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Monitoring Direct Laser Interference Patterning of metallic substrates using an infrared camera system

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Abstract

Direct Laser Interference Patterning (DLIP) is a technique that enables the fabrication of homogeneous microstructures in the micrometer and sub-micrometer range. Typically, the topography of these structures is evaluated ex-situ, using methods such as confocal microscopy or white light interferometry. However, these techniques are not suitable for real-time process observation due to their long measurement time. In this study, an Infrared camera system is used to explore the correlation between the captured average temperature during DLIP treatment and topographical parameters in real-time. The results show a linear relationship between the applied laser fluence (0.7 to 4.9 J/cm²) and the measured average temperature, as well as significant changes in surface roughness, skewness, and kurtosis within this fluence range. These findings suggest that the presented method could be used for in-situ indirect monitoring of topography during DLIP treatment, enabling quick identification of process fluctuations.

Keywords: Direct Laser Interference Patterning; in-line monitoring; surface topography; infrared camera

1. Introduction

Direct laser interference patterning (DLIP) is an established method for structuring the surface of various materials, such polymers, metals and ceramics. It creates repetitive, periodic surface patterns with feature sizes up to the sub-micrometer range. This approach can be used to improve surfaces properties such as

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friction, wetting, or contact resistance by specifically adapting the surface structure. In DLIP, a periodic modulation of the laser intensity is produced by interfering two or more coherent laser beams. Additionally, controlling the process parameters, such as pulse-to-pulse overlap, laser fluence and repetition rate, enables the production of homogeneous, large-area textured surfaces as reported by several authors [Rosenkranz et al., 2016; Zabila et al., 2009; Aguilar-Morales et al., 2018].

Moreover, like every laser-based method, this process can be fully automated, being real-time monitoring an essential aspect for automation, enabling the determination of the process stability and/or providing indirect information about the produced surface textures. This ensures process stability, repeatability, and the elimination of subsequent quality control, which is time-consuming.

Several measurement methods have been implemented to monitor a laser-based process, which can be categorized into optical and acoustic methods, as shown for instance by Purtonen et al., 2014. In the case of DLIP, Steege et al., 2021 utilized a condenser microphone positioned close to the process zone to detect the acoustic emission and found a correlation between the sound level and the working distance. However, no correlation was observed between the sound level and the quality of the fabricated structures. Schröder et al., 2022 followed a different approach for in-line monitoring of a DLIP process. They used a diffraction-based measurement system to determine the intensity of the diffraction orders resulting from illuminating the structured area with a laser source. A correlation between the structure depth and the intensity of different diffraction orders was established, although this method can be implemented behind the process zone and thus provide information with a certain delay.

Another approach is to detect the emitted radiation intensity from the process zone. Pyrometers, calibrated cameras, or infrared camera systems are well-established systems used for laser surface applications like hardening or cladding [Seifert et al., 2006; Ali et al., 2022].

This study is dedicated to evaluate an inline monitoring process during DLIP using an IR camera system. Line-like periodic structures are produced on a steel plate at different laser fluence values (0.7 to 4.9 J/cm²). The characteristics of the produced topographies are analyzed using a confocal microscope and a scanning electron microscope, and potential correlations between the structural parameters and the measured temperatures are investigated.

2. Material and methods

Stainless steel plates (AISI 304) with a thickness of 0.8 mm were processed using a DLIP workstation (self-developed, TU Dresden, Germany), equipped with a xDLIP optics (SurFunction GmbH, Germany). The workstation includes an IR ns-laser (IS400-3-GH, Edgewave GmbH, Germany), having a pulse duration of 7 ns and was operated at a frequency f of 5 kHz. The laser source provided pulse energies of up to 40 mJ and the irradiated area by the two-beam configuration was about 6 mm x 50 µm. Each structuring experiment produced 40 mm long tracks (6 mm x 40 mm) with a separation distance d between the laser spots of 50 µm. The angle of the interfering beams Θ was set to 5.7°, resulting in a 6.0 µm spatial period Λ.

To determine the temperature during the process, an IR-camera (PYROVIEW 380L, DIAS Infrared GmbH, Germany) was positioned at a lateral angle of 60°. The camera consists of a microbolometer array of 384 x 288 pixels and can detect temperatures between - 20 °C and 500 °C. It has a sensitivity in the spectral range of 8 to 14 µm and a resolution of 0.4 mm per pixel and a measuring frequency of up to 50 Hz. Prior to the structuring treatment, the process path was inspected to ensure that there were no emitters in the environment that could reflect on the sample surface and provide false temperature measurements.

The properties of the textured surfaces were subsequently analyzed using both a confocal microscope (Sensofar S Neox 3D Surface Profiler, Spain) and a scanning electron microscope (SEM, ZEISS Supra 40VP, Germany).

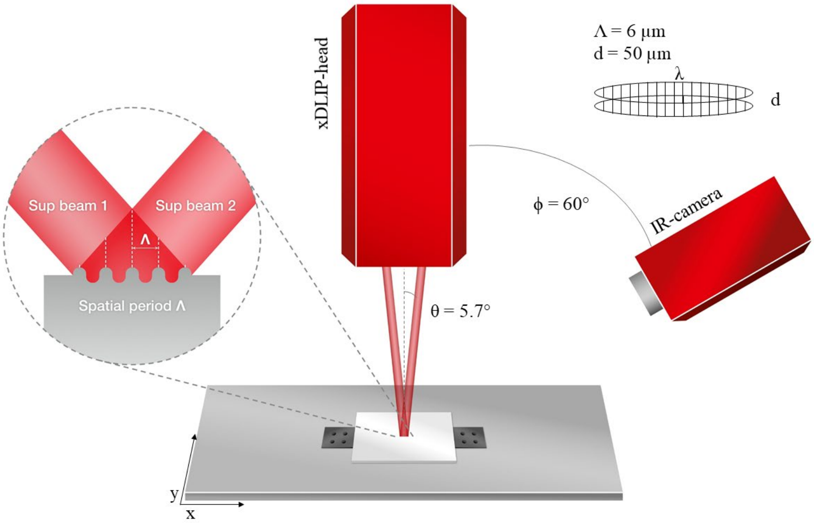

Fig. 1. Schematic illustration of the experimental set-up (modified from Olawsky et al., 2023).

3. Results and discussion

Line-like DLIP structures with a spatial period *Λ* of 6.0 µm were created on a stainless steel plate by varying the laser fluence *Φ* between 0.7 J/cm² and 4.9 J/cm². Exemplary images of confocal and SEM micrographs at fluence levels of 0.7 J/cm² (a, d), 2.5 J/cm² (b, e), and 4.9 J/cm² (c, f) are presented in Fig. 2. The average structure depth indicated in each figure. Three distinct structured regions resulting from three individual pulses, separated by a distance of 50 µm, can be observed in all images. Additionally, an increase in laser fluence led to slightly more flattened surfaces with lower structure depths due to the significant amount of molten phase produced within the given range, similarly to the findings reported by Zwahr et al., 2017.

During the DLIP process, the infrared camera system was used to detect the average temperature of the process zone. Exemplary thermal images of the DLIP process at different positions and laser fluences are shown in Fig. 3. No thermal signal was detected for laser fluence levels equal to or lower than 0.7 J/cm² (Fig. 3a-c). At this fluence value, the material could be heated above the melting point at the interference maxima positions and forming the periodic structure. However, due to the integration of temperature over a large area and time, no significant increase in the average temperature could be observed.

As the laser fluence increased (and thus the energy input at the substrate), a thermal signal from the process area could be detected, as shown in Fig. 3d-f. In this case, the elongated laser spot was visible in the center of the thermal image, with a recognizable tail below it that was associated with previously processed areas.

Fig. 4 shows the maximum detected average temperature as a function of process position for different laser fluences. From the image, it can be seen that the average temperature did not show any significant variation within the process. The results also show that thermal IR signal could be detected from fluence values over 1.0 J/cm² as well as a significant increase in the IR signal were visible at higher laser fluences (> ~ 2 J/cm²), resulting in a measured maximum average temperature of 52 °C at a laser fluence value of 4.9 J/cm².

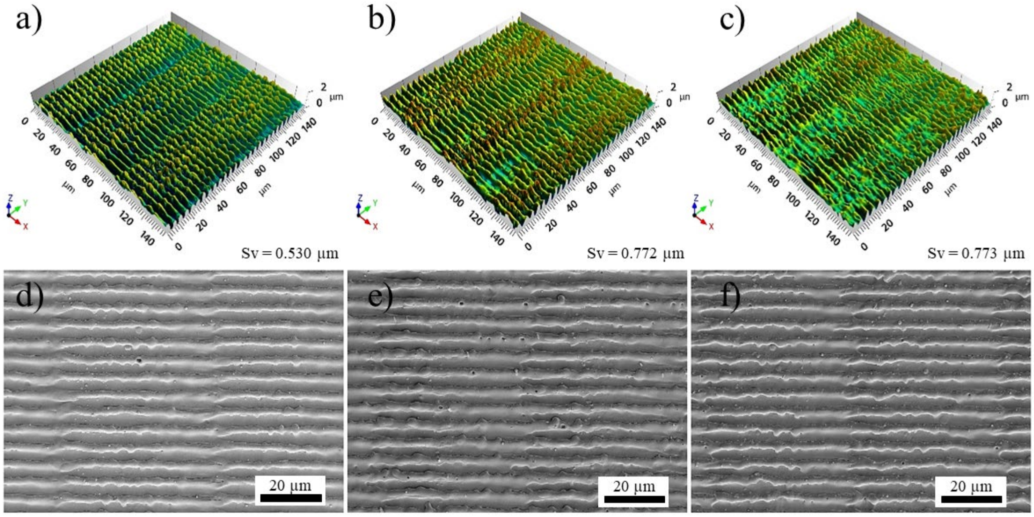

Fig. 2. Confocal microscope measurements (a-c) and corresponding SEM images (d-f) of the DLIP structured stainless steel plate; *f* = 5 kHz, *Λ* = 6.0 µm; (a, d): *Φ* = 0.7 J/cm²; (b, e): *Φ* = 2.5 J/cm²; (c, f): *Φ* = 4.9 J/cm² (modified from Olawsky et al., 2023).

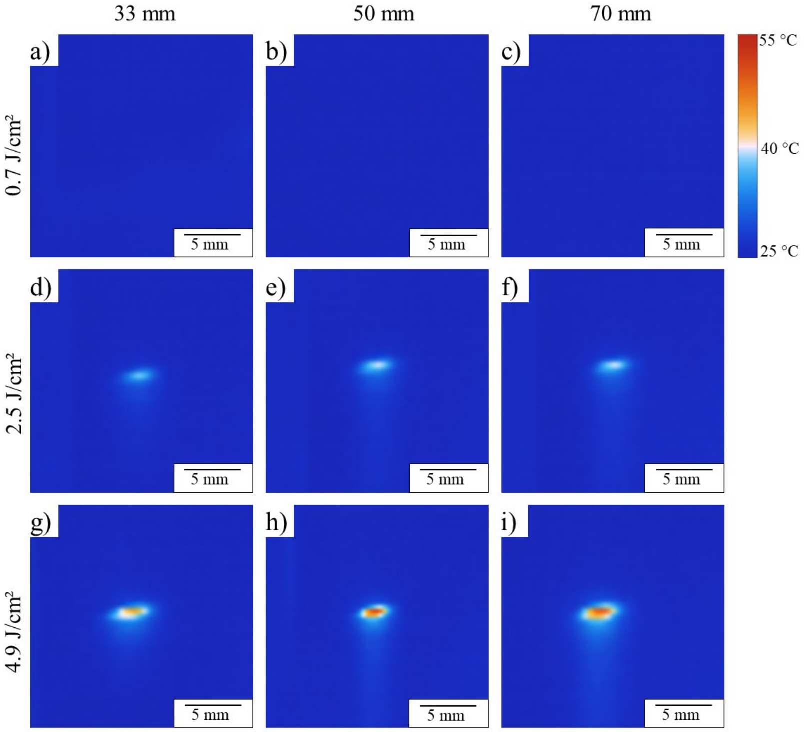

Fig. 3. Thermal images for the position of 33 mm (a, d, g), 50 mm (b, e, h) and 70 mm (c, f, i) at (a-c) *Φ* = 0.7 J/cm², (d-f) *Φ* = 2.5 J/cm² and (g-i) *Φ* = 4.9 J/cm² (modified from Olawsky et al., 2023).

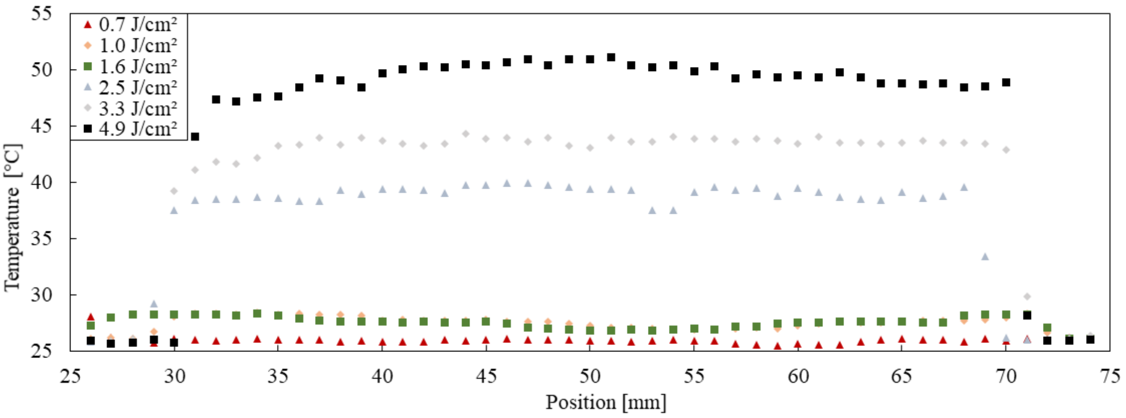

Fig. 4. Maximum measured temperature at laser fluences of Φ = 0.7 J/cm² to 4.9 J/cm² (Olawsky et al., 2023).

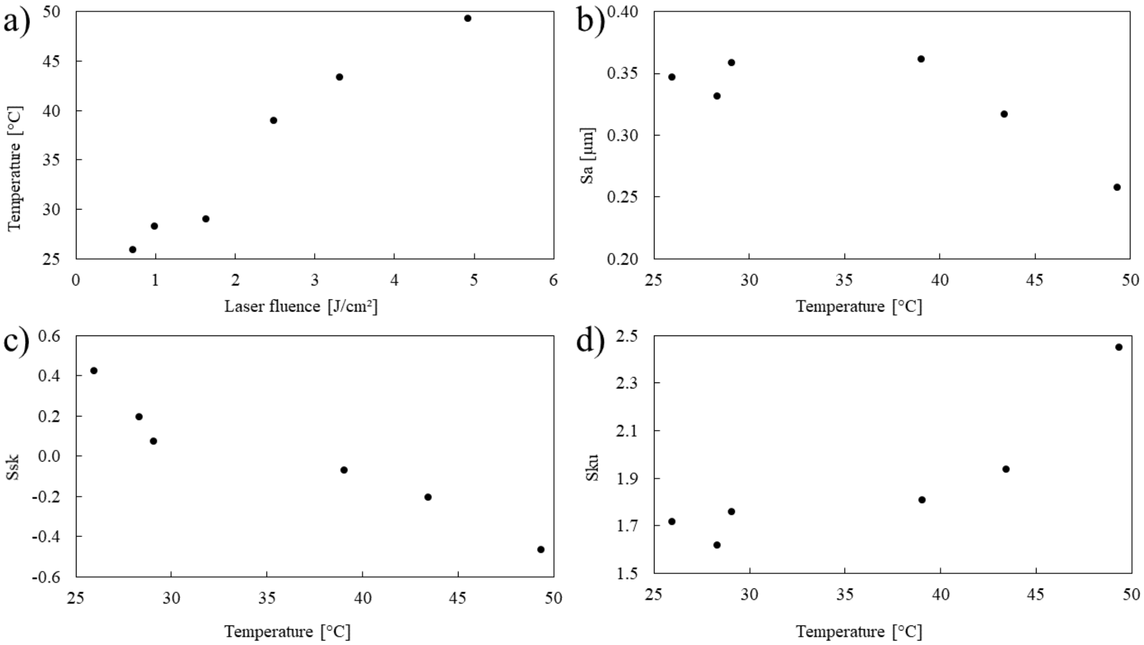

Fig. 5. Average measured temperature depending on the laser fluence (a); *Sa* (b), *Ssk* (c) and *Sku* (d) depending on the temperature.

Finally, the measured average temperatures were compared to different topographical parameters to determine possible relationships. Firstly, in Fig. 5a a linear correlation between the applied laser fluence and the recorded temperature is observed. From Fig. 5b to 5d, the relationships between the mean arithmetic height *Sa*, skewness *Ssk*, and kurtosis *Sku* are presented as function of the measured temperature. It can be observed that as the recorded average temperature increases, both the *Ssk* and *Sa* values decrease due to the excessive melting produced (Fig. 5b and 5c, respectively). This can be explained by the fact that in the fluence range where a change in the average temperature is observed, the structure depth also decreases due to excessive melting, as reported by Bieda, 2016. On the other hand, the *Sku* value increases with increasing temperatures (Fig. 5d) since flattened peaks and valleys are obtained. However, it shows that the information about the measured temperature is not sufficient to provide a precise indication of the quality of the entire surface.

4. Conclusion

DLIP structures with a spatial period of 6.0 µm were produced by utilizing various laser fluences with a pulsed ns laser source. To measure the process emission in real-time, an infrared imaging camera was used, being sensitive in the range of 8 to 14 µm. The characteristics of the topography were then analysed through the use of confocal and scanning electron microscopes. From this analysis, several conclusions can be drawn. Firstly, a linear correlation between the applied laser fluence and the average measured temperature could be established, with the temperature of the process area rising up to approximately 52 °C. Additionally, at fluence levels below 0.7 J/cm², the thermal signal was undetectable due to the low energy input and sensitivity of the infrared camera. Significant changes in the surface roughness, skewness and kurtosis were also observed within the range of applied fluences, which could be linked to specific process average temperatures. Overall, this approach can be used to detect variations in produced topographies due to process fluctuations in real-time. Future research will focus on determining the influence of other process parameters, such as repetition rate and pulse duration.

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