

Article

Effect of Laser Scanning Parameters on Topography and Morphology of Femtosecond Laser-Structured Hot-Work Tool Steel Surfaces

Robert Thomas ^{1,*}, Hermann Seitz ^{1,2}  and Georg Schnell ¹ 

¹ Microfluidics, Faculty of Mechanical Engineering and Marine Technology, University of Rostock, Justus-von-Liebig Weg 6, 18059 Rostock, Germany; hermann.seitz@uni-rostock.de (H.S.); georg.schnell@uni-rostock.de (G.S.)

² Department Life, Light & Matter, University of Rostock, Albert-Einstein-Str. 25, 18059 Rostock, Germany

* Correspondence: robert.thomas@uni-rostock.de

Abstract

In mechanical engineering, interest in reliable and practicable technologies for nano- and microstructuring of tool surfaces is increasing. Femtosecond laser structuring offers a promising approach that combines high processing speeds with high precision. However, a knowledge gap remains regarding the optimal process parameters for achieving specific surface patterns on hot-work tool steel substrates. The current study aims to investigate the effects of laser scanning parameters on the formation of self-organized surface structures and the resulting topography and morphology. Therefore, samples were irradiated using a 300 fs laser with linearly polarized light ($\lambda = 1030$ nm). Scanning electron microscopy revealed four structure types: laser-induced periodic surface structures (LIPSSs), micrometric ripples, micro-crater structures, and pillared microstructures. The results for surface area and line roughness indicate that high laser pulse overlaps lower the strong ablation threshold more effectively than high scanning line overlaps, promoting the formation of pillared microstructures. For efficient ablation and increased surface roughness, higher pulse overlaps are therefore advantageous. In contrast, at low fluences, higher scanning line overlaps support a more homogeneous formation of nanostructures and reduce waviness.

Keywords: surface roughness; nano-/microstructures; surface texture; ablation threshold; laser pulse overlap; scanning line overlap; fluence; ultrashort laser pulse; isotropy; roughness homogeneity



Academic Editors: Shayan Dehghan and Mehdi Safari

Received: 18 December 2025

Revised: 3 February 2026

Accepted: 4 February 2026

Published: 7 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

The nano- and microstructuring of surfaces is becoming increasingly crucial in surface engineering and micromachining. In recent decades, ultrashort-pulse-laser technology, characterized by femtosecond or picosecond pulse durations, has expanded surface processing opportunities due to its capacity for high-precision material removal with minimal thermal damage to the non-ablated material [1–4]. The ability to process almost any material and to achieve high production speeds, along with the scalability of the process, has resulted in a wide range of applications [3,5,6]. This has led to a growing interest in surface texturing and the modification of topographical and morphological surface features after ultrashort laser pulse processing [7–9].

The surface structures created by laser pulses during single-beam processing can be divided into two types. Firstly, laser-inscribed structures, with dimensions corresponding

to the laser focus diameter in the micrometer range, can be achieved. They can be utilized in tribological, biomimetic, and medical applications, among others [10–13]. Secondly, self-organized structures can form within the laser spot as a result of light–material interactions and solidification phenomena [14–16]. The resulting topography and morphology of these self-organized structures arise from complex interactions between laser light, material properties [6,17], scanning strategy [6,18,19], and ambient conditions [20].

Several studies have investigated the applications and effects of laser-induced self-organized surface structures on wettability [21–26], friction reduction [27,28], and self-cleaning [29,30], among others. It has previously been observed that self-organized structures can also superimpose on hierarchical structures, exhibiting combined effects of significantly enhanced broadband absorption, superhydrophobicity, and self-cleaning [25]. For wettability applications, research in this area has shown that self-organized surface structures can have approximately the same droplet adhesion forces and sliding angles as the natural lotus leaf [31]. The potential and advantages of ultrashort-pulse-laser surface modification have also attracted significant interest in the field of tool engineering. A key area of application lies in the nano- and microstructuring of tool surfaces, particularly for the functionalization of injection molds and cutting tools [3,32,33].

For these purposes, hot-work tool steels are preferred due to their favorable combination of fundamental properties such as high hardness (yield strength), temper resistance, and ductility, as well as technological attributes including thermal-fatigue resistance, thermal-shock resistance, and wear resistance [34,35]. The application scope of hot-work tool steels further extends to tools for die casting, the extrusion of polymers and metals, hot pressing of copper alloys, and steel forging [34–37].

Across a wide range of engineering applications, self-organized surface structures offer substantial functional advantages in tool processing. For example, laser-structured metal surfaces in injection molds can enhance the wall-slip effect between the polymer melt and the mold surface, resulting in a notable reduction in cavity pressure and flow resistance during the injection process [3,9,38]. In the context of micro-injection molding, such surface structuring enables improved mold filling and facilitates the fabrication of smaller, more geometrically complex components [32,39]. Furthermore, self-organized surface structures can contribute to the self-cleaning of injection vents, preventing the accumulation of polymer residues and thereby increasing mold cycle life [29]. It is known that the mold's surface finish has a strong influence on frictional forces during the demolding phase. By modifying the tribological behavior at the polymer–tool interface, self-organized structures can effectively reduce demolding forces and improve part release [40]. Additionally, structured molds can also be used to functionalize the molded part directly during the molding process. This enables the tailoring of surface properties, such as enhanced hydrophobicity or anti-adhesive behavior, in plastic components [41,42].

However, to select appropriate surface structures tailored to specific functionalities, extensive parameter studies are required to understand the influence of laser process parameters on the resulting surface topography and morphology. When applying relatively high repetition rates, heat accumulation due to laser energy input that is not converted into material ablation by consecutive pulses also influences the resulting surface properties [18,43,44]. Currently, there is a notable lack of systematic investigations into the femtosecond laser processing of hot-work tool steel surfaces, particularly considering heat accumulation. Existing studies are limited to specific laser parameters and surface analyses, thereby offering only limited insights into the morphology and topography of self-organized structures relevant to tool processing.

This study addresses this gap through a detailed and comprehensive investigation of key femtosecond laser processing parameters and their influence on the surface topography

and morphology of the hot-working steel substrate X37CrMoV5-1. Comprehensive parameter matrices were created to systematically generate a wide range of surface structures, enabling a direct correlation between the laser process variables and the resulting morphological and topographical features. Surface characteristics are analyzed using scanning electron microscopy (SEM) in combination with quantitative roughness measurements by confocal laser scanning microscopy (CLSM). This parameter study establishes a fundamental understanding of self-organized structure formation on hot-work tool steel surfaces and reveals the influence of key laser parameters on topographical and morphological surface properties. The findings of this study provide a foundation for the tailoring of functional surfaces in tool engineering and related engineering applications.

2. Materials and Methods

2.1. Materials

The experimental investigations were performed using hot-work steel plates (X37CrMoV5-1, material designation 1.2343 according to ISO 4957 [45]), purchased from ABRAMS Industries GmbH & Co. KG (Osnabrück, Germany) with dimensions of 70 mm × 70 mm × 5 mm. The chemical composition of the material used complies with the requirements of ISO 4957 [45], which are shown in Table 1.

Table 1. Chemical composition of material used in this study, according to ISO 4957 [45].

Composition (%)	C	Si	Mn	Cr	Mo	V
X37CrMoV5-1	0.33–0.41	0.80–1.20	0.25–0.50	4.80–5.50	1.10–1.50	0.30–0.50

To ensure a similar, low initial roughness for all plates used, grinding and polishing were performed in 4 steps. The grinding process was carried out using a grinding and polishing machine of the type SAPHIR 520 (ATM Qness GmbH, Mammelzen, Germany) with silicon carbide abrasive sandpaper (grain sizes P600, P1200, P2500, and P4000) under pure water. After the grinding treatment, the surface was cleaned with ethanol (purity 99.9%) and dried with dust-free precision wipes and clean, dry compressed air. The grinding and polishing treatment resulted in an average arithmetical mean height of approximately $S_a = 0.026 \pm 0.005 \mu\text{m}$ and arithmetical mean height deviation in the x-direction of approximately $R_a = 0.018 \pm 0.004 \mu\text{m}$ and in the y-direction of approximately $R_a = 0.019 \pm 0.004 \mu\text{m}$, determined using the confocal laser scanning microscope described in Section 2.3.

2.2. Laser Treatment

A 300 fs UFFL_60_200_1030_SHG fiber laser (Active Fiber Systems GmbH, Jena, Germany) with a Yb-doped amorphous glass core was used for laser surface structuring. The laser system has an average power of $P = 60 \text{ W}$, whereby the pulse repetition rate can be varied from $f_{\text{REP}} = 50.3 \text{ kHz}$ to $f_{\text{REP}} = 18.6 \text{ MHz}$. The entire laser system is integrated into a Microgantry GU4 five-axis micromachining center (Kugler GmbH, Salem, Germany). The scanning system intelliSCAN III 14 (Scanlab GmbH, Puchheim, Germany) contains galvanic mirrors that deflect the Gaussian laser beam in the x- and y-directions. The laser produces linearly polarized light with a wavelength of 1030 nm. An f-theta lens with a focal length of $f = 163 \text{ mm}$ results in a theoretical circular focus diameter of $d_f = 31.6 \mu\text{m}$ at the $1/e^2$ intensity level, assuming a Gaussian beam profile. This theoretical circular focus diameter is used in all the following laser parameter calculations. During laser treatment, the ablated particles were removed by a local exhaust ventilation system close to the processing area. A schematic representation of the laser scanning configuration, along with the corresponding scanning parameters, is provided in Figure 1.

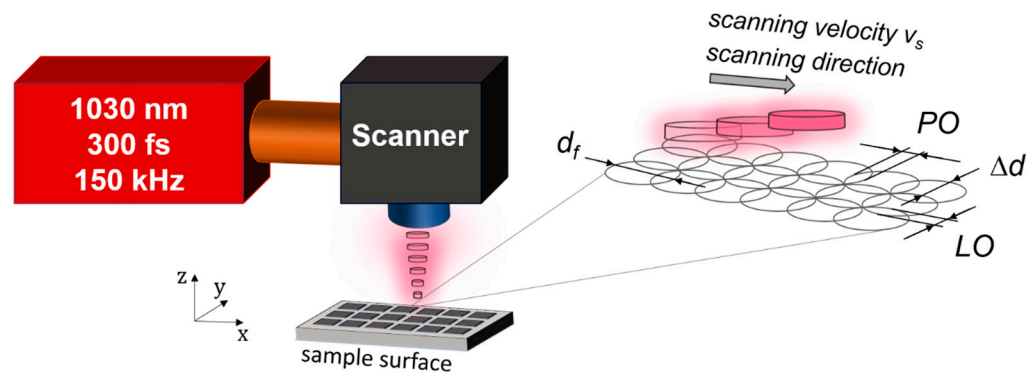


Figure 1. Schematic illustration of the laser setup and scanning system with the corresponding scanning parameters: theoretical circular focus diameter d_f , line distance of the scanning lines Δd , scanning velocity v_s , laser pulse overlap PO, as well as scanning line overlap LO.

As shown in Figure 1, the laser pulse overlap PO and the scanning line overlap LO can be used to develop area scanning strategies. The laser pulse overlap PO is calculated using the following equation

$$PO = \left(1 - \frac{v_s}{d_f \times f_{REP}} \right) \times 100\% \quad (1)$$

where v_s is the scanning velocity, d_f is the theoretical circular focus diameter, and f_{REP} the pulse repetition rate. The scanning line overlap LO is calculated using the following equation

$$LO = \left(1 - \frac{\Delta d}{d_f} \right) \times 100\% \quad (2)$$

where Δd is the scanning line distance, and d_f is the theoretical circular focus diameter, as in Equation (1). As there are different ways of calculating the fluence (peak fluence, average fluence, threshold fluence, etc.), and these are sometimes stated differently in various studies, the equation used to calculate the fluence ϕ is given below

$$\phi = \frac{E_P}{A} = \frac{E_P}{\frac{\pi}{4} \times d_F^2} \quad (3)$$

where E_P is the pulse energy, and A is the area of the laser spot diameter with the theoretical circular focus diameter d_f . The pulse energy E_P is calculated as follows

$$E_P = P_m \times T = \frac{P_m}{REP} \quad (4)$$

where P_m is the average power (average power of the laser over a defined period of time), T is the time interval between the different pulses, and REP is the pulse repetition rate. For the experiments carried out in this study, the wavelength λ , pulse duration τ , and pulse repetition rate f_{REP} were kept constant at specific values. These values are shown below in Table 2, in addition to the M^2 -factor (i.e., the beam quality) and the calculated theoretical circular focus diameter d_f .

Table 2. Laser process parameters, wavelength λ , pulse duration τ , and pulse repetition rate f_{REP} , were kept unchanged at specific values for this study.

Laser Process Parameter	Symbol	Unit	Value
Wavelength	λ	nm	1030 (IR)
Theoretical circular focus diameter ($1/e^2$ intensity level)	d_f	μm	31.6
Pulse duration	τ	fs	300
Frequency/Pulse repetition rate	f_{REP}	kHz	150
M^2 -factor (beam quality)	M^2	-	1.2

To investigate the influence of laser scanning parameters on the morphology and topography of femtosecond laser-structured hot-work tool steel surfaces in this study, specific scanning strategies were designed. For this purpose, important laser scanning parameters were varied, which will be addressed in more detail below.

The laser fluence is known to be one of the most crucial parameters in ultrashort pulse laser ablation and materials processing, and the resulting threshold fluence for the material depends on its thermal and dynamic properties [46]. For different tool steels, threshold fluences below $\phi = 1 \text{ J/cm}^2$ have been reported, and for multi-shot ablation (i.e., the number of pulses or overscans), it is possible that the fluences are below the single-shot threshold [46,47]. To map the entire range of structure formation, laser structuring experiments were conducted from a fluence close to the material's threshold fluence ($F_{\text{threshold}} = 0.53 \text{ J/cm}^2$, determined from single-pulse experiments) and increased stepwise, aiming to achieve nanostructures and significant microstructure formation at higher fluences. For each combination of laser pulse overlap (PO) and scanning line overlap (LO), the pulse energy was gradually increased from $3.9 \mu\text{J}$ to $133.9 \mu\text{J}$, resulting in a fluence of $\phi = 0.5 \text{ J/cm}^2$ to $\phi = 17 \text{ J/cm}^2$. To design area scanning strategies, the laser pulse overlap (PO) and the scanning line overlap (LO) were each varied from 40% to 90% in 10% increments. For the laser pulse overlap (PO), this resulted in a scanning velocity from $v_s = 2.85 \text{ m/s}$ to $v_s = 0.475 \text{ m/s}$, and for the scanning line overlap (LO), this resulted in a scanning line distance from $\Delta d = 19 \mu\text{m}$ to $\Delta d = 3 \mu\text{m}$. When the laser pulse overlap was varied, the scanning line overlap was fixed at 50% and vice versa. In addition to the irradiation wavelength used ($\lambda = 1030 \text{ nm}$) and the fluence values mentioned, the number of pulses or overscans (N) is among the key factors in surface processing using ultrashort laser pulses [48]. In this study, the number of overscans was kept constant at $N = 50$ overscans. The structured areas for every single parameter variation had a size of $7 \text{ mm} \times 9 \text{ mm}$. In Table 3 below, the laser scanning parameters listed are accompanied by their variation ranges.

Table 3. Laser scanning parameters and variations. Laser pulse overlap (PO) and scanning line overlap (LO) were varied for each pulse energy/fluence value.

Laser Scanning Parameter + Variations	Symbol	Unit	Values
Laser pulse overlap (at fix LO of 50%)	PO	-	40%; 50%; 60%; 70%; 80%; 90%
Scanning velocity	v_s	m/s	2.850; 2.375; 1.900; 1.425; 0.950; 0.475
Scanning line overlap (at fix PO of 50%)	LO	-	40%; 50%; 60%; 70%; 80%; 90%
Scanning line distance	Δd	μm	19; 16; 13; 10; 6; 3
Pulse energy	E_p	μJ	3.9; 11.8; 23.6; 39.3; 63.0; 86.6; 110.2; 133.9
Fluence	ϕ	J/cm^2	0.5; 1.5; 3.0; 5.0; 8.0; 11.0; 14.0; 17.0
Number of overscans	N	-	50

2.3. Surface Characterizations

A confocal laser scanning microscope (CLSM), LEXT OLS 4000 (Olympus, Hamburg, Germany), was used to characterize the surface and measure the elevation profiles (depth and width of the resulting pillars and profiles). For surface characterization, and to enhance the qualitative assessment of the results with quantitative data and enable more precise comparisons, the different area roughness parameters S_a , S_z , and S_q as well as the different line roughness parameters R_a , R_z , and R_q in both the x- and y-directions (see Figure 1) were measured, to cover all essential roughness parameters [40,49]. All roughness measurements were performed using the MPLAPON50XLEXT objective (Olympus, Hamburg, Germany) with a constant optical magnification ($50\times$) and a numerical aperture (NA) of 0.95, resulting in a total magnification of the system of $1080\times$. The scan area with the objective was thus $256\text{ }\mu\text{m} \times 256\text{ }\mu\text{m}$ with a resolution of 1024×1024 pixels for the resulting scans. Each measurement was repeated five times. For data calculation and analysis, OLS4000 software (Version 2.2.3, Olympus, Hamburg, Germany) was used. The metrological characteristics of confocal microscopy are defined in the international standard ISO 25178 [50]. For the various profile roughness measurements, all total measuring distances were longer than the objective-related scan length of $256\text{ }\mu\text{m}$. These were then created using image montage, whereby an overlap of the individual scan areas of 10% was selected to ensure an exact merging of the roughness profiles. Since the international standard ISO 25178 currently does not define specifications for total measuring distances, cut-off wavelengths, and low-pass filters for confocal measuring systems, we followed the guidelines provided in ISO 21920 and ISO 3274 [51,52]. Accordingly, the total measuring distances for profile roughness measurements were selected based on the previously determined R_a -values. The classifications of the cut-off wavelength λ_C , the low-pass filter λ_S , and the total measuring distance $l_{n,max}$, according to the respective R_a -values are shown below in Table 4.

Table 4. Classifications according to values of arithmetical mean height (R_a) for cut-off wavelength, low-pass filter, and total measuring distance.

Arithmetical Mean Height $R_a/\mu\text{m}$	Cut-Off Wavelength $\lambda_C/\mu\text{m}$	Low-Pass Filter $\lambda_S/\mu\text{m}$	Total Measuring Distance $l_{n,max}/\mu\text{m}$
$0.020 < R_a \leq 0.100$	250	2.5	585
$0.100 < R_a \leq 2.000$	800	2.5	1872
$2.000 < R_a \leq 10.00$	2500	8.0	5853

A total measurement area of $256\text{ }\mu\text{m} \times 256\text{ }\mu\text{m}$ was used for the surface roughness analysis, and a cut-off wavelength of $80\text{ }\mu\text{m}$ was applied in the software settings. No low-pass filter was used in this case, as such filters typically simulate the radius of the stylus in tactile measurements to adjust the roughness profile for comparability. However, since tactile measurement methods do not allow for areal surface roughness measurements, this adjustment was omitted. Table 5 below presents the surface roughness value classifications, corresponding cut-off wavelengths, and the total measuring area.

Table 5. Classifications according to values of arithmetical mean height (S_a) for cut-off wavelength, low-pass filter, and total measuring distance.

Arithmetical Mean Height $S_a/\mu\text{m}$	Cut-Off Wavelength $\lambda_C/\mu\text{m}$	Low-Pass Filter $\lambda_S/\mu\text{m}$	Total Measuring Area
$0.020 < S_a \leq 0.100$	80	-	$256\text{ }\mu\text{m} \times 256\text{ }\mu\text{m}$
$0.100 < S_a \leq 2.000$	80	-	$256\text{ }\mu\text{m} \times 256\text{ }\mu\text{m}$
$2.000 < S_a \leq 10.00$	80	-	$256\text{ }\mu\text{m} \times 256\text{ }\mu\text{m}$

To obtain high-resolution images and further evaluate the surface morphology after USPL processing, scanning electron microscopy (SEM) was performed using a SUPRA 25 field emission scanning electron microscope (Zeiss, Oberkochen, Germany).

2.4. Sa/Sq Ratio

Based on the values of area roughness and line roughness, further analyses were carried out to investigate the surface texture. To assess the distribution characteristics of the surface heights, the ratio of the arithmetical mean height S_a and the root mean square height S_q was employed as an evaluative parameter. For areal measurements, the arithmetical mean height S_a is defined as [50]:

$$S_a = \frac{1}{A} \iint_A |Z(x,y)| dx dy, \quad \text{with } A = x \times y. \quad (5)$$

In this formulation, the height values $Z(x,y)$ are considered linearly. In contrast, for the root mean square height S_q , the height values are incorporated quadratically [50]:

$$S_q = \sqrt{\frac{1}{A} \iint_A Z^2(x,y) dx dy}, \quad \text{with } A = x \times y. \quad (6)$$

The key distinction lies in the treatment of the height values. While S_a is a linear average of absolute deviations, S_q emphasizes larger deviations due to the squaring of height values before averaging. As a consequence, the larger the magnitude of isolated height deviations, the greater the discrepancy between the arithmetical mean height S_a and the root mean square height S_q . The S_a/S_q ratio can therefore be used as an indicator of the height distribution characteristics and as an indicator of the uniformity of the height values across the measured surface. The S_a/S_q ratio thus also provides additional information about the statistical distribution, as it is based on the statistical values S_a and S_q . Furthermore, Pawlus et al. found that the quotient of S_q and S_a is better suited to characterizing the ordinate distribution of the surface structure than S_{sk} (Skewness of height distribution) and S_{ku} (Kurtosis of height distribution) [53]. We use the reciprocal of this S_a/S_q ratio in this study as a unitless parameter, allowing for values between 0 and 1, which can also be expressed as a percentage between 0% and 100%. Additionally, we note the advantage that the S_a/S_q ratio can be calculated quickly and easily based on the standard area roughness parameters typically included in surface characterization. We have opted for a percentage representation for the S_a/S_q ratio. Values close to 100% suggest a relatively uniform distribution with few extreme peaks or valleys, i.e., a flat-peaked or plateau-like surface. In contrast, values significantly less than 100% indicate a higher degree of variability, with sharper peaks and deeper valleys, as typically observed on stochastically rough or irregular surfaces.

2.5. Surface Roughness Isotropy

Under certain parameter combinations, the laser structuring manufacturing process can produce highly anisotropic surface structures, resulting in highly anisotropic surface roughnesses that may be desirable or undesirable, depending on their characteristics and the application. For this reason, it is useful to consider structural isotropy quantitatively. In addition to more complex spatial parameters such as texture aspect ratio Str , texture direction Std , or dominant spatial wavelength S_{sw} [50], surface roughness isotropy can also be determined from the ratio of arithmetical mean height values measured orthogonally to each other. For practicality and simplicity, we calculated surface roughness isotropy based on orthogonal arithmetical mean height ratios. As with the S_a/S_q ratio, the arithmetical mean height values are already included in the standard roughness parameters typically

recorded in surface characterization. By definition, the arithmetical mean height Ra is the arithmetical mean of all ordinate values $Z(x)$ within a single measurement distance l [51]:

$$Ra = \frac{1}{l} \int_0^l |Z(x)| dx. \quad (7)$$

The arithmetical mean height was measured in two directions on the structural fields, in one direction parallel to the scanning direction ($Ra_{\parallel}$, in the x-direction, see Figure 1) and in the orthogonal direction perpendicular to the scanning direction ($Ra_{\perp}$, in the y-direction, see Figure 1). We have determined the surface roughness isotropy factor, such that all values are below 1. The closer the factor is to 1, the more isotropic the surface is. For the calculation, this means that for $Ra_{\parallel} > Ra_{\perp}$:

$$IF = Ra_{\perp} / Ra_{\parallel} \quad (8)$$

and for $Ra_{\parallel} < Ra_{\perp}$:

$$IF = Ra_{\parallel} / Ra_{\perp} \quad (9)$$

apply.

3. Results and Discussion

3.1. Surface Characterization of Femtosecond Laser-Structured Hot-Work Tool Steel Surfaces

All structuring experiments described in Section 2 were successfully performed, resulting in surfaces with different structural characteristics (topography and morphology). Figure 2 shows exemplary SEM images with the corresponding height elevation profiles and the arithmetical mean height Ra of three structure types, which were generated at a PO of 50% and a LO of 70% with increasing fluence from $\phi = 0.5 \text{ J/cm}^2$ to $\phi = 8 \text{ J/cm}^2$.

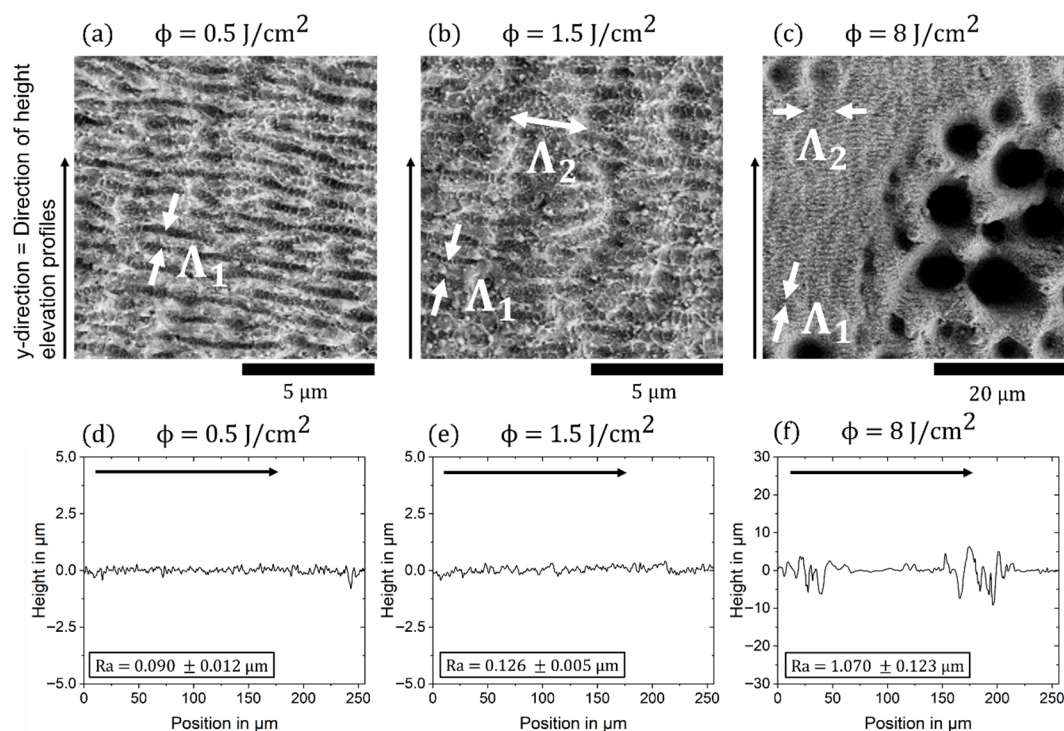


Figure 2. (a–c) Exemplary SEM images of the resulting nanostructures with a spatial period Λ_1 , micrometric ripples with a spatial period Λ_2 , and micro-crater structures, generated with a laser pulse overlap of PO = 50%, scanning line overlap of LO = 70%, number of overscans of N = 50, and fluence variation of $\phi = 0.5 \text{ J/cm}^2 - 8 \text{ J/cm}^2$. (d–f) Corresponding height elevation profiles in y-direction with values of the arithmetical mean height Ra . Note that different magnifications were selected to represent the typical structural features adequately.

The resulting structure sizes range from nanometers to micrometers. Figure 2a shows so-called (femtosecond-) laser-induced periodic surface structures (FLIPSSs or LIPSSs), hereinafter called LIPSSs, with a spatial period Λ_1 . At a fluence of $\phi = 1.5 \text{ J/cm}^2$, the LIPSSs are then superimposed with the so-called (sub-)micrometric ripple (MR), hereinafter called micrometric ripples, with a spatial period Λ_2 , as shown in Figure 2b. In Figure 2c, the first micro-crater structures can be seen, which become increasingly larger as the fluence is further increased [6,54]. In addition to the detailed SEM images shown in Figure 2a–c, height elevation profiles can be used to assess the topography. Height elevation profiles provide a precise, cross-sectional view of the surface topography, allowing for a detailed characterization of the surface roughness and its periodicity. For this purpose, the height elevation profiles in the y-direction associated with the exemplary selected structural areas from Figure 2a–c, as well as the corresponding values of the arithmetical mean height R_a , including the standard deviation, are shown below the corresponding SEM image in Figure 2d–f. For the first structure class of a LIPSS with a spatial period Λ_1 , the height elevation profile, as illustrated in Figure 2d, exhibits an arithmetical mean height of $R_a = 0.090 \pm 0.012 \text{ }\mu\text{m}$. The regular progression of the height elevation profile reflects the regularity of the LIPSS and its periodicity. For the second structure class of LIPSS with a spatial period Λ_1 superimposed with micrometric ripples with a spatial period Λ_2 from Figure 2b, the height elevation profile shown in Figure 2e results in the corresponding value for the arithmetical mean height of $R_a = 0.126 \pm 0.005 \text{ }\mu\text{m}$. The increased roughness compared to the pure LIPSS results from the superimposed micrometric ripples. The height elevation profile shown in Figure 2f, with the corresponding value for the arithmetical mean height of $R_a = 1.070 \pm 0.123 \text{ }\mu\text{m}$, results from the third structure class of micro-crater structures from Figure 2c. The height elevation profile reflects the locally increased occurrence of micro-crater structures. The values of the line roughness R_a , R_q , and R_z in the x- and y-directions of all structure areas considered in this study are attached in the Supplementary Material. The different types of micro-crater structures, ranging from smaller to larger, and the fourth structure class of pillared microstructures are shown in Figures 3 and 6. In ablation, depending on the laser fluence, there are basically two ablation regimes to be subdivided [55,56]. These are characterized by their respective threshold fluences and can therefore be distinguished from one another. The minimum fluence required for ablation is referred to as the gentle ablation fluence and represents the first threshold fluence [55,56]. This is mainly dependent on the irradiated material [54], the number of pulses per irradiated area [55,56], the laser wavelength [57], and the laser pulse duration [57]. If the laser fluence is very slightly above the threshold fluence, LIPSSs occur, as illustrated in Figure 2a [6]. There are basically two different types of LIPSSs, which can be distinguished mainly by their spatial orientation and size [6,17]. The so-called *low-spatial-frequency* LIPSSs (LSFL) are typically oriented perpendicular to the laser beam polarization on metals. The spatial period Λ_{LSFL} is usually equal to or slightly less than the irradiation wavelength: $\lambda/2 \leq \Lambda_{LSFL} \leq \lambda$ [17,48]. The so-called *high-spatial-frequency* LIPSSs (HSFL) are characterized by an orientation that is typically parallel to the laser beam polarization on metals and are characterized by a rather flatter surface structure [17]. Furthermore, their spatial period Λ_{HSFL} is usually in the range of less than half the irradiation wavelength: $\Lambda_{HSFL} < \lambda/2$ [17,48]. All LIPSSs observed in this study are LSFLs, as they are oriented perpendicular to the laser beam polarization and have a spatial period equal to or slightly less than the irradiation wavelength of $\lambda = 1030 \text{ nm}$. As already described, at a slightly increased fluence compared to the fluence of the LIPSS formation, the LIPSSs with a spatial period Λ_1 are superimposed with micrometric ripples with a spatial period Λ_2 , which are typically oriented perpendicular to the LIPSS orientation (parallel to the laser beam polarization) [55,58]. The mechanisms that lead to the formation of micrometric ripple

are still under debate. Different mechanisms are considered, such as heat accumulation and electromagnetic/scattering-enhanced absorption in ripple valleys, leading to selective ablation and initiation of micrometric grooves [19,43]. With a further slight increase in laser fluence, crater formation on surface inhomogeneities has been reported. Zuhlke et al. observed that craters are formed on MR or are generated by the redeposition of material [54]. The MRs can serve as precursor cells for craters [43,54]. When the next pulses follow, these surface inhomogeneities continue to grow due to two mechanisms: preferential valley ablation (PVA) and heat-driven phenomena (vapor–liquid–solid growth and melt flow). The PVA process is characterized by reflections on the side walls of the local cavity, which increases the local laser light fluence in the center of the crater, causing the crater to grow at an accelerated rate [54]. The growth mechanism of a crater can also be affected by heat accumulation, leading to vapor–liquid–solid growth and melt flow [43,54]. At a lower fluence, PVA dominates, whereas at higher fluences, vapor–liquid–solid growth and melt flow dominate [43]. Furthermore, Zuhlke et al. and Schnell et al. had shown that circular crater structures then form continuously [43,54]. These phenomena can be particularly seen in the height elevation profiles of the exemplary crater structure in Figure 2f, as well as in the corresponding SEM image in Figure 2c. The crater structures can be regarded as transitional structures between nano- and microstructures, as microstructures are created when the fluence, the level of overlap (LO or PO), or the number of overscans (or pulses) is increased [54,55]. The number of craters also rises with increasing fluence, a higher level of overlap (LO or PO), and the number of overscans (or pulses), which will be discussed in more detail later in this study [54,55]. If the accumulated fluence is further increased, the strong ablation fluence is exceeded, and microstructures are formed [55,56]. Two basic formation principles can be distinguished based on their structure formation processes. The structures grow either with their peaks above or below the original surface, depending on the parameters used and the ablation processes [54]. Suppose the crater structures or microstructures grow above the original height level of the surface due to melt flow and the rearrangement of ablated material during the structure formation process. In that case, they are referred to as *above-surface growth* mounds (ASG) [59]. If the structures form below the original height level due to ablation, refraction, and diffraction effects, this is referred to as *below-surface growth* mounds (BSG) [59]. Both microstructure types, ASG mounds and BSG mounds, are otherwise similar in their appearance and in their height-to-width aspect ratio [59]. These growth mechanisms lead to a merging of crater structures, which finally results in the formation of homogeneous formation of microstructures (Figures 3 and 6). These microstructures are particularly covered by nanostructures as a result of the Gaussian intensity profile of the laser beam and thus significantly lower fluence values at the periphery of the profile [19]. In our previous comprehensive study on Ti6Al4V [35], we demonstrated the formation of nanostructures and microstructures for a fixed PO of 90%, including chemical and crystallographic effects. While the structures reported here follow similar formation mechanisms, they exhibit distinct morphological and topographical characteristics, which are discussed below.

3.2. Effect of Laser Scanning Parameters on Texturing of Hot-Work Tool Steel Surfaces

To investigate the influence of laser pulse overlap and scanning line overlap on the topography and morphology of femtosecond laser-structured hot-work tool steel surfaces, various scanning strategies were employed to create the parameter matrices.

3.2.1. Effect of Scanning Line Overlap on Topography and Morphology

To investigate the effect of scanning line overlap, the overlap was varied between $LO = 40\%$ and $LO = 90\%$ with a fixed laser pulse overlap of $PO = 50\%$ and a constant

number of overscans of $N = 50$. The results of the parameter study of the structured hot-work tool steel (X37CrMoV5-1) surfaces with a fixed laser pulse overlap of $PO = 50\%$ and a varied scanning line overlap of $LO = 40\text{--}90\%$ are shown in Figure 3.

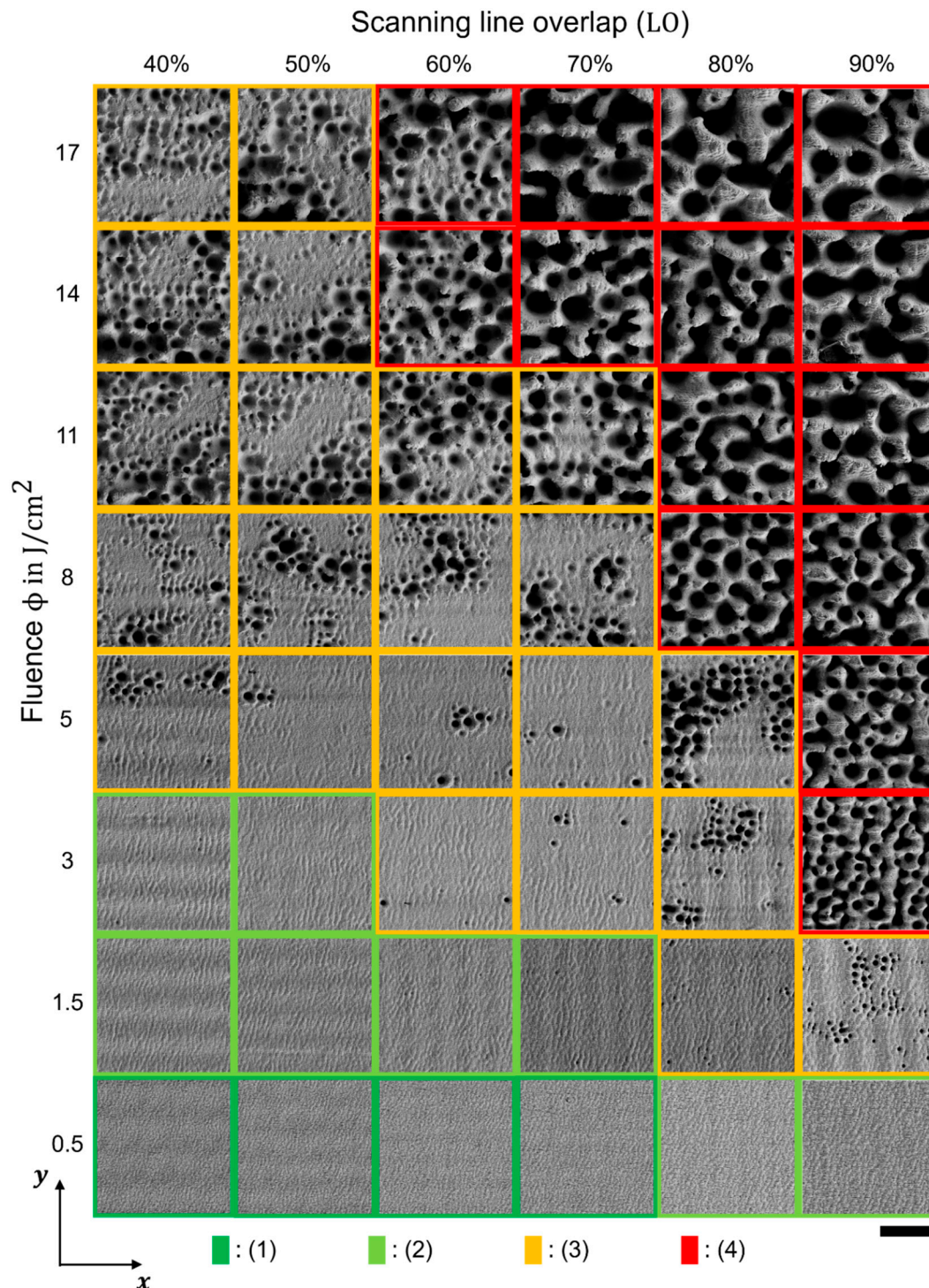


Figure 3. Matrix of SEM images of structured hot-work tool steel (X37CrMoV5-1) surfaces with a fixed laser pulse overlap of $PO = 50\%$, varied scanning line overlap of $LO = 40\text{--}90\%$, number of overscans of $N = 50$, and fluence variation of $\phi = 0.5\text{--}17 \text{ J}/\text{cm}^2$. The scanning lines ran parallel to the x-axis; the offset was changed accordingly in the y-direction. Structure classes: (1)—LIPSSs with a spatial period Λ_1 ; (2)—LIPSSs with a spatial period Λ_1 superimposed with micrometric ripples with a spatial period Λ_2 ; (3)—(smaller and larger) micro-crater structures; (4)—pillared microstructures. Scale bar at bottom right corner: $30 \mu\text{m}$.

Figure 3 shows the results in the form of a matrix of SEM images, with the rows corresponding to the specified fluence ($\phi = 0.5\text{--}17\text{ J/cm}^2$) and the columns to the specified scanning line overlap (LO = 40–90%). The x-axis indicates the scanning direction of the laser beam (and thus the direction for PO) for all individual SEM images, while the y-axis indicates the direction of the line feed for the LO. The parameters mentioned in the following description of the results are always related to a fixed laser pulse overlap (PO = 50%) and a fixed number of overscans (N = 50). Upon examining the structural results, these can be categorized into four basic types of structures, primarily based on their morphology and topography. For better clarity and comparability, the SEM images in the matrices of this study were framed in color according to the four different structure classes. As the first structure class, the LIPSSs with a spatial period Λ_1 are identified. As can be seen in Figure 3, the LIPSSs are formed in the laser scanning line overlap range of LO = 40% to LO = 70% at a fluence of $\phi = 0.5\text{ J/cm}^2$, just above the ablation threshold. LIPSSs with a spatial period Λ_1 superimposed with micrometric ripples with a spatial period Λ_2 were identified as the second structure class. These structures arise at a fluence of $\phi = 1.5\text{ J/cm}^2$ and a scanning line overlap of LO = 40% to LO = 70%, as well as at a fluence of $\phi = 3\text{ J/cm}^2$ and a scanning line overlap of LO = 40% to LO = 50%. The (smaller and larger) micro-crater structures were grouped into the third structure class. These structures are already formed from a fluence of $\phi = 1.5\text{ J/cm}^2$ and a high scanning line overlap of LO = 80% and LO = 90%. The higher the selected fluence, the sooner (with a lower scanning line overlap in each case) the smaller micro-crater structures are formed. At a fluence of $\phi = 3\text{ J/cm}^2$, these structures are already formed from a scanning line overlap of LO = 60% for all fluence ranges above this, and from a scanning line overlap of LO = 40% for all fluence ranges below this. The higher the fluence or the selected scanning line overlap, the larger the micro-crater structures that are created within a considered area of the structure class. Pillared microstructures were identified as the fourth structure class. These are already formed from a fluence of $\phi = 3\text{ J/cm}^2$, but require a high scanning line overlap of LO = 90%. From a fluence of $\phi = 8\text{ J/cm}^2$, the pillared microstructures are created from a scanning line overlap of LO = 80% and higher. And for a fluence of $\phi = 14\text{ J/cm}^2$, these pillared microstructures are already created from LO = 60% and higher. In general, it can be observed that a relatively high scanning line overlap is necessary to generate pillared microstructures. The higher the fluence, the more distinct the individual pillars of the microstructure are in their dimensions. Upon examining all the results, it can be stated that the scanning line overlap has a significant influence on structure formation, and that the structure characteristics can be specifically adjusted through variation. Figure 4 shows the surface roughness data Sa associated with the parameter matrix (see Figure 3) for further surface characterization. The surface roughness data is presented as a three-dimensional bar chart, which maps the respective roughness value to the corresponding matrix fields in the parameter matrix from Figure 3.

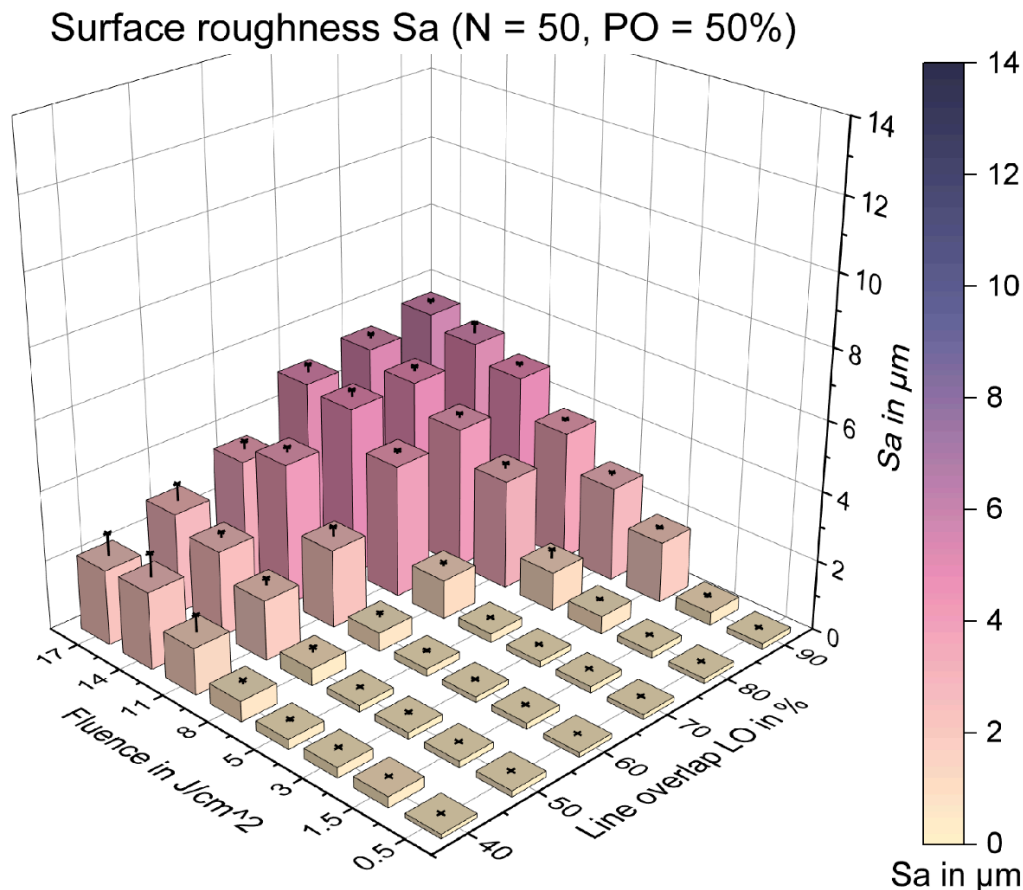


Figure 4. Matrix of surface roughness values Sa (arithmetical mean height) of structured hot-work tool steel (X37CrMoV5-1) surfaces with a fixed laser pulse overlap of $PO = 50\%$, varied scanning line overlap of $LO = 40\text{--}90\%$, number of overscans of $N = 50$, and fluence variation of $\phi = 0.5\text{--}17 J/cm^2$.

The bar chart shows very low roughness values in the lower fluence range, starting at $Sa = 0.123 \mu m \pm 0.004 \mu m$, with a relatively even distribution across the spectrum of scanning line overlap variations. These relatively low roughness values are due to the ablation induced in this region, which is in the gentle ablation phase. From the middle fluence range onwards, the roughness values then increase abruptly, initially starting in the higher scanning line overlap range. This sudden increase in roughness values is due to the strong ablation threshold being exceeded. In the higher fluence ranges, the roughness values (up to a maximum $Sa = 5.648 \mu m \pm 0.099 \mu m$) increase relatively evenly, in each case in the direction of increasing fluence and scanning line overlap. In this range, the ablation is entirely in the strong ablation phase. The roughness values for Sa , Sz , and Sq are given in tabular form in the Supplementary Material. The effect of scanning line overlap on the morphology and topography of self-organized, laser-induced surface structures is evident in the matrix in Figure 3, particularly for the microstructures at high fluence ranges. To illustrate the effect of scanning line overlap on the morphology and topography of self-organized, laser-induced surface structures even more precisely at low fluence values, detailed SEM images of selected areas were chosen from the matrices as examples. Figure 5 shows the detailed SEM images of the low fluence regime at $\phi = 0.5 J/cm^2$ and three exemplary selected levels of scanning line overlap ($LO = 40\%$, 60% , and 80%) at a fixed laser pulse overlap of $PO = 50\%$.

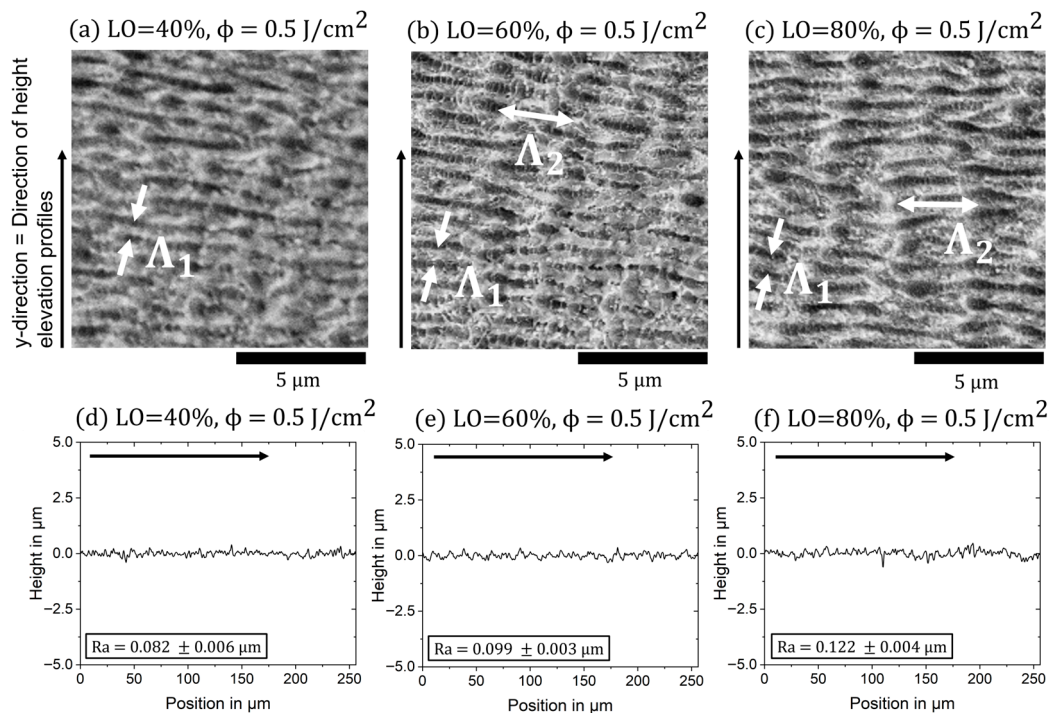


Figure 5. (a–c) Exemplary SEM images of the resulting LIPSSs with a spatial period Λ_1 and micrometric ripples with a spatial period Λ_2 , with varied scanning line overlap of $LO = 40\text{--}80\%$, fixed laser pulse overlap of $PO = 50\%$, number of overscans of $N = 50$, and the fluence of $\phi = 0.5 \text{ J/cm}^2$. (d–f) Corresponding height elevation profiles in the y-direction with values of the arithmetical mean height R_a .

For the scanning line overlap of $LO = 40\%$ (Figure 5a), the LIPSSs with a spatial period Λ_1 can be recognized as the predominant structure class. At a scanning line overlap of $LO = 60\%$ (Figure 5b), the first micrometric ripples begin to appear, but the structure class of LIPSSs with a spatial period Λ_1 still dominates. If the scanning line overlap is further increased to $LO = 80\%$ (Figure 5c), the LIPSSs with a spatial period Λ_1 superimposed with micrometric ripples with a spatial period Λ_2 are formed. In addition to the detailed SEM images, the corresponding height elevation profiles in the y-direction, as well as the corresponding values of the arithmetical mean height R_a , including the standard deviation, are shown for the evaluation of the topography and morphology. For the scanning line overlap of $LO = 40\%$, the height elevation profile in the y-direction shows a uniform roughness distribution with a recognizable periodicity in the profile line. If the scanning line overlap is increased, the roughness of the structures increases gradually. The periodicity of the profile lines in the y-direction changes with an increasing scanning line overlap in the low fluence regime towards an increasing wavelength (i.e., rougher structures, compare Figure 5d,e) and the superimposed ripple (see Figure 5f), caused by the resulting micrometric ripples superimposed on the LIPSSs. An increased scanning line overlap increases the amount of energy introduced into the material per unit area over the entire surface processing period. This results in a higher number of interactions between the laser light (i.e., the incident photons) and the material area, with otherwise constant individual pulse energy. With increased scanning line overlap, the higher number of photons affects the material surface over the time interval between individual line scans (here, in the x-direction). The longer the line scan takes (due to a low repetition rate or a long scanning line), the more time the material has to cool down before the following line scan. Furthermore, Raciukaitis et al. and Mannion et al. have demonstrated that the number of pulses per irradiated area affects ablation [60,61]. The results of this study are

consistent with these findings. An increased scanning line overlap results in a pronounced formation of microstructures on hot-work tool steel, consistent with our previous study on Ti6Al4V [19]. The results of the effects of scanning line overlap on topography and morphology are compared with the effects of laser pulse overlap on topography and morphology in the next section of this study.

3.2.2. Effect of Laser Pulse Overlap on Topography and Morphology

For the second sample, the laser pulse overlap was varied between $PO = 40\%$ and $PO = 90\%$ with a constant scanning line overlap of $LO = 50\%$ and a fixed number of overscans of $N = 50$. The results of the parameter study of the structured hot-work tool steel (X37CrMoV5-1) surfaces with a fixed scanning line overlap of $LO = 50\%$ and a varied laser pulse overlap from $PO = 40\%$ to $PO = 90\%$ are shown in Figure 6.

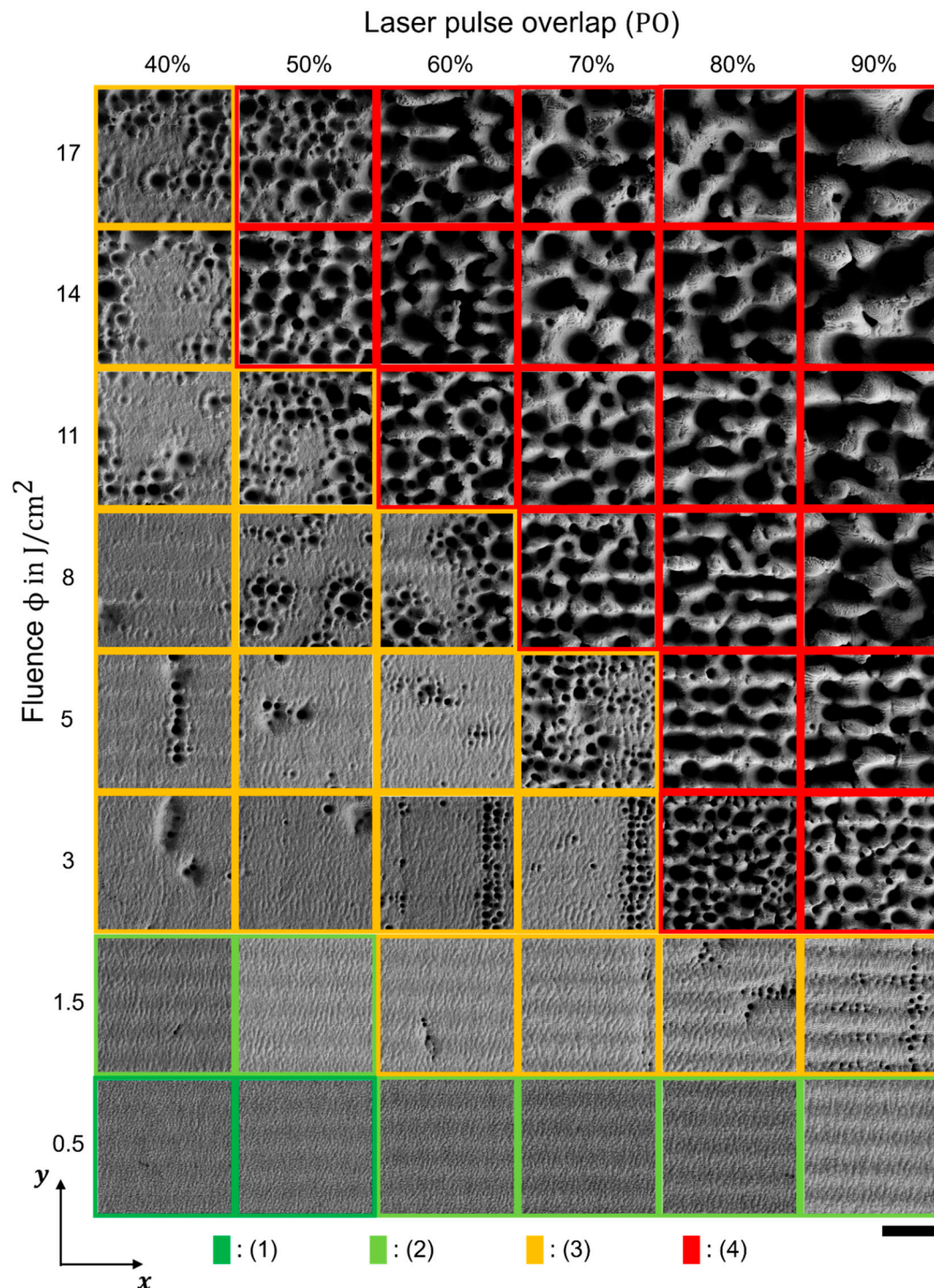


Figure 6. Matrix of SEM images of structured hot-work tool steel (X37CrMoV5-1) surfaces with a varied laser pulse overlap of $PO = 40\text{--}90\%$, fixed scanning line overlap of $LO = 50\%$, number of overscans of $N = 50$, and fluence variation of $\phi = 0.5\text{--}17\text{ J/cm}^2$. The x-axis indicates the scanning direction for the laser pulse overlap PO. Structure classes: (1)—LIPSSs with a spatial period Λ_1 ; (2)—LIPSSs with a spatial period Λ_1 superimposed with micrometric ripples with a spatial period Λ_2 ; (3)—(smaller and larger) micro-crater structures; (4)—pillared microstructures. Scale bar at bottom right corner: $30\text{ }\mu\text{m}$.

As with the first sample, the x-axis for all individual SEM images indicates the scanning direction of the laser beam (and thus the direction for PO), while the y-axis indicates the direction of line feed for LO. When observing the structural results, these can be divided

into four basic structure types according to their morphology and topography, in analogy to the variation in the LO. In this matrix, the SEM images were also framed in color according to the four different structure classes for better clarity and comparability. The LIPSSs with a spatial period Λ_1 are also characterized here as the first structure class. These form in the scanning line overlap range from $PO = 40\%$ to $PO = 50\%$ at a fluence of $\phi = 0.5 \text{ J/cm}^2$, just above the ablation threshold (see Figure 6). The LIPSSs with a spatial period Λ_1 superimposed with micrometric ripples with a spatial period Λ_2 were marked as the second structure class. These structures arise in the low fluence regime at a fluence of $\phi = 0.5 \text{ J/cm}^2$ and a laser pulse overlap of $PO = 60\%$ to $PO = 90\%$, as well as at a fluence of $\phi = 1.5 \text{ J/cm}^2$ and a laser pulse overlap of $PO = 40\%$ to $PO = 50\%$. The (smaller and larger) micro-crater structures were categorized as the third structure class. These structures are already formed from a fluence of $\phi = 1.5 \text{ J/cm}^2$ and a laser pulse overlap of $PO = 60\%$. In general, it can be observed that micro-crater structures initially form very locally at low PO or low fluence, and then the formation zones become more widely distributed at higher fluences or laser pulse overlaps. At a fluence of $\phi = 3 \text{ J/cm}^2$, these structures are already formed from a laser pulse overlap of $PO = 40\%$. The higher the fluence or the selected laser pulse overlap, the larger micro-crater structures are formed within the structure class. The pillared microstructures were identified as the fourth structure class. These are already created from a fluence of $\phi = 3 \text{ J/cm}^2$, for which a high laser pulse overlap of $PO = 80\%$ is necessary. From a fluence of $\phi = 8 \text{ J/cm}^2$, the pillared microstructures are created from a laser pulse overlap of $PO = 70\%$ and higher. The higher the selected fluence, the lower the PO can be set to generate pillared microstructures. Here, too, the higher the selected PO or fluence, the more pronounced the pillared microstructures are. Furthermore, it can be determined that the laser pulse overlap has a significant influence on structure formation, and this influence can be specifically adjusted by varying the laser pulse overlap. For further surface characterization, the surface roughness data S_a associated with the parameter matrix (see Figure 6) is shown in Figure 7.

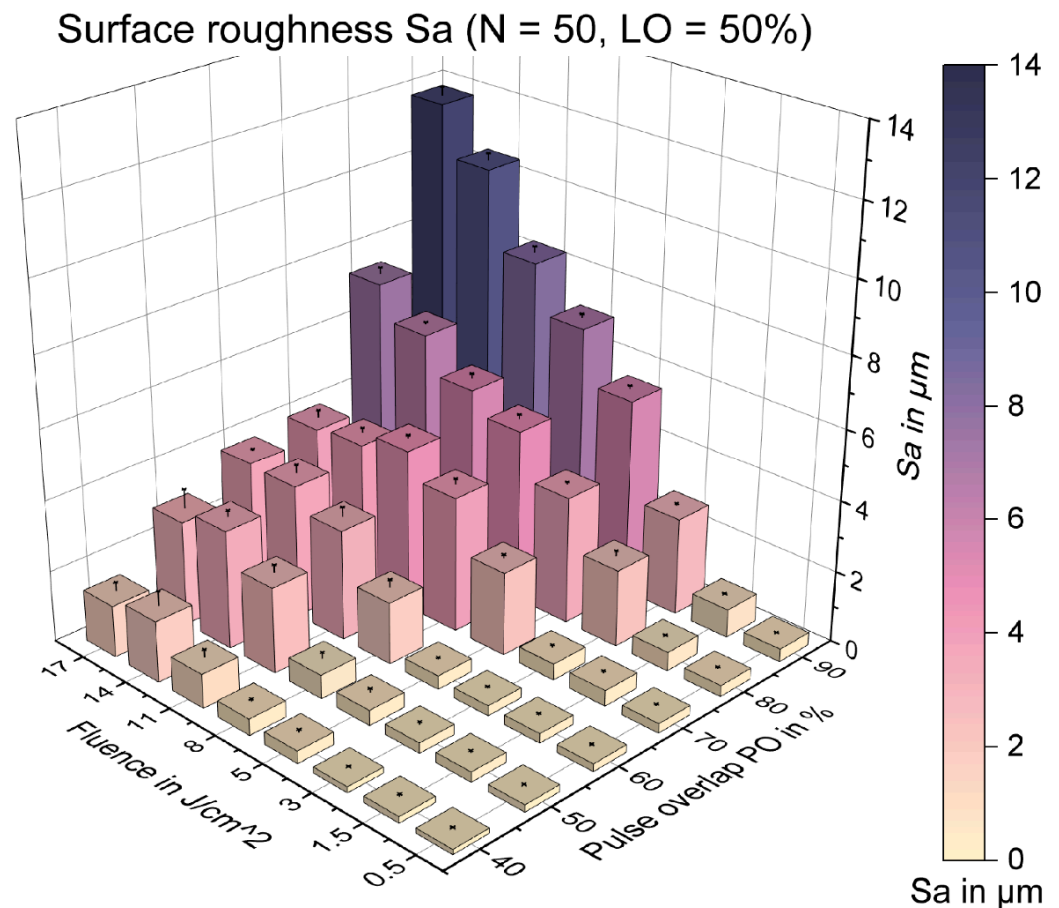


Figure 7. Matrix of surface roughness values S_a (arithmetical mean height) of structured hot-work tool steel (X37CrMoV5-1) surfaces with a varied laser pulse overlap of $PO = 40\text{--}90\%$, fixed scanning line overlap of $LO = 50\%$, number of overscans of $N = 50$, and fluence variation of $\phi = 0.5\text{--}17\text{ J/cm}^2$.

At low fluence ($\phi = 0.5\text{ J/cm}^2$), very low roughness values of the arithmetical mean height were generally achieved, which rose only slightly with an increase in the laser pulse overlap from $PO = 40\%$ ($S_a = 0.142 \pm 0.022\text{ }\mu\text{m}$) to $PO = 90\%$ ($S_a = 0.363 \pm 0.010\text{ }\mu\text{m}$). The low roughness values in the low fluence ranges are due to the induced ablation being in the area of the gentle ablation phase. At this fluence level, the change from the second structure class (LIPSSs with a spatial period Λ_1 superimposed with MR with a spatial period Λ_2) to the third structure class (micro-crater structures) occurs with a laser pulse overlap of $PO = 60\%$, resulting in slightly increased roughness values at a laser pulse overlap of $PO = 90\%$. From a fluence of $\phi = 3\text{ J/cm}^2$, pillared microstructures then form in the upper laser pulse overlap area, resulting in a sharp increase in roughness. This increase in the roughness value is due to the strong ablation threshold being exceeded. In the higher fluence ranges, the roughness values increase relatively evenly in each case, in the direction of increasing fluence and scanning line overlap. In this range, the ablation is completely in the strong ablation phase. For the fourth structure class, i.e., the pillared microstructures, the values for the arithmetical mean height lie between $S_a = 2.163 \pm 0.130\text{ }\mu\text{m}$ and $S_a = 11.836 \pm 0.230\text{ }\mu\text{m}$. The roughness values for S_a , S_z , and S_q are given in Tables S1 and S2 in the Supplementary Material. The effect of laser pulse overlap on the topography and morphology of self-organized, laser-induced surface structures is particularly evident in Figure 8 for the microstructures in the high fluence range. Detailed SEM images of selected areas of the low fluence regime at $\phi = 0.5\text{ J/cm}^2$ from the matrices were selected and shown in Figure 8 in order to illustrate the effect of the laser pulse overlap in the area of the nanostructures more precisely.

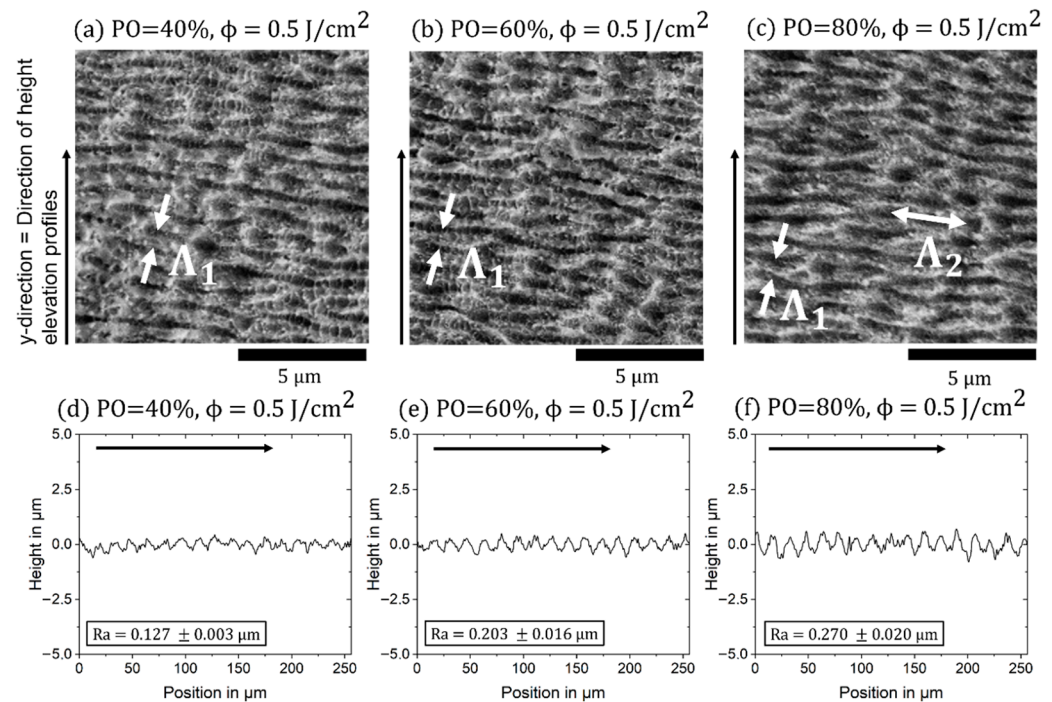


Figure 8. (a–c) Exemplary SEM images of the resulting LIPSSs with a spatial period Λ_1 and micrometric ripples with a spatial period Λ_2 , with varied laser pulse overlap of $PO = 40\text{--}80\%$, scanning line overlap of $LO = 50\%$, number of overscans of $N = 50$, and fluence of $\phi = 0.5 \text{ J/cm}^2$. (d–f) Corresponding height elevation profiles in the y-direction with values of the arithmetical mean height Ra .

For the laser pulse overlap of $PO = 40\%$ (Figure 8a), the LIPSSs with a spatial period Λ_1 can be recognized as the predominant structure class. The first micrometric ripples are already beginning to appear here, but the structure class of LIPSSs with a spatial period Λ_1 still predominates. From a laser pulse overlap of $PO = 60\%$ (Figure 8b), the LIPSSs with a spatial period Λ_1 superimposed with micrometric ripples with a spatial period Λ_2 also prevail up to a laser pulse overlap of $PO = 80\%$. In addition to the detailed SEM images, the corresponding height elevation profiles in the y-direction, as well as the corresponding values of the arithmetical mean height Ra , including the standard deviation, are shown in the lower row in Figure 8 for the evaluation of topography and morphology. In the low fluence regime at a fluence of $\phi = 0.5 \text{ J/cm}^2$, the height elevation profile in the y-direction for the laser pulse overlap of $PO = 40\%$ and $PO = 60\%$ (Figure 8d,e) shows a consistent roughness distribution with a visible periodicity in the profile lines. With a laser pulse overlap of $PO = 80\%$, the first irregularities in the periodic roughness profile can already be observed (see Figure 8c), which results in a roughness value of $Ra = 0.270 \mu\text{m} \pm 0.020 \mu\text{m}$. If the laser pulse overlap is increased, the amount of energy absorbed by the material per unit area also increases over the entire surface treatment period. This also results in a higher number of interactions between the laser light (i.e., the incident photons) and the material area under consideration. At the same time, the individual pulse energy otherwise remains constant. Basically, with increased laser pulse overlap, two effects, which are mutually dependent, have an increased influence on the structure formation, especially from medium fluences upwards. Firstly, the increased number of photons over time, with the time interval between individual laser pulses, has an effect on the material surface per unit area. The higher the laser pulse overlap, the less time the material, which is irradiated several times during an overscan due to the overlap, has to cool down before the next incident laser pulse. Compared to the effect of scanning line overlap, the irradiated material therefore has significantly less time to dissipate the

heat introduced with the same overlap. This effect increases accordingly as a higher pulse repetition rate or a higher laser pulse overlap is selected. At high pulse repetition rates, it has already been demonstrated that the time between two successive individual pulses is insufficient for the irradiated material to dissipate all the heat generated [43]. This effect is significantly more pronounced with a high laser pulse overlap than with a comparable scanning line overlap, as the sequence of individual pulses occurs directly one after the other with a high laser pulse overlap. In contrast, with a high scanning line overlap, the time interval between the individual scanning line overscans is also significant. Secondly, as the laser pulse overlap increases, the number of pulses per irradiated area also increases. As mentioned in the previous section, Raciukaitis et al. and Mannion et al. have shown that the number of pulses per irradiated area unit influences ablation [60,61]. These findings are consistent with the results of this study on the influence of laser pulse overlaps. The higher the laser pulse overlap with constant fluence and scanning line overlap, the greater the ablation that takes place on the material surface. When comparing the morphological and topographical changes shown in this study for the effects of scanning line overlap and laser pulse overlap, these two effects are clearly evident, particularly in the characteristics of the surface structures produced and in the roughness data.

3.3. Surface Height Distribution (S_a/S_q Ratio)

The results show that the surface structures generated by ultrashort laser processing are not always homogeneous and uniform. Consequently, their roughness distributions are also subject to local irregularities (e.g., in crater formation). Since the objective for a technical surface is usually a homogeneous distribution of the desired roughness, it is helpful to be able to derive a statement about the uniformity of the roughness distribution and a possible directional dependence based on the recorded roughness values. To evaluate the height distribution characteristics, the S_a/S_q ratio has been used as an indicator. Figure 9 shows the surface roughness values S_a and S_q as well as the S_a/S_q ratio for a structure series with increasing fluence, a laser pulse overlap of $PO = 50\%$, and a scanning line overlap of $LO = 70\%$.

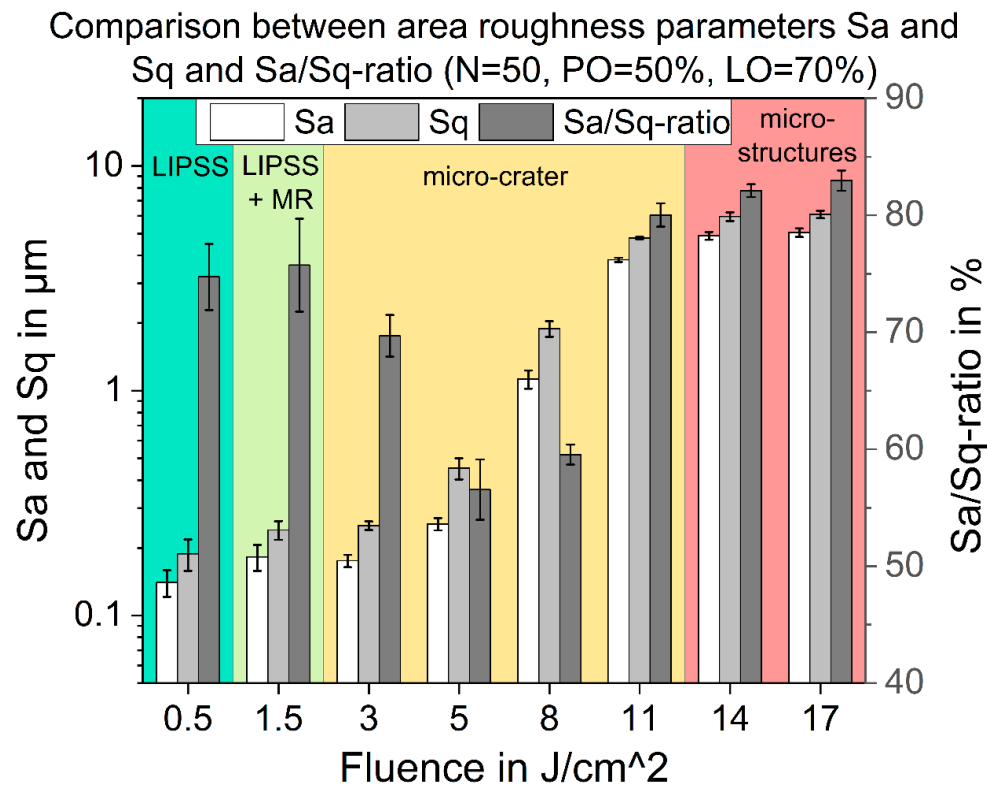


Figure 9. Surface roughness values Sa (arithmetical mean height) and Sq (root mean square height), and calculated Sa/Sq ratio for an exemplary surface structure row (N = 50, PO = 50%, LO = 70%). Note: The axis in the y-direction is logarithmic to better illustrate the relations.

An examination of the corresponding SEM images (see Matrix of SEM images in Figure 3) shows that the structures in the low and high fluence range exhibit a higher homogeneity than the structures in the medium fluence range (especially the smaller and larger micro-crater structures). This qualitative observation can be measured quantitatively using the Sa/Sq ratio we have introduced, as shown in Figure 9. For the inhomogeneous structures and roughness distributions, the Sa/Sq ratio in this case is below 60%. For more homogeneous structures and roughness distributions, it is significantly higher, i.e., above 75%. The higher the Sa/Sq ratio, the more homogeneous the structures and roughness distributions on the surface under consideration. The Sa/Sq ratio is therefore very suitable for quantitatively assessing and comparing different surface structures in terms of the homogeneity of their structural characteristics and roughness distributions. For this purpose, all Sa and Sq values of all structure fields are given in Tables S1 and S2 in the Supplementary Material. The Sa/Sq ratios are shown below in Figure 10 as a heat map for the parameter matrix from Figure 3 (fixed PO = 50%, varied LO = 40–90%).

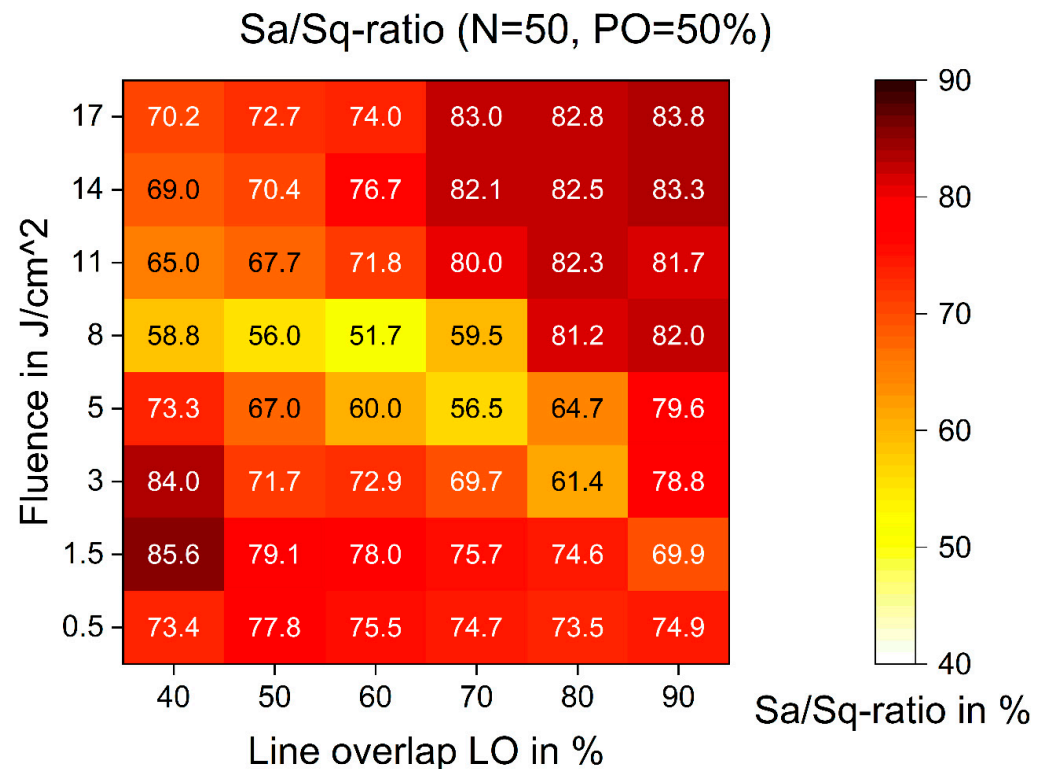


Figure 10. Heatmap of Sa/Sq ratios exemplary for the parameter matrix according to Figure 3 (fixed PO = 50%, varied LO = 40–90%).

In the heatmap shown, the individual areas are colored according to the size of the Sa/Sq ratio. In this case, they represent values between 51.7% and 85.6%. This representation makes it very clear in which area of the parameter matrix the more homogeneous and inhomogeneous structures arise. Many areas with a low Sa/Sq ratio can be seen in the middle area of the matrix, in particular. This value is consistent with the qualitative, visual analysis of the SEM images in Figure 3, where the structure class of smaller and larger micro-crater structures in particular stands out due to its high inhomogeneity. In the area of LIPSSs and pillared microstructures, the Sa/Sq ratios indicate a higher homogeneity of the surface structures, which is also consistent with the qualitative, visual analysis of the SEM images in Figure 3.

3.4. Surface Height Distribution (Isotropy-Factor)

Anisotropic roughness formation and structure formation can occur, such as in the direction-dependent LIPSS formation, but also in all other structure formations or due to relatively large differences between the scanning line and laser pulse overlap. To generate this information from the recorded roughness data, we propose to consider the isotropy factor, as introduced in Section 2.4. This is formed from the direction-dependent arithmetical mean height Ra. When considering the corresponding SEM images (see Figure 3), it becomes clear that the surface structures in the lower and middle fluence range in particular exhibit a higher anisotropy than in the higher fluence range. This qualitative observation can be measured quantitatively using the surface roughness isotropy factor. The surface roughness isotropy factor for the selected structures also shows a considerable distance from 1, particularly in the lower and middle fluence range. The higher this distance is, the more anisotropic the structure formation and the formation of the surface structure. The surface roughness isotropy factor is therefore very well suited to quantitatively assess and compare different surface structures in terms of their anisotropies in structure characteristics and roughness distributions. To evaluate the anisotropy of the

entire structural fields of the parameter matrices, the surface roughness isotropy factor for each individual structural field can be calculated. These are shown below in Figure 11 as a heat map, for the parameter matrix from Figure 3 (fixed PO = 50%, varied LO = 40–90%).

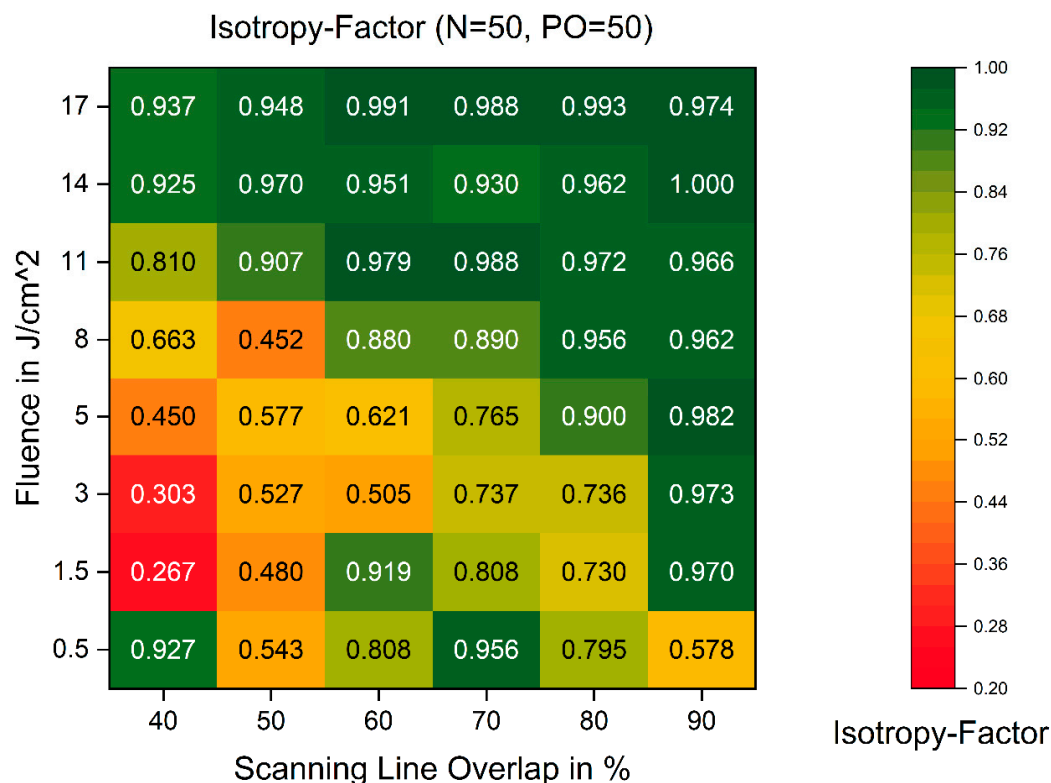


Figure 11. Heatmap of the surface roughness isotropy factor for the parameter matrix from Figure 3 (fixed PO = 50%, varied LO = 40–90%).

In the heatmap shown, the individual areas are colored according to the size of the isotropy factor, which in this case represents values ranging from 0.267 to 1.000. By comparing the values from the surface roughness isotropy factor, it becomes clear in which area of the parameter matrix isotropic and anisotropic structural characteristics and roughness distributions predominate. Differences between the surface roughness isotropy factors are particularly evident in the lower fluence range and in the middle fluence range, particularly when there is a low scanning line overlap. This is consistent with the qualitative, visual analysis of the SEM images in Figure 3, which characterizes the LIPSS structure class by its anisotropy. Still, areas in the middle fluence range also exhibit an anisotropic structure and roughness distribution. It is therefore advisable to calculate and display the surface roughness isotropy factor for the quantitative assessment of the isotropy of the shape and roughness distribution of surface structures.

4. Conclusions

In this study, the effects of laser scanning parameters and fluence on the formation of laser-induced, self-organized surface structures, as well as the resulting topography and morphology on hot-work tool steel surfaces, were comprehensively investigated. Depending on the applied laser fluence, the scanning line overlap, and the pulse overlap, four different surface structure types were identified. LIPSSs with a spatial period Λ_1 could be generated as the first structure type; LIPSSs with a spatial period Λ_1 superimposed with micrometric ripples with a spatial period Λ_2 could be identified as the second type of structure. Furthermore, smaller and larger micro-crater structures as well as pillared

microstructures could be generated. Typically, the pillared microstructures are superimposed with nanostructures, resulting in a double-scale formation. The Sa/Sq ratio and the surface roughness isotropy factor were used in this study to describe the surface roughness homogeneity and the directional dependence of the resulting surface structures. Upon summarizing all the results, the following are the main findings from this study:

1. All investigated laser parameters and scanning strategies have a significant influence on the generation of the self-organized, laser-induced surface structures. It was shown that the strong ablation threshold depends on the laser pulse overlap, the scanning line overlap, as well as on the fluence.
2. High laser pulse overlaps lead to more pronounced phase explosion and greater heat accumulation compared to high scanning line overlaps, ultimately resulting in a reduction in the strong ablation threshold.
3. For high efficiency in terms of material removal rate and surface roughness, a relatively high laser pulse overlap should be preferred.
4. To efficiently achieve high roughness with the lowest possible fluence, high overlaps should be used (at a fixed LO = 50%, POs from 70 to 90%; and at a fixed PO = 50%, LOs from 70 to 90%).
5. To achieve an isotropy factor close to 1, the focus should be on the realization of nano- and self-organized microstructures. Crater structures that result in higher surface anisotropy should be avoided. For microstructures, isotropic structures are created in the fluence range of $\phi = 14\text{--}17\text{ J/cm}^2$, for all laser pulse overlaps and scanning line overlaps. At lower fluences, relatively high pulse and line overlaps (PO and LO) are preferable to obtain nanostructured surfaces that are as isotropic as possible, aside from the inherent alignment characteristic of LIPSS. To achieve relatively isotropic nanostructured surfaces, the isotropy factor is an important metric, since changes in processing parameters can otherwise result in highly directional structures.
6. At low fluence levels, higher scanning line overlap promotes a more homogenous formation of nanostructures with reduced waviness.
7. The calculation of the Sa/Sq ratio revealed differences in surface homogeneity exceeding 30% between the resulting surface structures, depending on the applied structuring parameters.
8. By calculating the surface roughness isotropy factor using the orthogonal arithmetical mean heights Ra, it was quantitatively demonstrated that anisotropic structures primarily occur in the lower fluence range and in the medium fluence range when both scanning line overlap and laser pulse overlap are low.

Our comprehensive parameter study can provide a fundamental understanding of the structural design of self-organized surface structures on hot-work tool steel surfaces and identify the effects of the most significant process parameters on topography and morphology. These studies can therefore be utilized to create customized structures for various applications and can also be employed, for example, for laser parameter control and the advancement of quality assurance systems [62].

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/jmmp10020058/s1>, Table S1: Surface area roughness Sa, Sz, and Sq (N = 50, PO = 50%); Table S2: Surface area roughness Sa, Sz, and Sq (N = 50, LO = 50%); Table S3: Surface line roughness Ra, Rz, and Rq (N = 50, PO = 50%); Table S4: Surface line roughness Ra, Rz, and Rq (N = 50, LO = 50%).

Author Contributions: Conceptualization, R.T. and G.S.; methodology, R.T. and G.S.; investigation, R.T.; resources, H.S.; data curation, R.T.; writing—original draft preparation, R.T.; writing—review

and editing, G.S. and H.S.; visualization, R.T.; supervision, G.S.; funding acquisition, H.S. All authors have read and agreed to the published version of the manuscript.

Funding: This study was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) [grant number INST 264/124-1 FUGG and project number 567110535] and the Federal Ministry for Economic Affairs and Energy [funding code KK5037203BS0 and ZF4018413LL9].

Data Availability Statement: Additional material for the data set can be provided upon request from the corresponding author.

Acknowledgments: The authors thank Benjamin Eichler, Niklas Dubhorn, and Felix Wittig for their technical support. The authors would also like to thank the Institute for Device Systems and Circuit Technology at the University of Rostock for the access and permission to use the SEM.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

LIPSSs	Laser-induced periodic surface structures
MR	(Sub-)micrometric ripple
PO	Laser pulse overlap
LO	Scanning line overlap
SEM	Scanning electron microscope
LSFL	Low-spatial-frequency LIPSS
HSFL	High-spatial-frequency LIPSS
IF	Isotropy factor

References

1. He, Z.; Lei, L.; Lin, S.; Tian, S.; Tian, W.; Yu, Z.; Li, F. Metal Material Processing Using Femtosecond Lasers: Theories, Principles, and Applications. *Materials* **2024**, *17*, 3386. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Finger, J.; Kalupka, C.; Reininghaus, M. High power ultra-short pulse laser ablation of IN718 using high repetition rates. *J. Mater. Process. Technol.* **2015**, *226*, 221–227. [\[CrossRef\]](#)
3. Masato, D.; Piccolo, L.; Lucchetta, G.; Sorgato, M. Texturing Technologies for Plastics Injection Molding: A Review. *Micromachines* **2022**, *13*, 1211. [\[CrossRef\]](#)
4. Calabrese, L.; Azzolini, M.; Bassi, F.; Gallus, E.; Bocchi, S.; Maccarini, G.; Pellegrini, G.; Ravasio, C. Micro-Milling Process of Metals: A Comparison between Femtosecond Laser and EDM Techniques. *J. Manuf. Mater. Process.* **2021**, *5*, 125. [\[CrossRef\]](#)
5. Ahmmed, K.; Grambow, C.; Kietzig, A.-M. Fabrication of Micro/Nano Structures on Metals by Femtosecond Laser Micromachining. *Micromachines* **2014**, *5*, 1219–1253. [\[CrossRef\]](#)
6. Vorobyev, A.Y.; Guo, C. Direct femtosecond laser surface nano/microstructuring and its applications. *Laser Photonics Rev.* **2013**, *7*, 385–407. [\[CrossRef\]](#)
7. Ince, F.D.; Özel, T. Laser surface texturing of materials for surface functionalization: A holistic review. *Surf. Coat. Technol.* **2025**, *498*, 131818. [\[CrossRef\]](#)
8. Chen, Z.; Yang, J.; Liu, H.; Zhao, Y.; Pan, R. A short review on functionalized metallic surfaces by ultrafast laser micromachining. *Int. J. Adv. Manuf. Technol.* **2022**, *119*, 6919–6948. [\[CrossRef\]](#)
9. Orazi, L.; Sorgato, M.; Piccolo, L.; Masato, D.; Lucchetta, G. Generation and Characterization of Laser Induced Periodic Surface Structures on Plastic Injection Molds. *Lasers Manuf. Mater. Process.* **2020**, *7*, 207–221. [\[CrossRef\]](#)
10. Ghadiri Zahrani, E.; Fakharzadeh Jahromi, A.; Azarhoushang, B. Development of Polymer Hydrophobic Surfaces Through Combined Laser Ablation and Hot Embossing Processes. *J. Manuf. Mater. Process.* **2024**, *8*, 262. [\[CrossRef\]](#)
11. Florian, C.; Skoulas, E.; Puerto, D.; Mimidis, A.; Stratakis, E.; Solis, J.; Siegel, J. Controlling the Wettability of Steel Surfaces Processed with Femtosecond Laser Pulses. *ACS Appl. Mater. Interfaces* **2018**, *10*, 36564–36571. [\[CrossRef\]](#)
12. Stratakis, E.; Bonse, J.; Heitz, J.; Siegel, J.; Tsibidis, G.D.; Skoulas, E.; Papadopoulos, A.; Mimidis, A.; Joel, A.-C.; Comanns, P.; et al. Laser engineering of biomimetic surfaces. *Mater. Sci. Eng. R Rep.* **2020**, *141*, 100562. [\[CrossRef\]](#)

13. Schnell, G.; Studemund, H.; Thomas, R.; Seitz, H. Experimental investigations on the friction behavior of partially femtosecond laser-textured journal bearing shells. *Tribol. Int.* **2023**, *188*, 108764. [[CrossRef](#)]
14. Gamaly, E.G.; Rode, A.V.; Luther-Davies, B.; Tikhonchuk, V.T. Ablation of solids by femtosecond lasers: Ablation mechanism and ablation thresholds for metals and dielectrics. *Phys. Plasmas* **2002**, *9*, 949–957. [[CrossRef](#)]
15. Rethfeld, B.; Sokolowski-Tinten, K.; von der Linde, D.; Anisimov, S.I. Timescales in the response of materials to femtosecond laser excitation. *Appl. Phys. A Mater. Sci. Process.* **2004**, *79*, 767–769. [[CrossRef](#)]
16. Zhigilei, L.V.; Lin, Z.; Ivanov, D.S. Atomistic Modeling of Short Pulse Laser Ablation of Metals: Connections between Melting, Spallation, and Phase Explosion. *J. Phys. Chem. C* **2009**, *113*, 11892–11906. [[CrossRef](#)]
17. Bonse, J.; Kirner, S.V.; Krüger, J. Laser-Induced Periodic Surface Structures (LIPSS). In *Handbook of Laser Micro- and Nano-Engineering*; Sugioka, K., Ed.; Springer International Publishing: Cham, Switzerland, 2020; pp. 1–59, ISBN 978-3-319-69537-2.
18. Petelin, J.; Marš, M.; Mur, J.; Petkovšek, R. Managing Residual Heat Effects in Femtosecond Laser Material Processing by Pulse-on-Demand Operation. *J. Manuf. Mater. Process.* **2024**, *8*, 254. [[CrossRef](#)]
19. Schnell, G.; Duenow, U.; Seitz, H. Effect of Laser Pulse Overlap and Scanning Line Overlap on Femtosecond Laser-Structured Ti6Al4V Surfaces. *Materials* **2020**, *13*, 969. [[CrossRef](#)] [[PubMed](#)]
20. JJ Nivas, J.; Allahyari, E.; Gesuele, F.; Maddalena, P.; Fittipaldi, R.; Vecchione, A.; Bruzzese, R.; Amoroso, S. Influence of ambient pressure on surface structures generated by ultrashort laser pulse irradiation. *Appl. Phys. A Mater. Sci. Process.* **2018**, *124*, 198. [[CrossRef](#)]
21. Berczeli, M.; Tajti, F.; Juhász, G.; Weltsch, Z. Changing the High Strength Steel Surface Properties with Femtosecond Laser Beam. *Opt. Laser Technol.* **2024**, *174*, 110556. [[CrossRef](#)]
22. Schnell, G.; Piehl, J.; Hartig, T.; Dubhorn, N.; Aliyeva, A.; Springer, A.; Strunskus, T.; Faupel, F.; Schröder, S.; Seitz, H. PFAS-free superhydrophobic surfaces using femtosecond laser processing and hot-filament chemical vapor deposition. *Surf. Interfaces* **2025**, *73*, 107605. [[CrossRef](#)]
23. Chen, Z.; Zhou, J.; Cen, W.; Yan, Y.; Guo, W. Femtosecond Laser Fabrication of Wettability-Functional Surfaces: A Review of Materials, Structures, Processing, and Applications. *Nanomaterials* **2025**, *15*, 573. [[CrossRef](#)]
24. Müller, F.A.; Kunz, C.; Gräf, S. Bio-Inspired Functional Surfaces Based on Laser-Induced Periodic Surface Structures. *Materials* **2016**, *9*, 476. [[CrossRef](#)]
25. Vorobyev, A.Y.; Guo, C. Multifunctional surfaces produced by femtosecond laser pulses. *J. Appl. Phys.* **2015**, *117*, 033103. [[CrossRef](#)]
26. Orazi, L.; Gnilytskyi, I.; Serro, A.P. Laser Nanopatterning for Wettability Applications. *J. Micro Nano-Manuf.* **2017**, *5*, 021008. [[CrossRef](#)]
27. Abdel-Aal, H.A. Functional surfaces for tribological applications: Inspiration and design. *Surf. Topogr. Metrol. Prop.* **2016**, *4*, 43001. [[CrossRef](#)]
28. Bonse, J.; Kirner, S.V.; Griepentrog, M.; Spaltmann, D.; Krüger, J. Femtosecond Laser Texturing of Surfaces for Tribological Applications. *Materials* **2018**, *11*, 801. [[CrossRef](#)] [[PubMed](#)]
29. Sorgato, M.; Zanini, F.; Masato, D.; Lucchetta, G. Submicron laser-textured vents for self-cleaning injection molds. *J. Appl. Polym. Sci.* **2020**, *137*, 49280. [[CrossRef](#)]
30. Xu, Q.; Zhang, W.; Dong, C.; Sreeprasad, T.S.; Xia, Z. Biomimetic self-cleaning surfaces: Synthesis, mechanism and applications. *J. R. Soc. Interface* **2016**, *13*, 20160300. [[CrossRef](#)]
31. Schnell, G.; Polley, C.; Thomas, R.; Bartling, S.; Wagner, J.; Springer, A.; Seitz, H. How droplets move on laser-structured surfaces: Determination of droplet adhesion forces on nano- and microstructured surfaces. *J. Colloid Interface Sci.* **2023**, *630*, 951–964. [[CrossRef](#)]
32. Sorgato, M.; Masato, D.; Lucchetta, G.; Orazi, L. Effect of different laser-induced periodic surface structures on polymer slip in PET injection moulding. *CIRP Ann.* **2018**, *67*, 575–578. [[CrossRef](#)]
33. Deng, J.; Lian, Y.; Wu, Z.; Xing, Y. Performance of femtosecond laser-textured cutting tools deposited with WS₂ solid lubricant coatings. *Surf. Coat. Technol.* **2013**, *222*, 135–143. [[CrossRef](#)]
34. Norström, L.-Å.; Öhrberg, N. Development of hot-work tool steel for high-temperature applications. *Met. Technol.* **1981**, *8*, 22–26. [[CrossRef](#)]
35. Hafenstein, S.; Werner, E.; Wilzer, J.; Theisen, W.; Weber, S.; Sunderkötter, C.; Bachmann, M. Influence of Temperature and Tempering Conditions on Thermal Conductivity of Hot Work Tool Steels for Hot Stamping Applications. *Steel Res. Int.* **2015**, *86*, 1628–1635. [[CrossRef](#)]
36. Sorgato, M.; Masato, D.; Piccolo, L.; Lucchetta, G. Plastic intensity reduction using thermally insulating coatings for injection molds. *CIRP J. Manuf. Sci. Technol.* **2020**, *30*, 79–86. [[CrossRef](#)]
37. Klocke, F.; Arntz, K.; Teli, M.; Winands, K.; Wegener, M.; Oliari, S. State-of-the-art Laser Additive Manufacturing for Hot-work Tool Steels. *Procedia CIRP* **2017**, *63*, 58–63. [[CrossRef](#)]
38. Ebrahimi, M.; Konaganti, V.K.; Moradi, S.; Doufas, A.K.; Hatzikiriakos, S.G. Slip of polymer melts over micro/nano-patterned metallic surfaces. *Soft Matter* **2016**, *12*, 9759–9768. [[CrossRef](#)]

39. Bellantone, V.; Surace, R.; Modica, F.; Fassi, I. Evaluation of mold roughness influence on injected thin micro-cavities. *Int. J. Adv. Manuf. Technol.* **2018**, *94*, 4565–4575. [[CrossRef](#)]
40. Sorgato, M.; Masato, D.; Lucchetta, G. Effects of machined cavity texture on ejection force in micro injection molding. *Precis. Eng.* **2017**, *50*, 440–448. [[CrossRef](#)]
41. Piccolo, L.; Sorgato, M.; Batal, A.; Dimov, S.; Lucchetta, G.; Masato, D. Functionalization of Plastic Parts by Replication of Variable Pitch Laser-Induced Periodic Surface Structures. *Micromachines* **2020**, *11*, 429. [[CrossRef](#)]
42. Gao, P.; MacKay, I.; Gruber, A.; Krantz, J.; Piccolo, L.; Lucchetta, G.; Pelaccia, R.; Orazi, L.; Masato, D. Wetting Characteristics of Laser-Ablated Hierarchical Textures Replicated by Micro Injection Molding. *Micromachines* **2023**, *14*, 863. [[CrossRef](#)]
43. Schnell, G.; Lund, H.; Bartling, S.; Polley, C.; Riaz, A.; Senz, V.; Springer, A.; Seitz, H. Heat accumulation during femtosecond laser treatment at high repetition rate—A morphological, chemical and crystallographic characterization of self-organized structures on Ti6Al4V. *Appl. Surf. Sci.* **2021**, *570*, 151115. [[CrossRef](#)]
44. Jia, X.; Luo, J.; Li, K.; Wang, C.; Li, Z.; Wang, M.; Jiang, Z.; Veiko, V.P.; Duan, J. Ultrafast laser welding of transparent materials: From principles to applications. *Int. J. Extrem. Manuf.* **2025**, *7*, 32001. [[CrossRef](#)]
45. ISO 4957:2018; Tool Steels. ISO International Organization for Standardization: Geneva, Switzerland, 2018.
46. Byskov-Nielsen, J.; Savolainen, J.-M.; Christensen, M.S.; Balling, P. Ultra-short pulse laser ablation of metals: Threshold fluence, incubation coefficient and ablation rates. *Appl. Phys. A* **2010**, *101*, 97–101. [[CrossRef](#)]
47. Wu, P.H.; Cheng, C.W.; Chang, C.P.; Wu, T.M.; Wang, J.K. Fabrication of large-area hydrophobic surfaces with femtosecond-laser-structured molds. *J. Micromech. Microeng.* **2011**, *21*, 115032. [[CrossRef](#)]
48. Bonse, J.; Hohm, S.; Kirner, S.V.; Rosenfeld, A.; Kruger, J. Laser-Induced Periodic Surface Structures—A Scientific Evergreen. *IEEE J. Select. Top. Quantum Electron.* **2017**, *23*, 9000615. [[CrossRef](#)]
49. Todhunter, L.D.; Leach, R.K.; Lawes, S.; Blateyron, F. Industrial survey of ISO surface texture parameters. *CIRP J. Manuf. Sci. Technol.* **2017**, *19*, 84–92. [[CrossRef](#)]
50. ISO 25178; Geometrical Product Specifications (GPS)-Surface Texture. ISO International Organization for Standardization: Geneva, Switzerland, 2021.
51. ISO 21920; Geometrical Product Specifications (GPS). ISO International Organization for Standardization: Geneva, Switzerland, 2021.
52. ISO 3274; Geometrical Product Specifications (GPS)-Surface Texture: Profile Method-Nominal Characteristics of Contact (Stylus) Instruments. ISO International Organization for Standardization: Geneva, Switzerland, 1996.
53. Pawlus, P.; Reizer, R.; Wiczorowski, M.; Królczyk, G. Parametric description of one-process surface texture. *Measurement* **2022**, *204*, 112066. [[CrossRef](#)]
54. Zuhlke, C.A.; Anderson, T.P.; Alexander, D.R. Understanding the formation of self-organized micro/nanostructures on metal surfaces from femtosecond laser ablation using stop-motion SEM imaging. In *Laser-Based Micro- and Nanoprocessing VIII. SPIE LASE, San Francisco, CA, USA, 1 February 2014*; Klotzbach, U., Washio, K., Arnold, C.B., Eds.; SPIE: Bellingham, WA, USA, 2014; p. 89680C.
55. Moradi, S.; Kamal, S.; Englezos, P.; Hatzikiriakos, S.G. Femtosecond laser irradiation of metallic surfaces: Effects of laser parameters on superhydrophobicity. *Nanotechnology* **2013**, *24*, 415302. [[CrossRef](#)]
56. Nolte, S.; Momma, C.; Jacobs, H.; Tünnermann, A.; Chichkov, B.N.; Wellegehausen, B.; Welling, H. Ablation of metals by ultrashort laser pulses. *J. Opt. Soc. Am. B* **1997**, *14*, 2716. [[CrossRef](#)]
57. Hashida, M.; Semerok, A.; Gobert, O.; Petite, G.; Izawa, Y.; Wagner, J. Ablation threshold dependence on pulse duration for copper. *Appl. Surf. Sci.* **2002**, *197–198*, 862–867. [[CrossRef](#)]
58. Bizi-bandoki, P.; Benayoun, S.; Valette, S.; Beaugiraud, B.; Audouard, E. Modifications of roughness and wettability properties of metals induced by femtosecond laser treatment. *Appl. Surf. Sci.* **2011**, *257*, 5213–5218. [[CrossRef](#)]
59. Zuhlke, C.A.; Anderson, T.P.; Alexander, D.R. Formation of multiscale surface structures on nickel via above surface growth and below surface growth mechanisms using femtosecond laser pulses. *Opt. Express* **2013**, *21*, 8460–8473. [[CrossRef](#)]
60. Raciukaitis, G.; Brikas, M.; Gecys, P.; Gedvilas, M. Accumulation effects in laser ablation of metals with high-repetition-rate lasers. In *High-Power Laser Ablation VII. High-Power Laser Ablation 2008, Taos, New Mexico, 20 April 2008*; Phipps, C.R., Ed.; SPIE: Bellingham, WA, USA, 2008; p. 70052L.
61. Mannion, P.; Magee, J.; Coyne, E.; O'Connor, G.; Glynn, T. The effect of damage accumulation behaviour on ablation thresholds and damage morphology in ultrafast laser micro-machining of common metals in air. *Appl. Surf. Sci.* **2004**, *233*, 275–287. [[CrossRef](#)]
62. Thomas, R.; Westphal, E.; Schnell, G.; Seitz, H. Machine Learning Classification of Self-Organized Surface Structures in Ultrashort-Pulse Laser Processing Based on Light Microscopic Images. *Micromachines* **2024**, *15*, 491. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.