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FT-Based Device for Characterization of Laser-textured Periodic Surface Topographies

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Abstract

Laser-induced periodic surface structures (LIPSS) and direct laser interference patterning (DLIP) offer scalable approaches for functionalizing surfaces with sub-micron precision. Ensuring process reliability and reproducibility in such applications requires robust, real-time monitoring solutions. In this study, a compact diffraction-based optical system is employed to characterize surface topographies indirectly by analyzing the intensity distribution of the resulting diffraction patterns. LIPSS, as well as dot-like periodic structures generated by DLIP, are fabricated on stainless steel using picosecond pulsed lasers at wavelengths of 1064 nm and 532 nm, respectively. By correlating the intensities of the 0th and ±1st diffraction orders with structure depth, the system enables accurate estimation of the average depth and spatial period of the surface features, with mean errors below 15% and 2%, respectively. This method provides a rapid, non-destructive, and industrially compatible monitoring solution for quality assurance in laser surface texturing processes.

Keywords: Laser-induced periodic surface structures (LIPSS); Direct laser interference patterning (DLIP); Scatterometry; Process monitoring.

1. Introduction

Nature-inspired surface functionalities, such as self-cleaning, anti-reflectivity, and enhanced wettability, can be replicated by fabricating micro- and nanostructures on solid materials (Schroeder et al., 2018). Among the most versatile and scalable technologies to produce such textures, laser-based surface structuring techniques stand out due to their high precision, flexibility, and throughput (Vorobyev and Guo, 2012). In particular, methods like Direct Laser Interference Patterning (DLIP) and the formation of Laser-Induced Periodic Surface Structures (LIPSS) have demonstrated exceptional capabilities in generating periodic features across a wide range of materials (Bonse and Gräf, 2021; Lasagni et al., 2017).

To enable industrial adoption of these technologies, robust and rapid process monitoring tools are required to ensure reproducibility and maintain surface quality. Conventional characterization methods, such as scanning electron microscopy (SEM), atomic force microscopy (AFM), and confocal microscopy (CM), although accurate, are inherently ex-situ and too slow for in-line industrial applications (ISO 25178-6, 2010).

In this context, scatterometry-based techniques have emerged as a promising solution for in-line monitoring of laser-induced periodic topographies. These optical approaches rely on the analysis of diffraction patterns resulting from coherent light interacting with the structured surface. By correlating the intensity and distribution of the diffraction orders with the surface geometry, key parameters such as structure depth and spatial period can be inferred non-destructively and with high sensitivity (Schröder et al., 2022, 2023).

The present work combines recent developments in scatterometry-based monitoring systems applied to both LIPSS and DLIP-fabricated topographies. Compact optical setups using low-power lasers and CCD cameras are deployed to analyze dot-like and line-like periodic structures on stainless steel surfaces. By evaluating the 0th and ±1st diffraction orders, and calibrating them against reference measurements from CM and SEM, the proposed methods enable the extraction of topographical information with relative errors below 15% for the structure depth, as well as lower than 2% for the spatial period. This integrated strategy demonstrates the feasibility of real-time, in-line surface monitoring for advanced laser texturing applications.

2. Materials and methods

2.1. Substrates and Preparation

All structuring experiments were performed on electropolished stainless-steel AISI 304 substrates with a thickness of 0.7 mm. The mean surface roughness of the samples prior to laser processing was 52 nm. No additional cleaning steps were applied beyond polishing.

2.2. Laser Surface Patterning

Two laser-based structuring strategies were employed for periodic structure formation: DLIP and Direct Laser Writing (DLW) for LIPSS formation:

- **For the fabrication of LIPSS**, a picosecond laser system (EdgeWave PX200, 1064 nm wavelength, 10 ps pulse duration, 10 kHz repetition rate) was employed. The laser beam was focused to a spot diameter of 77 µm and scanned over 5 × 5 mm² areas following a meander-like pattern. The hatch distance was varied from 60 to 120 µm, while the pulse-to-pulse spacing ranged from 10 to 50 µm. All structures were processed at a constant fluence of 3.8 J/cm².
- **In the DLIP experiments**, periodic dot-like structures were produced using a four-beam interference setup driven by a 70 ps pulsed Nd:YAG laser (neoMOS, 532 nm, NeoLase GmbH). Spatial periods of 1.7, 2.6, and 5.3 µm were achieved by varying the interference angle. Pulse energies up to 26.5 µJ and repetition rates of 1 kHz were used, with the number of pulses per spot (N_p) ranging from 1 to 5. The laser beam was scanned over the sample with zero overlap between spots using a motorized stage.

2.3. Diffraction-Based Optical Monitoring

The structured surfaces were characterized ex-situ using a custom-built optical scatterometry setup composed of two coaxially integrated subsystems: an illumination module (top part of the setup) and a detection module (bottom part of the setup) as shown in Fig. 1. In the illumination path, light from a 0.9 mW diode laser (λ = 532 nm) is shaped by a lens assembly to provide uniform illumination over a defined region of the structured surface. The detection path performs an optical Fourier transform of the illuminated area, projecting the resulting diffraction pattern onto the sensor of a CCD camera (IDS UI-5240CP-M-GL). Polarizers positioned in both the illumination and detection arms enable controlled modulation of the light intensity reaching the sensor, thereby minimizing pixel saturation and enhancing measurement contrast. To eliminate background noise and parasitic reflections from the optical system, a reference image acquired without a sample was subtracted from each captured diffraction pattern.

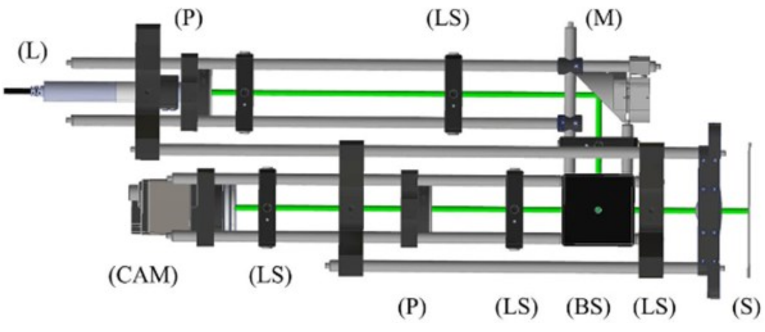

Figure 1. Schematic representation of the diffraction-based monitoring system, highlighting the main optical components: laser source (L), camera (CAM), lens system (LS), polarizers (P), mirrors (M), beam splitter (BS), and the stainless steel sample (S). Modified from Schröder et al., 2023 under Creative Commons Attribution 4.0 International License.

Image analysis was performed using a custom-developed script that identified and quantified the diffraction intensities in the recorded patterns. A fixed grayscale threshold was applied consistently to count the number of pixels exceeding this value within each diffraction order. Five positions were analyzed per structured field, and the results were averaged to improve reliability. The spatial period was calculated from the distance between the 0th and ±1st diffraction orders using calibration samples with known periodicities.

2.4. Topographical Characterization

For validation, the surface topographies were analyzed using a confocal microscope (Sensofar S Neox), having lateral and vertical resolutions of 140 nm and 1 nm, respectively. Scanning electron microscopy (ZEISS Supra 40VP / Sigma 300) was also used, specially from the characterization of the LIPSS features. Confocal measurements were performed on stitched images from six subfields per area, while SEM imaging provided morphological validation of the produced structures.

3. Results

To demonstrate the differences in the acquired diffraction patterns resulting from distinct surface topographies, representative examples of DLIP and LIPSS structures fabricated during experiments and their corresponding diffraction patterns are presented below.

The SEM micrograph of the representative example of a DLIP-structured surface is shown in Fig. 1a, displaying the morphology of a dot-like pattern produced by four-beam DLIP using three laser pulses. The resulting structure features shallow craters with raised rims and an average depth of 0.11 µm. The associated diffraction pattern, measured with the scatterometric optical device (Fig. 1b), exhibits a central 0th order and four symmetrically arranged 1st orders, characteristic of two-dimensional periodic structures with square symmetry.

A typical LIPSS-structured surface shown in Fig. 2a was produced using a hatch distance of 100 µm and a pulse-to-pulse distance of 10 µm using a single focused laser beam. The surface displays line-like features with an average depth of ~48 nm. Two types of LIPSS were observed: LSFL (800–1000 nm period, perpendicular to polarization) and HSFL (300–500 nm, parallel). Only LSFL were evaluated, as HSFL diffraction orders lay outside the detection range of the measurement system. The corresponding diffraction pattern for the LSFL structure (Fig. 2b) shows a central round 0th order and a pair of moon-like +1st and –1st orders, indicating LIPSS period and orientation variations according to Bonse et al., 2005.

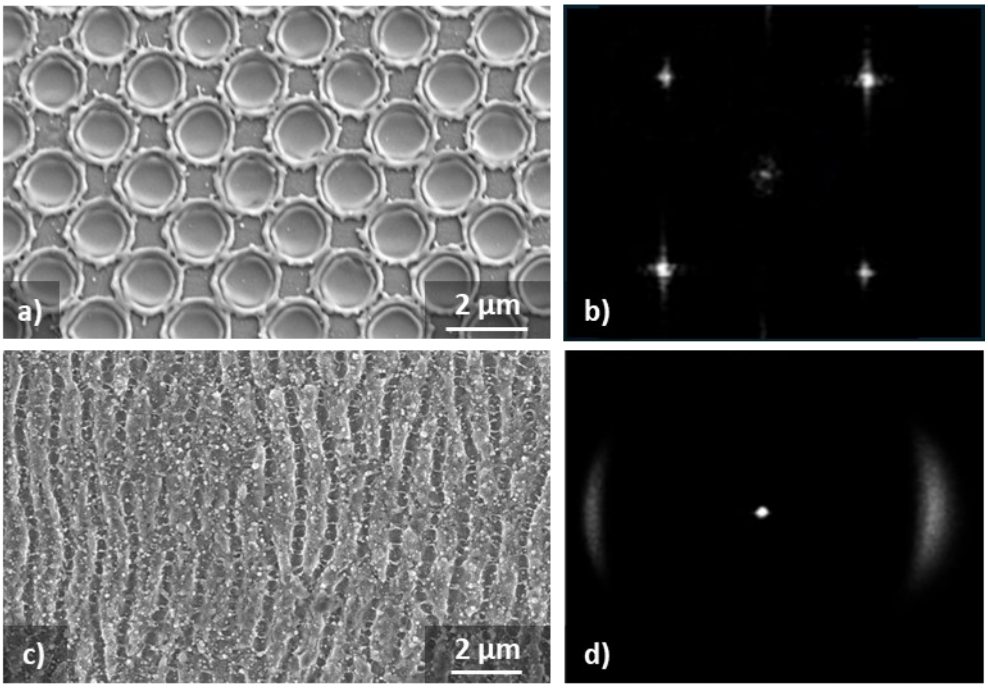

Figure 2. SEM images DLIP structures (a), fabricated with 3 laser pulses of 1.39 J/cm² laser fluence, and LIPSS structures (b), fabricated with 3.8 J/cm² laser fluence, 10 µm and 60 µm pulse and hatch distances, respectively. The measured corresponding diffraction images for DLIP (b) and LIPSS (d) structures are also shown. Modified from Schröder et al., 2022, 2023 under Creative Commons Attribution 4.0 International License.

To investigate the correlation between structure depth and diffraction behavior, process parameters were varied to modulate surface depth. As described in Section 2.2, for DLIP, pulse energy and number of pulses were adjusted, while for

LIPSS, hatch and pulse-to-pulse distance were modified. The surface topographies were measured using confocal microscopy, while the corresponding diffraction patterns were recorded using the scatterometric setup. From each diffraction image, the pixel area corresponding to the 0th and ±1st diffraction orders was extracted. These values, hereafter referred to as intensities, were then compared to the confocal measured structure depths. The results are summarized in Figure 3 for both DLIP and LIPSS.

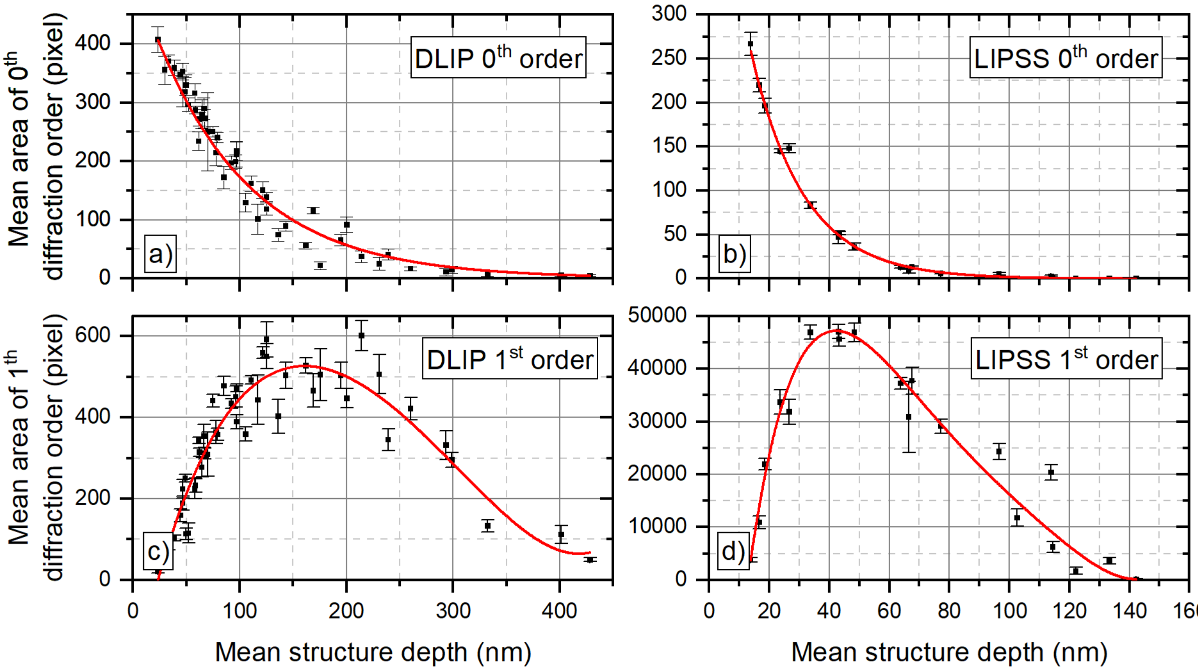

Figure 3. Mean area of the 0th (a, b) and +1st (c, d) diffraction orders as a function of the mean structure depth of the produced DLIP structures and LIPSS. The red curves represent the fit functions. Modified from Schröder et al., 2022, 2023 under Creative Commons Attribution 4.0 International License.

The graphs show a clear trend. The 0th order diffraction intensity decreases exponentially with increasing structure depth, becoming negligible above ~300 nm for DLIP and ~100 nm for LIPSS patterns. Conversely, the intensity of the 1st order initially rises with depth, reaching an intensity peak near 150 nm for DLIP and 40–50 nm for LIPSS, before declining almost linearly and vanishing around 400 nm and 140 nm, respectively. These trends align with the expected behavior for sinusoidal phase gratings (Harvey and Pfisterer, 2019). Fitting the data with an exponential function (0th order) and a 5th-order polynomial (1st order) showed strong agreement, supporting the use of this method for reliable, real-time, and non-contact estimation of structure depth in laser microstructuring. More detailed information, including depth dependence on structure parameters and the analysis of DLIP patterns with different periodicities, can be found in the original publications by Schröder et al., 2022 and 2023.

4. Conclusions

This work demonstrated the feasibility of using a scatterometry-based diffraction measurement system to monitor laser-induced periodic surface structures (LIPSS and DLIP) on stainless steel. By analyzing the 0th and ±1st diffraction orders, key topographical features such as structure depth and spatial period were reliably extracted with relative errors below 15% and 2%, respectively. The method proved applicable across different structure geometries, from line-like LSFL to dot-like DLIP patterns, and correlated well with conventional microscopy techniques. Owing to its compact, non-destructive, and cost-efficient design, the system shows strong potential for integration into industrial laser structuring platforms for real-time quality control and process optimization.

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