A Process Optimization Strategy for Texturing 3D Surfaces Using Direct Laser Interference Patterning

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Laser-based surface modification methods have attracted considerable interest in the last 20 years due to their flexibility, efficiency, and multiple technical applications that are possible. A particular challenge for these methods is the treatment of curved 3D surfaces. The presented study reports on the process optimization in laser texturing of 3D surfaces using Direct Laser Interference Patterning (DLIP). Periodic line-like structures are fabricated using a picosecond-pulsed laser on spherical stainless-steel parts. The aim is to identify the possibility of processing curved geometries using an innovative hexapod positioning system. For this purpose, the effect of two different structuring strategies is investigated and compared by evaluating the obtained structure depths and the structure period of the fabricated structures as function of the position over the samples. All treated surfaces are examined using a confocal microscope. The results demonstrate an improvement in the structure homogeneity in terms of structure depth and period when using the fitted hexapod positioning approach.

Due to its flexibility and adaptability, laser materials processing is used in various fields of applications, such as cutting, welding or surface modifications, breaking in several cases the limits of conventional processing methods.[1–4] Ultrashort pulsed laser modification enables the creation of microstructures for individual functionalities on almost every material.[5,6] For example, direct laser writing (DLW) or direct laser interference patterning (DLIP) are laser micromachining techniques that are capable to create surface structures with high resolutions down to μm-range.[7–9] Such microstructures enable the realization of unique surface properties such as hydrophobic or antibacterial characteristics as well as optimized tribological properties.[10–12] A particular challenge in laser surface functionalization is the adaptability to 3D freeform components, which has become a significant importance for technical applications in recent years.[13] Typical approaches that are being implemented in industry or research laboratories for treated 3D parts are for instance, Computerized Numerical Control (CNC) systems as well as robot systems, which are in some cases limited in accuracy (in particular the robot systems).[14,15] Further progress requires the adaption of texturing results to real parts with 3D shaped geometries.

In this frame, the presented work herein examines the utilization of the DLIP technology in combination with a new hexapod positioning system and its influence on the uniformity of the produced microstructures. The main advantage of the new hexapod system is the high motion accuracy and repeatability as well as its simplicity to be combined with existing DLIP optical heads.

The structures were fabricated using the DLIP technology. The used setup is illustrated in Figure 1a. To produce the line-like pattern geometry, two Gaussian laser beams were overlapped on the substrate at a certain angle (θ). At the region where the beams overlap, a periodic intensity profile is produced which can be directly transferred to the materials surface by selective melting or ablation at the interference maxima positions.[16] The used system utilizes a solid-state Nd:YVO4 laser (Edgewave PX200) emitting 1064 nm wavelength with 10 ps pulse duration and maximum output power of 100 W. The laser fluence was set to 1.21 J cm⁻² and the spot diameter of the interference area was about 100 μm (irradiated spot on the sample). Further relevant processing parameters are the distance between the DLIP pixels which can be described by the overlap and the hatch distance (HD). For instance, Aguilar-Morales et al. mentioned that the HD has been identified as the most critical parameter for the homogeneity.[17] Additional information about the experimental setup has already been published in previous work.[18] The positioning of the samples were performed using a hexapod (Aerotech HEX500-350 HL) (see Figure 1a). The main advantages of this system are the flexible sample positioning with six degrees of freedom (three lateral and three rotational) with high accuracy (up to ±0.5 μm and ±2.5 μrad) and high repeatability (bidirectional repeatability up to ±0.35 μm and ±1.0 μrad). The structure period (A) was set to ≈6.0 μm (corresponding to an interference angle of 10.2°) and the overlap...
was set to 95% to generate patterns with a structure depth of \( \approx 1.4 \, \mu m \). The considered pulse-positioning strategy relies in controlling the pulse overlap (OV) and the HD are shown in Figure 1b. In particular, the HD was selected to 0%, to avoid overlapping effects in the direction perpendicular to the interference lines. Figure 1c,d show schematically the positioning strategies utilized in this work. The standard movement (Figure 1c) corresponds to an established scanning technology at one height level. In this case, the hexapod moves only in the two horizontal directions \( x \) and \( y \) and does not follow to the vertical position of the surface. The newly developed positioning strategy (Figure 1d) uses the flexibility of the six-freedom hexapod system which allows a nearly unrestricted treatment of a 3D surface. This is enabled by continuous workpiece rotation during the process of the hexapod legs. In this case, it is possible to rotate and move the workpiece in any direction to achieve a beam entry of both beams symmetrically to the surface normal at any position. For this purpose, the normal vector of each laser spot (depending on the OV and HD) on the surface was used to calculate the rotational angles around the \( X \) and \( Y \) axis (pitch and the roll angle) and transferred to the programming language (G-code). The experiments were performed on spherical stainless-steel samples (1.4034) with a diameter of 30 mm as well as on flat substrates for comparison reasons. The total textured area was set to 78.5 mm² (\( d = 10 \, \text{mm} \)), which was chosen due to the restriction of motion limitation (rotation angle) of the hexapod system. The samples were polished and have a quality grade G100 according to DIN 5401 (\( Ra < 0.1 \, \mu m \)).

To examine the influence of the process strategy on the uniformity of the microstructures, the spheres were processed using the standard positioning strategy and modified positioning strategy with the hexapod. Exemplary confocal microscope images of produced line-like structures at different positions (1–5) for both strategies are shown in Figure 2a,b. The vertical and lateral resolution of the confocal microscope are 1 and 140 nm, respectively.

First of all, it can be seen that for both strategies, in the central position of the sphere (position 1 in Figure 2a,b), that the structure depths reaches its highest value within the middle of the DLIP-treated area (\( \approx 1.3–1.4 \, \mu m \)). Then, the structure depth decreases with the distance from the center (in the direction perpendicular to the interference lines) following the Gaussian intensity distribution envelop of the interference pattern. This situation is typical as the treated areas were not overlapped according to this direction and has been observed typically for line-like structures on metallic surfaces.[19]

The surface topography analysis of the sphere (Figure 2a) treated with the standard configuration (Figure 1c), shows for the associated structure that the structure depth of the patterns decreases to the edges of the processing field (Figure 2a, positions 2–5). Moreover, it can be observed that the structure depth strongly differs at positions 2–5 (\( \approx 0.5–0.8 \, \mu m \)) than at position 1 (center position, \( \approx 1.3 \, \mu m \)). For instance, the structure depth at position 4 and 5 are in the range of 0.50 \( \mu m \) ± 0.06, respectively, which represents the extrema position along the interference pattern. These results can be explained by the unchanged height level of the overlapped beams used in the structuring process, which results in a changed angle of incidence of the laser beams depending on the position due to the curved surface. In consequence, the laser fluence is reduced as the projection of the interference pattern over the sphere increases, in particular for larger inclination angles. The confocal images in Figure 2a also show that the spatial period of the periodic structures depends on the position of the structure over the sphere (e.g., 5.8 \( \mu m \) at position 1 and 3.4 \( \mu m \) at position 2).

In contrast, both the structure period as well as the structure depth are more homogenous using the optimized positioning strategy (see Figure 2b). The generated structure profiles look almost identical at the different analyzed positions. This is visible for all measurement positions and can be explained by the optimized angle of incidence of the laser beams.
In the last case, intensity distribution of the pattern hits the curved surface with the same orientation at any position and enables a uniform material ablation as the irradiated area is almost unchanged resulting in a constant laser fluence level.

After the qualitative description of the generated morphologies, the depth of the produced structures as well as the structure period were analyzed in more detail as function of the position (arc length) of the pattern over the spherical surface. As shown in Figure 3, very different results are obtained for both strategies. Figure 3a,b show the reached structure period, whereas Figure 3c,d show the structure depth for both strategies. The measurements were performed in x- and y-direction, according to the schema in Figure 1b.

As mentioned earlier, at the central position (arc length = 0), the structure depth values were around 1.3 ± 0.1 μm, independent of the positioning strategy utilized. This values is in agreement to the set structure depth (1.5 μm) on flat surfaces from preliminary investigations (not shown). The same results can be observed for the spatial period in the central position. For instance, the structure periods were 5.8 μm and 6.1 μm for the standard and the optimized strategy, respectively, which is in the range of the expected period for the flat surface (Λ = 6.0 μm). Clearly, the similarity of the aforementioned values when compared with the flat reference situation (not shown) can be explained by the vertical beam entry in the center position of the sphere which is comparable in case of the flat surface. Small deviations of the values observed in Figure 3b,d can be attributed to the specimen clamping and alignment, which have to be very accurate. For instance, a small offset (in x-, y- or z-direction) in the specimen clamping can lead to large deviation of the expected results due to the bigger displacement over the arc length.

Using the standard positioning strategy, a significant decrease in the spatial period (Λ) was observed by moving out of the center position. For example, the structure period (Figure 3a) drops from 5.8 μm in the center to 3.2 μm in the edge area, which approximately is a reduction of 45%. This clearly noticeable effect can be explained by the constant vertical position and the resulting change of the processing position in z-direction. Due to the z-shift different levels within the interference volume are used, which leads to a deviation of the structure period (see Figure S1, Supporting Information).[20] In case of the structure depth (Figure 3b), also a considerable reduction was observed. For instance, the structure depth in the middle position is 1.35 ± 0.11 μm and reduces to 0.50 ± 0.08 μm (63%) with increasing distance from the center. This effect is visible for both x- and y-movement directions. As mentioned earlier, this change can be explained by the local variation of the laser fluence due to the inclined angle of the surface in comparison to the interference pattern.

As the variation in both spatial period and structure depth result from the nonperpendicularity of the interference pattern with the sample, the use of the hexapod system should improve the pattern homogeneity. The results of the optimized positioning strategy with the hexapod system are shown in Figure 3b,d. As mentioned earlier, the period in the central segment is in the range of the expected period and shows the highest value (6.2 μm, see Figure 3b). Then, the period decreases up to 5.2 μm at 5 mm from the center (curvature angle of 18.9°), which

Figure 2. Topography images and profile sections of the structured sphere at different measuring positions using a) standard process strategy and using b) optimized strategy.
corresponds to a reduction of only 17%. A comparable characteristic can also be seen in the structure depth. The structure depth decreases less than 20% when analyzing the whole structure area. For example, the structure depth drops from $1.30 \pm 0.06 \mu m$ in the center to $1.08 \pm 0.08 \mu m$ at a distance of 5 mm from the center. Thus, it can be shown that the hexapod-based strategy ensures that the laser spot size (containing the interference pattern) and thus the laser fluence is kept almost constant as a result of the vertical beam entry. These constant conditions lead to a uniform material processing and thus to homogeneous structures. The slight reduction in structure period and structure depth (<20%) can be attributed to specimen misalignment as mentioned earlier and can be reduced through more accurate positioning of the sphere. This applies in particular to microstructuring technologies, where small deviations can lead to significant differences in the final result.\[21\]

In summary, a new strategy was developed to permit the fabrication of more homogenous structures using DLIP on 3D surfaces. It was shown that the accuracy of the spatial period and the structure height over the curved surface was significantly improved. In fact, it could be demonstrated that the deviation of the structure depth was 63% when using the standard strategy and only 17% when using the optimized strategy. A similar behavior was observed for the structure period. Consequently, the optimized strategy using a hexapod provides an excellent opportunity in all applications, where surface functionalization of 3D parts is required.

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.
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Research data are not shared.

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