULTS AND DISCUSSION

As mentioned in the previous section, DLIP was applied for structuring Stainless Steel using a NIR ns-pulsed laser system. The spatial period Λ of the interference pattern, the laser fluence ϕ and the pulse-to-pulse-overlap $\cap_{p2p}$ were varied systematically.

SEM images of treated stainless steel with an interference period of $\Lambda = 18 \mu\text{m}$ are shown in Figure 2a and 2b. The applied average fluence was $\phi_{\text{av}} = 2.7 \text{ J}\cdot\text{cm}^{-2}$ and the pulse-to-pulse feed distances were $d_{p2p} = 0.020 \text{ mm}$ (Figure 2a) and $d_{p2p} = 0.005 \text{ mm}$ (Figure 2b), corresponding to pulse-to-pulse overlaps of 80 and 95 %, respectively. .

It can be observed that the pattern orientation has a tilt (β) of $\sim 9^\circ$ to the direction of movement (v). This tilt is subject to the parallelism of the interfering laser beams, which depends on the alignment of the optics in the assembly and the relative orientation of the laser beam. A tilt of interference pattern can be both a purposeful feature to produce complex surface geometries or a cause of non-homogeneity. While some applications may require a certain tilt as feature, this characteristic can lead to a significant distortion of the surface pattern, resulting in the worst case in the complete destruction of the periodic morphology when using a combination of short pulse-to-pulse feed d_{p2p} with a long spot length w (or high pulse-to-pulse overlap).

Figure 2b displays the infeed into the process (end of process). At this location it becomes clear that the laser affected area is larger than the area at which the material is locally molten at the interference maxima positions, since a significant part of the irradiated area does not exceed the threshold fluence required to melt the material surface.

Fig. 2 DLIP treated stainless steel with period $\Lambda = 18 \mu\text{m}$ with pulse repetition frequency $f_{\text{rep}} = 2 \text{ kHz}$ and average laser fluence $\phi_{\text{av}} = 2.7 \text{ J}\cdot\text{cm}^{-2}$ with a) pulse-to-pulse feed $d_{2p2} = 0.020 \text{ mm}$ and b) pulse-to-pulse feed $d_{2p2} = 0.005 \text{ mm}$; SEM images with 1000x magnification taken by acceleration voltage of 5 kV.

By adjusting the alignment of the laser beam into the DLIP module, it is possible to correct the orientation of the interference lines relative to the elongated overlapped beams. This is demonstrated in Figure 3a, b, where the tilt angle (β) is smaller than 1° .

Fig. 3 DLIP treated stainless steel with period $\Lambda = 8 \mu\text{m}$ (repetition frequency $f_{\text{rep}} = 2 \text{ kHz}$ and average laser fluence $\phi_{\text{av}} = 2.7 \text{ J}\cdot\text{cm}^{-2}$ with pulse-to-pulse feed $d_{2p2} = 0.040 \text{ mm}$).

Figure 4 shows SEM (a, b) and confocal microscopic (c, d) images of treated stainless steel substrates with a spatial period $\Lambda = 8 \mu\text{m}$. The different applied pulse-to-pulse feed distances of $d_{2p2} = 0.020 \text{ mm}$ (Figure 4a, c) and $d_{2p2} = 0.005 \text{ mm}$ (Figure 4b, d) correspond to different pulse-to-pulse overlap of $\cap_{p2p} = 40 \%$ and $\cap_{p2p} = 90 \%$, respectively. Both illustrated cases are processed with the same average fluence $\phi_{\text{av}} = 2.7 \text{ J}\cdot\text{cm}^{-2}$.

While individual pulses can still be optically detected at higher feed distances, the structure appears continuously with reduced feed distances. The increase of the pulse-to-pulse overlap enhances the resulting structure height. Normalized by the spatial period Λ , the case with an overlap of 40 % ($d_{2p2} = 0.020 \text{ mm}$) shows an aspect ratio (AR) of about 0.1, while the case with an overlap of 90 % (for $d_{2p2} = 0.005 \text{ mm}$) shows an aspect ratio of about 0.8 (see Figure 3c and d). Compared to the larger interference periods ($\Lambda = 18 \mu\text{m}$), significantly higher structure heights could be achieved at the smaller interference periods $\Lambda = 8 \mu\text{m}$ (especially with more pulse overlap), which results in even higher aspect ratios.

In general, the processed surfaces show a smooth undulation. This is in accordance with the applied pulse duration ($\tau = 10$ ns) since surface melting is typical in this regime of pulse duration and thus producing a smoothen morphology, while ultra-short pulses ($\tau < 10$ ps) may tend to produce additional surface features like laser induced periodic surface structures (LIPSS) and thus covering the treated areas with a periodic roughness with amplitude in the nanometer range [12-15]. Furthermore, even for the case of high pulse-to-pulse overlaps (e.g. $\cap_{p2p} = 90\%$, Figure 4b and d), the surface affected by the laser radiation showed a low roughness, as has been reported by other authors [16]. With an increasing proportion of melt, a limitation of the achievable structure height is to be expected, which means that the process is strongly dependent on the pulse duration.

The use of high pulse-to-pulse overlaps seems to generate so much melting that the comparatively deep trench structures partially remelt down locally (Figure 4b). It is conceivable that a melt movement following the Marangoni convection leads to the formation of overhangs above the cavities as has been previously reported [17].

Fig. 4 DLIP treated stainless steel with period $\lambda = 8 \mu\text{m}$ with pulse repetition frequency $f_{\text{rep}} = 2 \text{ kHz}$ and average laser fluence $\varphi_{\text{av}} = 2.7 \text{ J} \cdot \text{cm}^{-2}$ with (a, c) pulse-to-pulse feed $d_{2p2} = 0.020 \text{ mm}$ and b,d) pulse-to-pulse feed $d_{2p2} = 0.005 \text{ mm}$; SEM images (a, b) with 4000x magnification taken by acceleration voltage of 5 kV.

Since DLIP is a boundary process in which selective modulated material processing takes place in the irradiated area, laser fluence must be applied in the appropriate range. Figure 5 shows the achieved structure height h_{st} above the applied average fluence φ_{av} for the two spatial periods of $\lambda = 8 \mu\text{m}$ (Figure 5a) and $\lambda = 18 \mu\text{m}$ (Figure 5b). It has to be taken into account that the fluence values represent average values, which in the case of dual beam interference leads to the fact that the local fluence at the maxima of the intensity distribution constitutes two times the mean fluence.

For $\Lambda = 8 \mu\text{m}$, the threshold value of the average fluence is about $\varphi_{\text{av,thr},\Lambda=8\mu\text{m}} = 2.5 \text{ J}\cdot\text{cm}^{-2}$, whereas for $\Lambda = 18 \mu\text{m}$ the threshold average fluence was $\varphi_{\text{av,thr},\Lambda=18\mu\text{m}} = 1.5 \text{ J}\cdot\text{cm}^{-2}$. This relation between the threshold fluence and the interference period has previously been observed and explained by the fact that with the same material-specific thermal diffusion length (for a certain pulse duration), higher temperature differences between maxima and minima of the intensity distribution can occur in larger periods [18,19].

Fig. 5 Structure height h_{st} in single pulses vs. average laser fluence φ_{av} achieved in DLIP processing Stainless Steel for a) spatial period $\Lambda = 8 \mu\text{m}$ and b) spatial period $\Lambda = 18 \mu\text{m}$.

While Figure 5 illustrates the achieved structure heights h_{st} vs. applied fluence for the case of single laser pulses, Figure 6 shows the influence of the multi pulsing due to pulse overlap at reduced feed distances (d_{p2p}). The x-axis represents the pulse-to-pulse feed d_{p2p} normalized above the spot width w . In consequence, values smaller than one denote the multi pulsing regime.

Fig. 6 Structure height h_{st} over pulse overlapping achieved in DLIP processing of Stainless Steel for a) spatial period $\Lambda = 8 \mu\text{m}$ and b) spatial period $\Lambda = 18 \mu\text{m}$; pulse repetition frequency $f_{\text{rep}} = 2 \text{ kHz}$ and average laser fluence $\varphi_{\text{av}} = 2.7 \text{ J}\cdot\text{cm}^{-2}$.

As in the previous case, two situations with spatial periods of $\Lambda = 8 \mu\text{m}$ and $\Lambda = 18 \mu\text{m}$ are investigated. For the used stainless steel substrates, it can be seen that the structure height increases with increasing the pulse-to-pulse overlap or

decreasing the feed distance to spot width ratio. The results furthermore point out that in the case of $\lambda = 8 \mu\text{m}$ (Figure 6a), higher structure heights h_{st} could be achieved, compared to $\lambda = 18 \mu\text{m}$ (Figure 6b). This fact might be explained by the principal growth mechanism of the structure height in the DLIP process when utilizing ns-pulses. With increasing process intensity (either fluence or overlap) a spatially expanding growth of burr-like formation starts to from the maxima of intensity distribution. Since several interference maxima coexist, the burr-like formations move with their spatial expansion towards each other and finally meet at the locations corresponding to the interference minima of intensity distribution (the mechanism is observable in Figure 3). With the spatial collision of the burr-like formations, a significant growth of the structure height is observed. Consequently, this effect is expected to occur earlier in the case of comparatively smaller spatial periods. In this context, it can be suggested that the growth of the structure height in DLIP processes (in the pulse duration regime of nanoseconds) is characterized more by melt accumulation than by material removal. Therefore, it can be expected that with adequate parameters (fluence or overlap) higher structure heights can also be produced for larger structural periods, so that finally comparable aspect ratios would result. This effect will be analyzed in detail in the future.

Clearly, the pulse-to-pulse overlap or the feed distance have a strong influence on the resulting process speed (also indicated in Figure 6, top x-axis). Since constant pulse repetition frequency $f_{rep} = 2 \text{ kHz}$ was used, the process speed is decreased with reduced pulse-to-pulse feed d_{p2p} . Therefore, in order to achieve high structure heights, restrictions on the achievable process speed must be considered.

Finally, the developed DLIP approach was investigated in terms of structure height homogeneity as function of the process position. Thus, the structure heights at the beginning of the process (infeed), at the end of the process (outfeed) and at intermediate positions were measured (see Figure 7). As it can be observed, a discrepancy between the structure heights, especially at the beginning and end of the process was observed (in this case, for a spatial period $\lambda = 18 \mu\text{m}$, pulse-to-pulse feed $d_{p2p} = 0.005 \text{ mm}$, pulse repetition frequency $f_{rep} = 2 \text{ kHz}$ and average laser fluence $\phi_{av} = 2.7 \text{ J}\cdot\text{cm}^{-2}$). In particular, a significant increase in structure height occurs during the first three millimeters of machining progress. Afterwards, a steady-state condition is reached. The displayed curve also allows the interpretation of a reduction of the structure height with a further process progression (e.g. for 20 mm). However, this effect must be precisely studied in the future.

Fig. 7 Structure height h_{st} of DLIP treated Stainless Steel sample as function of the position; spatial period $\lambda = 18 \mu\text{m}$, pulse-to-pulse feed $d_{p2p} = 0.005 \text{ mm}$, pulse repetition frequency $f_{rep} = 2 \text{ kHz}$ and average laser fluence $\phi_{av} = 2.7 \text{ J}\cdot\text{cm}^{-2}$ (dashed lines are given as guides to the eye).

Clearly, there are different possible mechanisms that initially lead to an increase in the structure height switching to a steady-state condition or even to a reduction of the structure height for longer distances. These mechanisms have to be understood in order to ensure a high quality of the process results for industrial applications.

Three different effects could explain the changes in the structure height. During the process, accumulation of thermal energy can heat up the entire substrate body, which in principle increases the mean temperature of the substrate (based on the photo-thermal nature of the laser process) [20]. Thus, a lower energy density might be necessary to locally melt the metallic substrate at the maxima positions resulting in an increase of the structure depth. Furthermore, the fabrication

of the periodic structure might have an influence on the absorption of subsequent laser pulses since the resulting leads to multiple reflections in the trenches [21]. In addition, the textured topography produced by the laser process influences the thermal diffusion of the inserted thermal energy into the periphery [22]. While all the effects listed above are possible, it should be investigated in detail how strong is the contribution of each effect. It is conceivable to carry out thermal simulations to investigate the effect of the heating substrate base material as well as to determine the change in absorption due to the produced topography [23].

4 CONCLUSIONS

In this work, a DLIP module for producing periodic surface patterns with high throughput was developed. For this propose, an optical configuration that permits to superimpose two laser beams obtaining the interference pattern within an elongated area (linear spot) was constructed. In addition, the performed experiments were focused on the influence of the process parameters on the quality of the surface patterns produced with the developed optical assembly. It could be shown that the pulse-to-pulse overlap, in contrast to the applied average laser fluence, has a more relevant influence on the resulting structure heights of the produced patterns. Furthermore, it became apparent that during the course of the process, the underlying physical process dynamics seem to change, which was indicated by the resulting structure heights changing over the course of the process with constant parameters. The gained findings will make a considerable contribution to improve the quality of surface patterns produced using the DLIP technology as well as enabling reliable surface qualities in the future. The shown effects will be further investigated by means of optical and thermal simulations.

ACKNOWLEDGEMENTS

The authors acknowledge the Bundesministerium für Bildung und Forschung (BMBF) for financial support (Verbundförderprojekt 'Laser Interference High Speed Surface Functionalization' (FKZ 13N13113). A.F.L. also acknowledges the support of the German Research Foundation (DFG), Excellence Initiative by the German federal and state governments to promote top-level research at German universities (Grant No. F-003661-553-71A-1132104).

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