

Article

Controllable Wettability on Nickel-Based Superalloys Achieved by Laser-Processed Unidirectional Parallel Grooves

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Abstract

To address the practical requirement for controllable wettability design of additively manufactured nickel-based superalloy surfaces, this paper systematically examines how laser processing techniques influence and regulate their wettability. Using a full factorial design combined with analysis of variance (ANOVA), we investigated how laser power, scanning speed, and spot diameter affect groove morphology at different scanning pitches and quantitatively assessed the main and two-way interaction effects of these parameters on wettability. To elucidate the intrinsic “laser parameters–surface morphology–wetting behavior” relationship, we adopted a progressive characterization approach, advancing from static water contact angles (WCAs) and contact angle hysteresis (CAH) to dynamic droplet bouncing behavior. The results indicate that: (1) Under the premise of forming stable grooves, increasing laser power, decreasing scanning speed, or reducing spot diameter promotes the formation of deep and narrow grooves, thereby enhancing the WCA (up to 158.8°) and reducing CAH (as low as 3.7° on engineered wedge structures). (2) CAH is identified as the key parameter characterizing dynamic droplet bouncing performance since lowering CAH effectively results in low adhesion and easy droplet shedding. (3) The WCA and CAH exhibit different sensitivity patterns to parameter coupling; consequently, parameter mismatch can lead to morphological degradation and loss of hydrophobicity, making multi-parameter synergistic optimization essential for maintaining highly stable surface hydrophobicity. This paper provides practical guidance for the surface functional design of additively manufactured superalloy components, holding significant application value for engineering surfaces in aerospace, energy, and other fields that require controllable droplet shedding, anti-icing, and self-cleaning properties.

Keywords: nickel-based superalloys; laser structuring; hydrophobicity; tunable adhesion; process parameter interaction

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1. Introduction

Advances in additive manufacturing have driven the broader adoption of nickel-based superalloy components with complex geometries in aerospace and energy applications [1–5]. However, these components are often susceptible to challenges such as droplet adhesion and icing during service, which significantly compromise operational safety [6,7]. Conventional post-processing approaches, such as shot peening, sandblasting, and electroless coating, struggle to achieve uniform functional surfaces on parts with complex geometries [8]. For applications demanding precise wettability control, current strategies for additively manufactured materials (e.g., stainless steel and titanium alloys) fall broadly into two categories. The first relies on direct chemical treatments such as acid etching, alkaline etching, and fluorination; although straightforward, these methods rarely resolve wettability inhomogeneity caused by inherent defects in laser powder bed fusion (LPBF), including unmelted particles and the balling effect [9–11]. The second employs laser surface texturing, which simultaneously tailors wettability and modifies topography, thereby mitigating typical additive manufacturing defects [12,13]. As a non-contact, high-precision technique, laser texturing is particularly promising for directly fabricating stable and uniform functional surfaces on additively manufactured components [14–16]. Prior work has shown that laser texturing enables precise regulation of hydrophobicity and on-demand adhesion design on various metals, underscoring its potential for advanced surface functionalization [17,18].

However, three critical challenges persist in current research:

(1) Previous research has predominantly focused on the application of laser processing to conventional materials such as stainless steel, aluminum alloys, and titanium alloys. In contrast, laser-induced wettability control of nickel-based superalloys—especially in their additively manufactured state—has received considerably less attention, despite their prevalent use in high-temperature, high-strength applications [12,19–25]. For example, Song et al. fabricated hydrophobic aluminum surfaces with tunable adhesion by tuning laser parameters and elucidated the underlying mechanism [23]. Martínez-Calderon et al. constructed micro-/nano-composite structures on stainless steel via laser texturing and characterized their hydrophobic properties [24]. By comparison, studies on the surface functionalization of additively manufactured nickel-based superalloys remain relatively limited. Jiang et al., for example, examined the influence of multiple laser parameters on the melt-pool wettability of alloy GH4169, but their study targeted internal metallurgy and forming control during AM rather than the functional wettability design of the finished surface [25].

(2) Prior studies have largely focused on examining the effects of either single or a limited set of laser parameters. However, how the coupled action of multiple parameters—laser power, scanning speed, spot diameter, and scanning pitch—regulates surface morphology, together with the mechanisms governing the resulting wettability and possible failure modes, warrants further investigation [26–28]. For instance, Vercillo et al. constructed specific morphologies on titanium alloy surfaces using different laser strategies and correlated them with hydrophobicity but did not elucidate the complete mechanistic chain from fundamental process parameters to the gradual evolution of morphology and properties [26]. Similarly, Khan et al. analyzed the effect of pulse width and scanning speed on the WCA across several metals, yet their investigation remained confined to the isolated effects of a few parameters [27]. Overall, these studies have not yet established a complete causal chain connecting the synergistic effects of multiple parameters, the resulting morphological characteristics, and the final complex wetting behaviors—including the risk of wettability failure.

(3) In response to the actual complex and variable service environments, the current evaluation of hydrophobic performance primarily relies on the static WCA, with

systematic and comprehensive investigations into CAH yet to be further explored. This creates a disconnect between surface design principles and practical wettability requirements, ultimately limiting their engineering application [7,29–33]. First, a significant body of research still uses the WCA as the core, or even the sole, evaluation criterion. For example, Shi et al. assessed hydrophobicity only via the WCA after fabricating micro-textures using water jet-guided laser processing [29]. Similarly, Bai et al. conducted a “multi-configuration design–contact angle–anti-icing” study on nickel-based superalloys by tuning laser parameters, yet their wettability analysis remained primarily focused on the static WCA [7]. Second, even the limited number of studies that acknowledge the importance of CAH have focused on macroscopic observations and their associated dynamic wetting behaviors. For instance, Hu et al. compared “lotus-effect” and “rose-petal-effect” surfaces, revealing the influence of CAH on droplet adhesion and motion under dynamic impact and wind-driven conditions [30]. Although this work correlated CAH with macroscopic dynamic performance, the intrinsic mechanism by which multi-parameter synergy governs CAH—the very key to regulating surface dynamic behavior—was not addressed. Butt et al. proposed an empirical formula for droplet sliding on flat surfaces and defined a friction coefficient β [31]; however, their framework excludes the complex micro-/nano-structured surfaces produced by laser texturing, and the determination of β requires intricate dynamic testing, hindering rapid surface design and wettability prediction. For laser-textured surfaces produced with multi-parameter coupling, correlating and predicting dynamic adhesion from readily accessible quasi-static metrics (such as CAH) is therefore a pivotal step toward bridging laboratory design and practical application [32,33].

To address these challenges, this work focuses on LPBF-fabricated GH3536 nickel-based superalloy and systematically examines how laser texturing parameters regulate its surface wettability, together with the underlying mechanisms. A full factorial design was employed to systematically examine the governing effects of laser power, scanning speed, and spot diameter on the morphology of surface grooves formed at varying scanning pitches, and ANOVA was performed to quantify the main effects and the two-way interaction coupling mechanisms of these parameters. A multi-scale wettability characterization was conducted to establish the connections among laser parameters, surface structure, and wetting behavior, advancing stepwise from the static WCA and CAH to dynamic droplet bouncing. To guide the design of high-performance hydrophobic surfaces, this study establishes a process-performance mapping for laser-textured, additively manufactured nickel-based superalloys, bridging fundamental understanding with practical processing guidelines.

2. Materials and Methodology

2.1. Sample Preparation and Fabrication of Surface Structures

2.1.1. Sample Preparation

The additively manufactured GH3536 nickel-based superalloy was cut into 10 mm × 10 mm × 1 mm substrates using wire electrical discharge machining. Before laser processing, all substrates were ultrasonically cleaned in anhydrous ethanol for 20 minutes to remove surface contaminants.

2.1.2. Laser Surface Structuring

Micro-/nano-structures were fabricated on the prepared samples using a laser system (CAPE series, Germany). Key laser parameters were: wavelength = 1064 nm, repetition rate = 30 kHz, and pulse width = 200 ns. A unidirectional line-by-line scanning strategy was adopted, with the beam focused at the substrate top surface (zero defocus) and

processing carried out in ambient laboratory air without any shielding or assist gas. A full factorial design was implemented to systematically investigate the influence of scanning speed (100, 200, and 300 mm/s), laser power (10, 12, and 14 W), and spot diameter (10, 20, and 40 μm) on the surface morphology at different scanning pitches (70, 100, and 130 μm), as summarized in Figure 1.

The investigated parameter ranges were chosen from the CAPE system's recommended processing window for nickel-based alloys, refined via preliminary ablation trials to span the full range from stable groove formation to incipient thermal damage. Within this window, a 3^4 full factorial matrix was adopted to permit unbiased estimation of all main effects and two-way interactions—directly aligned with this study's core objective of quantifying multi-parameter coupling. Three independently fabricated replicate samples were prepared for each parameter combination.

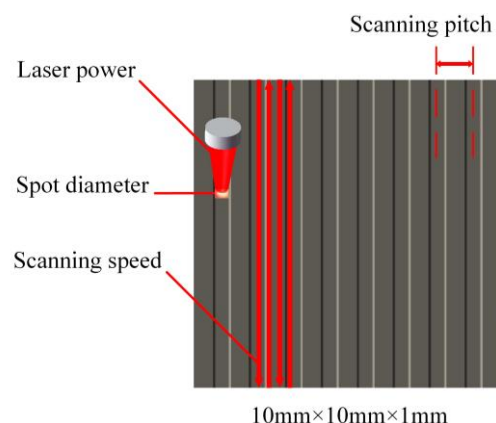


Figure 1. Schematic diagram of key parameters in laser micromachining.

2.1.3. Surface Hydrophobization Modification

The laser-textured samples were ultrasonically cleaned in ethanol for 20 minutes to remove ablation debris, immersed in a 1 wt% FAS-17/ethanol solution for 24 h, and dried in an air-circulating oven at 120 °C for 2 h, yielding a stable transition from hydrophilic to hydrophobic.

2.2. Performance Characterization and Testing

2.2.1. Surface Morphology

The surface morphology of the laser-processed samples was examined using an EVO 10 scanning electron microscope (SEM; Carl Zeiss AG, Oberkochen, Germany) equipped with an energy-dispersive spectrometer (EDS) for micro-area chemical composition analysis.

2.2.2. Wettability Characterization

Sample wettability was characterized at three levels—static, quasi-static, and dynamic—via the WCA, CAH, and droplet adhesion/bouncing analyses, respectively. For every parameter combination, the WCA and CAH were each measured at three randomly selected positions on each of three replicate samples (nine measurements per condition) and reported as the arithmetic mean. The inter-measurement standard deviation was typically within $\pm 1.5^\circ$ for the WCA and $\pm 2.5^\circ$ for CAH, consistent with the scatter range reported for comparable nanosecond-laser-textured, fluorosilane-modified metallic surfaces [22]. The measured dispersions substantially exceed the $\pm 0.1^\circ$ angular resolution of an optical contact angle analyzer (Kruss DSA100, Hamburg, Germany), confirming that

observed variability originates from intrinsic surface microscale heterogeneity rather than instrumental noise.

(a) WCA Measurement: The WCA of a 4 μL deionized water droplet was measured under ambient conditions using the optical contact angle analyzer with the sessile drop method.

(b) CAH Measurement: CAH was determined at room temperature by the volume-increment method [34–37], in which the droplet volume is gradually enlarged with a micro-syringe until sliding initiates, yielding the critical volume and the corresponding CAH. This approach circumvents the 70° tilt-angle limit of the conventional tilting-stage method—which fails on highly adhesive surfaces—and better reflects the wettability of the engineered wedge-like structures examined here, whose service angle reaches 71°.

(c) Dynamic Wettability and Adhesion Evaluation: Three representative samples with distinct wettability configurations were selected for droplet bouncing tests. A 4 μL distilled water droplet was released onto the sample surface, and its complete behavior—including impact, spreading, retraction, and rebound—was captured using a high-speed CCD camera. Surface adhesion was evaluated based on droplet deformation, rebound height, and residue. A low-adhesion surface is characterized by complete droplet rebound without residue, whereas a high-adhesion surface typically exhibits droplet splitting, severe pinning, or a residual liquid film.

2.3. Statistical Analysis of Multi-Parameter Main and Interaction Effects

2.3.1. Statistical Model

A 4-factor, 3-level full factorial design (81 runs) was constructed, with the WCA and CAH as response variables. ANOVA was used to test the significance of main and interaction effects, and effect magnitudes were quantified to assess each factor and its coupling.

A linear statistical model incorporating all main effects and two-way interactions was formulated as follows:

$$Y = \mu + \alpha_D + \alpha_V + \alpha_P + \alpha_S + \alpha_{DV} + \alpha_{DP} + \alpha_{DS} + \alpha_{VP} + \alpha_{VS} + \alpha_{PS} + \varepsilon \quad (1)$$

where Y is the measured value of the response (WCA or CAH). μ is the grand mean. $\alpha_D, \alpha_V, \alpha_P, \alpha_S$ are the main effects of spot diameter, scanning speed, laser power, and scanning pitch, respectively. $\alpha_{D \times V}, \alpha_{D \times P}, \alpha_{D \times S}, \alpha_{V \times P}, \alpha_{V \times S}, \alpha_{P \times S}$ terms denote the corresponding two-way interactions. The random error term ε is assumed to follow a normal distribution with a mean of zero and constant variance.

The validity of these distributional assumptions was verified on the model residuals prior to inference: normality was assessed by the Shapiro–Wilk test ($p = 0.095$ for the WCA; $p = 0.035$ for CAH), variance homogeneity by Levene’s test ($p = 0.180$ for the WCA; $p = 0.468$ for CAH), and independence was ensured through fully randomized run order. The marginal p -value for CAH residuals (0.035) reflects the well-known over-sensitivity of the Shapiro–Wilk test at moderate sample sizes and the broad response range of CAH (3.7°–120°) spanning Cassie–Baxter to Wenzel regimes [38], which a single linear model can only approximate. Given the balanced full factorial design, satisfied variance homogeneity, and large residual degrees of freedom ($df = 48$), the F-test remains robust to this mild departure from strict normality.

2.3.2. Analysis of Variance and Significance Testing

A significance level of $\alpha = 0.05$ was adopted with Type III sum-of-squares decomposition for this balanced full factorial design [38]. All analyses were implemented in Python (Version 3.9): statsmodels generated the ANOVA table, and scipy.stats

provided the F-distribution for exact p -value calculation. Standard decomposition of the total variation into main-effect, interaction, and residual components [38] was carried out, and the test statistics are defined as follows.

The mean square (MS), defined as SS divided by its df, removes the bias introduced by df differences. The effect MS and residual MS are

$$MS_{effect} = \frac{SS_{effect}}{df_{effect}} \quad (2)$$

$$MS_{residual} = \frac{SS_{residual}}{df_{residual}} \quad (3)$$

where MS_{effect} denotes the mean square of any main effect or interaction effect, and $MS_{residual}$ denotes the residual mean square.

The F-statistic, defined as the ratio of the effect MS to the residual MS, tests the statistical significance of each effect:

$$F = \frac{MS_{effect}}{MS_{residual}} \quad (4)$$

Under the null hypothesis of no effect, F follows an F-distribution with df_{effect} and $df_{residual}$ degrees of freedom.

The p -value is the right-tailed probability under the F-distribution of obtaining a value at least as large as the observed F:

$$p = P(F(df_{effect}, df_{residual}) \geq F_{observed}) \quad (5)$$

Based on the pre-specified significance level $\alpha = 0.05$, the statistical significance of each effect is determined according to the following criteria:

$p < 0.001$: highly significant;

$0.001 \leq p < 0.05$: significant;

$0.05 \leq p < 0.10$: marginally significant;

$p \geq 0.10$: not significant.

This procedure identifies the main and interaction effects with statistically meaningful influence on wettability.

2.3.3. Effect Quantification and Relative Importance

(a) Effect magnitude

The least-squares-mean method is used to estimate the magnitude, direction, and strength of each effect on the response.

The main effect value $\alpha_{A(i)}$ of factor A at level i is the deviation of the level mean from the grand mean:

$$\alpha_{A(i)} = \bar{y}_{A(i)} - \mu \quad (6)$$

A positive value indicates enhancement of the response, a negative value indicates suppression, and a larger magnitude corresponds to a stronger effect.

The interaction effect value $\alpha_{AB(i,j)}$ for the level combination (i, j) of factors A and B is the deviation of the observed cell mean from the value predicted by additive superposition of the two main effects:

$$\alpha_{AB(i,j)} = \bar{y}_{AB(i,j)} - [\mu + \alpha_{A(i)} + \alpha_{B(j)}] \quad (7)$$

A positive value indicates synergistic enhancement and a negative value indicates mutual suppression; a larger magnitude reflects stronger coupling.

(b) Contribution ratio

To quantify each effect's share of total variance and rank its relative importance, the contribution ratio is defined as

$$\text{Contribution ratio} = \frac{SS_{\text{effect}}}{SS_{\text{total}}} \times 100 \quad (8)$$

A higher value indicates a stronger regulating capability; significant effects are then ranked in order of relative importance.

3. Results and Discussions

3.1. Effect of Laser Parameters on Surface Topography

The results confirm that laser power, scanning speed, and spot diameter are the core variables governing groove morphology, and the morphological characterization below provides the basis for the subsequent analysis of contact angles, hysteresis, and droplet bouncing.

(a) Modulation by Laser Power

With the spot diameter, scanning speed, and scanning pitch held constant within the stable groove regime, increasing the laser power from 10 W to 14 W systematically deepened the grooves and slightly narrowed their width (Figure 2(a₁–a₆)) [7]. This trend reflects the longitudinal concentration of laser energy: enhanced central energy at higher power drives vaporization and melting along the depth direction, while peripheral energy insufficient for lateral diffusion narrows the groove [7].

Increasing power must nevertheless be matched to other parameters, such as scanning pitch. As shown in Figure 2(d₁–d₃), at the slowest scanning speed with a pitch (70 µm) close to the spot diameter (40 µm), inter-track heat accumulation and overlap became severe. At 10 W, distinct cavitation-like striations were still produced (Figure 2(d₁)); at 12 W, an enlarged heat-affected zone induced lateral remelting and only faint groove traces remained (Figure 2(d₂)); at 14 W, excessive energy input over-ablated the material, and the grooves vanished into a continuous remelted layer (Figure 2(d₃)). Pursuing high aspect ratios, therefore, requires careful power control to avoid thermal damage.

EDS compositional comparison between the normal ablated groove and the thermally accumulated remelted region is summarized in Figure 3, where elemental data of the normal ablated groove region are cited from our previous study [7]. Two clear trends emerge. First, the remelted region shows an enrichment in surface oxygen (10.18 → 16.80 wt.%) and carbon (8.43 → 13.73 wt.%), consistent with prolonged exposure of the molten pool to ambient air with sustained heat input, which promotes oxide formation and thermally driven carbonaceous deposition. Second, the matrix elements (Ni, Cr, and Fe) are correspondingly diluted. These observations confirm that thermal accumulation not only reshapes the surface topography but also alters the near-surface chemistry through intensified oxidation.

(b) Modulation by Scanning Speed

For fixed laser power and spot diameter, scanning speed is inversely related to energy density: higher speed shortens the laser–material interaction time and lowers the energy input per unit area, with the resulting morphology shown in Figure 2(b₁–b₆). Within the stable groove regime, higher scanning speed reduces deposited energy per spot, decreasing melting/vaporization and groove depth. The brief interaction also amplifies the relative share of lateral heat diffusion: forward heat flow preheats the material ahead of the beam, broadening the groove slightly and yielding an overall “shallow and slightly wider” morphology.

As noted in Section 3.1(a), low-speed combinations with small pitch, large spot diameter, and high power produce severe inter-track heat accumulation and morphological degradation.

(c) Modulation by Spot Diameters

With laser power, scanning speed, and pitch fixed, increasing the spot diameter distributes the beam energy over a larger area and lowers the energy density. Within the stable groove regime, the actual groove width is jointly governed by the spot diameter and the material ablation threshold: reduced energy density weakens depth-direction removal (shallower grooves), while the enlarged spot diameter enhances lateral diffusion (wider grooves and reduced roughness), yielding a “shallow and distinctly wide” morphology, as illustrated in Figure 2(c₁–c₆).

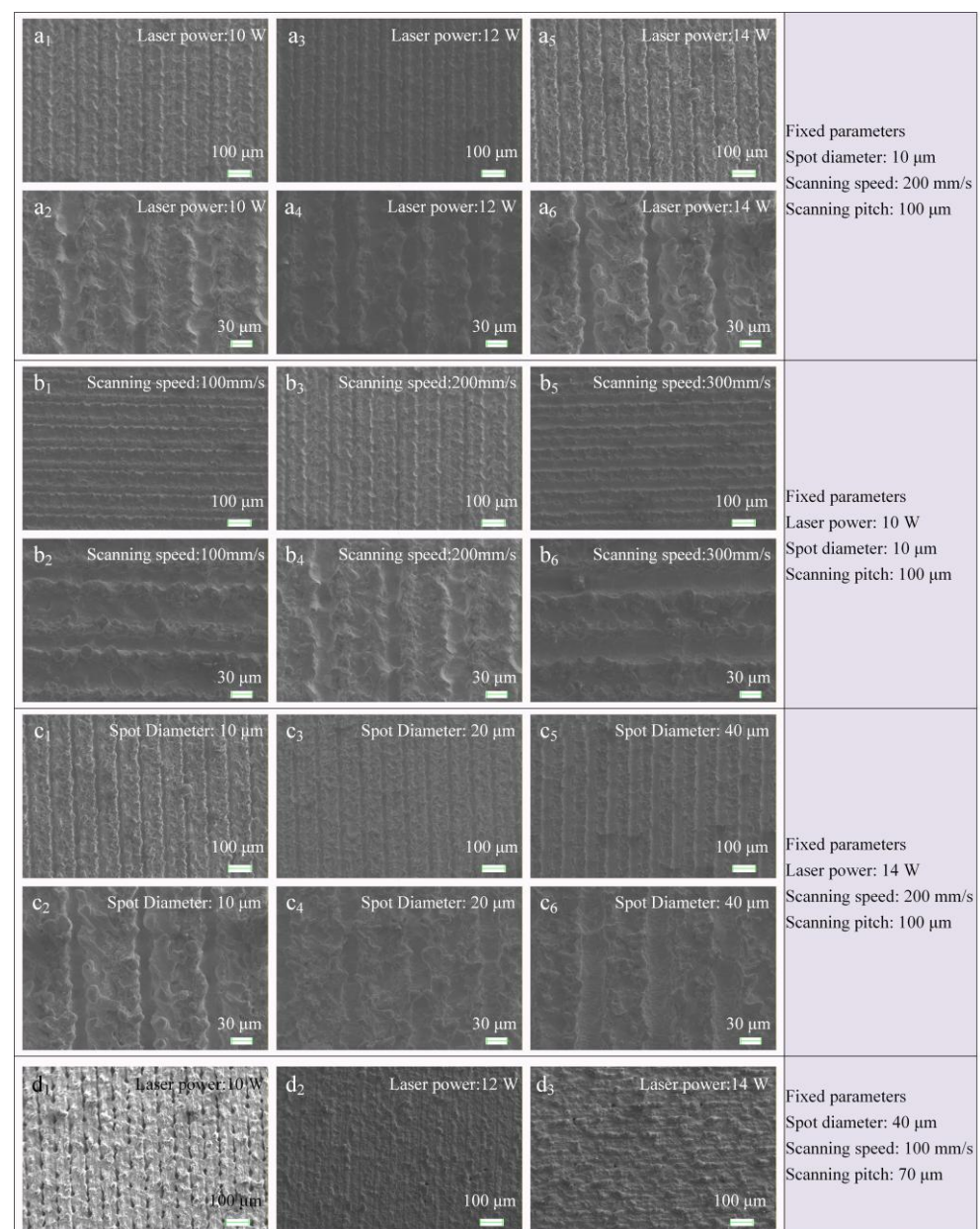


Figure 2. SEM images at different laser parameters. (a₁–a₆) Varying laser power (spot diameter 10 μm, scanning speed 200 mm/s, scanning pitch 100 μm). (b₁–b₆) Varying scanning speed (laser power 10 W, spot diameter 10 μm, scanning pitch 100 μm). (c₁–c₆) Varying spot diameter (laser power 14 W, scanning speed 200 mm/s, scanning pitch 100 μm). (d₁–d₃) Parameter combinations inducing heat accumulation (low speed, small pitch, large spot diameter, and high power).

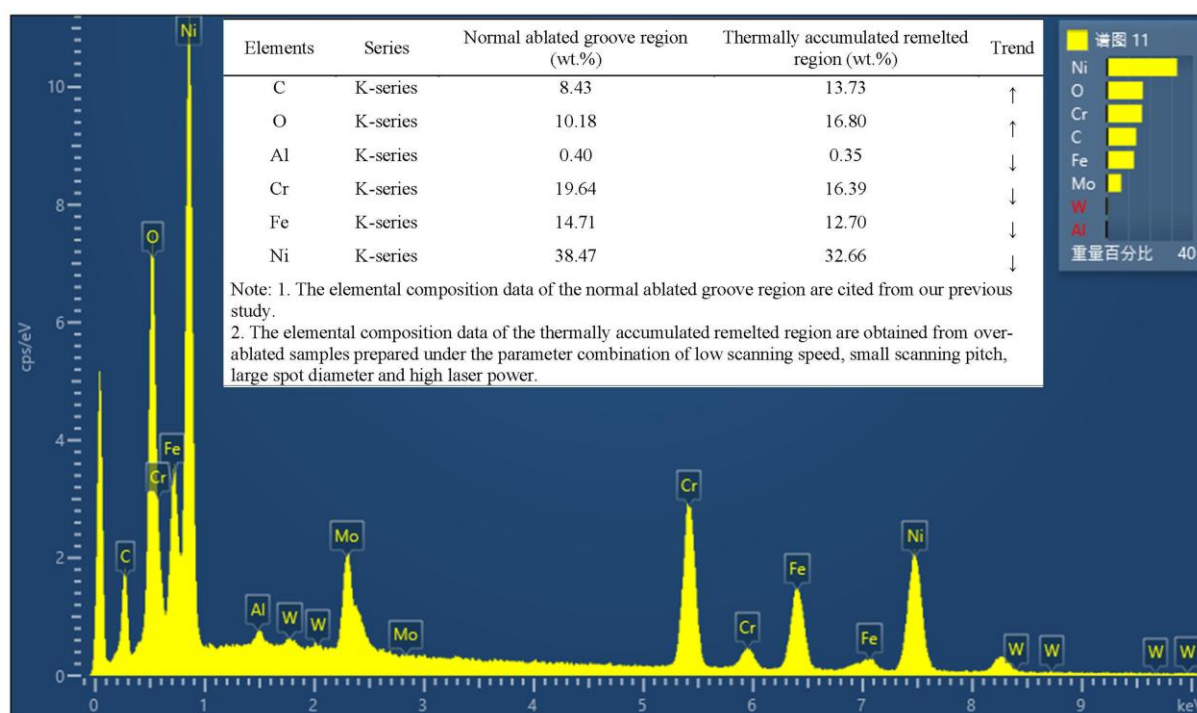


Figure 3. EDS spectrum and quantitative compositional comparison between the normal ablated groove and the thermally accumulated remelted region on the laser-processed GH3536 surface.

3.2. Wetting Behavior Analysis and Characterization

3.2.1. Static Wetting: Water Contact Angle

Building on Section 3.1, the influence of laser power, scanning speed, and spot diameter on the WCA is analyzed below; the results are presented in Figure 4.

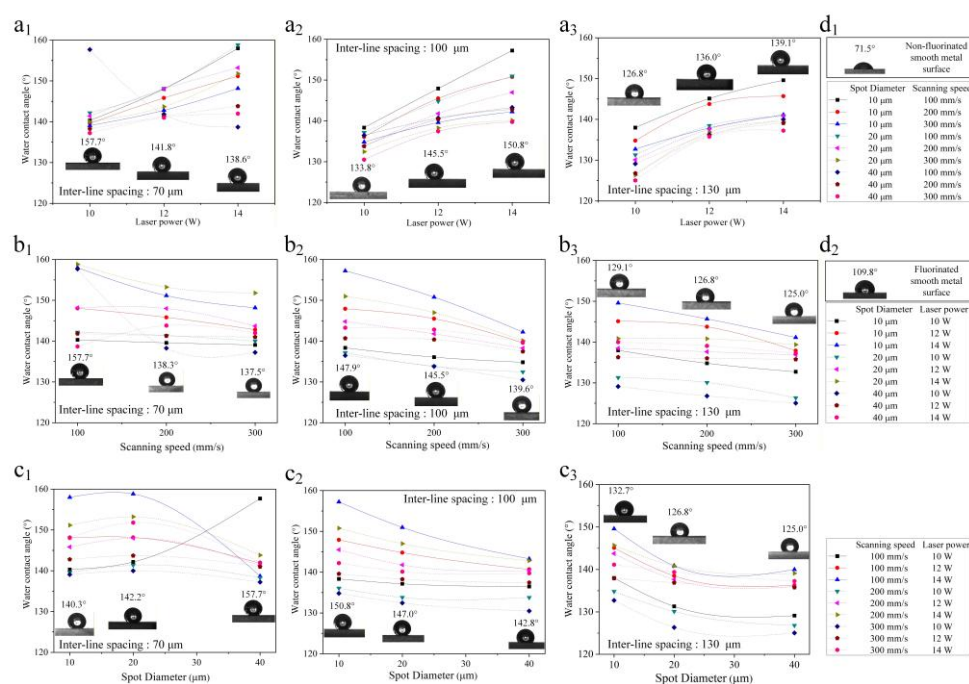


Figure 4. Effect of laser parameters on the WCA. (a1–a3) Variation in WCA with laser power. (b1–b3) Variation in WCA with scanning speed. (c1–c3) Variation in WCA with spot diameter. (d1–d2) WCA on fluorinated versus non-fluorinated smooth surfaces.

(a) Effect of Laser Power on WCA

As shown in Figure 4(a₁–a₃), at fixed spot diameter and scanning speed, the WCA increased monotonically with laser power from 10 W to 14 W within the stable groove regime, reaching 158.8°. The longitudinal energy concentration at higher power produces deeper grooves with slightly narrower widths as depicted in Figure 2(a₁–a₆), thereby increasing roughness and air entrapment and raising the WCA—consistent with Section 3.1(a).

It should be noted, however, that indiscriminately increasing laser power can compromise morphological integrity. For instance, at the slowest scanning speed with a spot diameter (40 µm) close to the scanning pitch (70 µm), higher power intensifies inter-track heat accumulation. At 12 W, groove edges became blurred due to remelting; at 14 W, the groove structure completely disappeared, as seen in Figure 2(d₁–d₃). In such cases, the rising trend in the WCA is reversed. These results indicate that parameter combinations involving low speed, small pitch, large spot diameter, and high power significantly increase the risk of thermal damage. Avoiding such mismatched sets is essential for preserving the micro-/nano-structures that promote hydrophobicity.

(b) Effect of Scanning Speed on WCA

At fixed spot diameter and laser power, the WCA decreased monotonically with scanning speed within the stable groove regime, as illustrated in Figure 4(b₁–b₃). Higher speed shortens interaction time and lowers energy density, producing shallower and slightly wider grooves (Figure 2(b₁–b₆)) that impair air entrapment and reduce the WCA to a minimum of ~125°—still well above the 109.8° measured on a fluorinated smooth surface (Figure 4(d₂)). This trend agrees with Section 3.1(b).

(c) Effect of Spot Diameters on WCA

At fixed laser power and scanning speed, the WCA decreased monotonically with spot diameter (10–40 µm) within the stable groove regime, as shown in Figure 4(c₁–c₃). Larger spots yield shallower, wider grooves, as evidenced in Figure 2(c₁–c₆), and weaker air entrapment, consistent with Section 3.1(c).

3.2.2. Quasi-Static Wetting: Contact Angle Hysteresis

CAH exhibits high sensitivity to microscopic surface heterogeneity and morphological pinning. This is evident from the treated smooth surfaces (Figures 4(d₁, d₂) and 5(d₁, d₂)): fluorination raised the WCA by nearly 30° yet lowered CAH by about 3°, confirming that CAH is governed primarily by micro-geometric features rather than surface chemistry. Although the EDS results in Figure 3 reveal localized oxygen and carbon enrichment in heat-accumulated regions, all samples subsequently received an identical FAS-17 monolayer; the post-modification surface chemistry is therefore not an independent variable across the parameter matrix, and within the stable groove regime the CAH variation is attributable to topography. Accordingly, following the morphological analysis framework of Section 3.1, the influence of laser power, scanning speed, and spot diameter on CAH is examined below, with results presented in Figure 5.

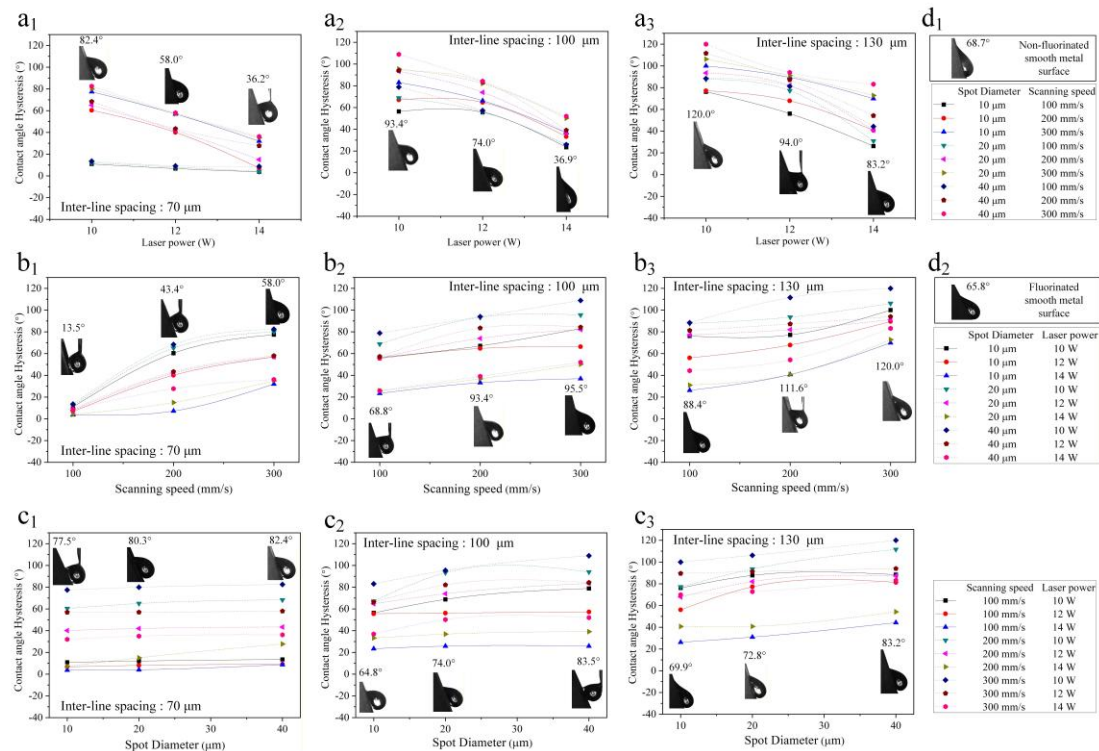


Figure 5. Effect of laser parameters on the CAH. (a₁–a₃) Variation in CAH with laser power. (b₁–b₃) Variation in CAH with scanning speed. (c₁–c₃) Variation in CAH with spot diameter. (d₁–d₂) CAH on fluorinated versus non-fluorinated smooth surfaces.

(a) Effect of Laser Power on CAH

As shown in Figure 5(a₁–a₃), with spot diameter and scanning speed held constant, the CAH demonstrated a monotonic decrease as the laser power increased from 10 W to 14 W—a trend generally opposite to that of the WCA. This opposing behavior is primarily governed by the reduction in the solid–liquid contact area. Regarding specific parameter sets: with a 14 W laser power, 100 mm/s scanning speed, 10 μm spot diameter, and 70 μm scanning pitch, the CAH as low as 3.7° was achieved on the engineered wedge structure, corresponding to the WCA of 158.0°. In contrast, under conditions of a 14 W laser power, 100 mm/s scanning speed, 20 μm spot diameter, and 70 μm scanning pitch, the WCA reached its maximum of 158.8°, while the CAH was 4°. These results indicate that although the WCA and CAH exhibit opposite macro trends, their extrema do not arise from the same set of parameters.

With the heat-accumulation–prone mismatches noted in Section 3.2.1(a), groove edges blur or vanish (Figure 2(d₁–d₃)), smoothing the surface; the WCA drops with reduced roughness, and the CAH drops with weakened pinning, both approaching the fluorinated smooth-surface values, as shown in Figure 4(d₂) and Figure 5(d₂), respectively.

(b) Effect of Scanning Speed on CAH

At fixed spot diameter and laser power, the CAH increased monotonically with scanning speed—opposite to the WCA trend (Figure 5(b₁–b₃)). Reduced energy density at higher speed yields shallower, wider grooves with weaker air entrapment, allowing droplet penetration into the microgrooves and enhancing solid–liquid adhesion, hence the rise in CAH.

(c) Effect of Spot Diameters on CAH

At fixed laser power and scanning speed, the CAH rose with spot diameter—opposite to the WCA trend, as shown in Figure 5(c₁–c₃). Larger spots drive a morphological transition from deep, narrow grooves that stabilize the Cassie–Baxter state

to shallow, wide grooves that favor the Wenzel state, expanding the solid–liquid contact and adhesion and thus markedly increasing CAH [39].

Consolidating the trends above, the measured CAH falls into three regimes per the classification of Wang et al. [40], corresponding to the dynamic behaviors of Samples 1–3 in Section 3.2.3: Cassie-dominated, Cassie–Wenzel transitional, and Wenzel, respectively. These thresholds are for qualitative reference only: they were obtained from tilt-to-slide tests on planar substrates, while our CAH was measured via the volume-increment method on 71° wedge structures. In addition, across the 81-combination matrix, Pearson correlation with scanning pitch gives $r = -0.49$ for the WCA and $r = +0.56$ for CAH (both $p < 0.001$), confirming that wider groove spacing lowers hydrophobicity and raises hysteresis. A full three-dimensional groove quantification is designated as future work (see Section 4).

3.2.3. Dynamic Wetting: Droplet Bouncing and Adhesion

To assess practical adhesion, droplet bouncing tests were performed on six configurations spanning a broad WCA–CAH range; three representative cases are presented in Figure 6. Samples 1 and 2 share similar WCAs but markedly different CAHs, isolating the role of CAH in droplet bouncing; Sample 3 (WCA = 158.0°, CAH = 3.7° on the engineered wedge structure) provides the lowest-CAH benchmark in the series. High-speed images of droplet bouncing on the three surfaces (Figure 6) reveal differences in rebound completeness, deformation, and residue.

(1) Sample 1 (WCA = 142.8°, CAH = 39.1° on the engineered wedge structure): At $T = 150$ ms the droplet showed pronounced stretching with a thickened tail, failed to retract and detach, and ultimately left a significant residue (Figure 6a). With its low WCA and high CAH, the surface favored the Wenzel state, where a large solid–liquid contact area produced strong adhesion, severe kinetic-energy dissipation, and high adhesion overall.

(2) Sample 2 (WCA = 143.3°, CAH = 25.8° on the engineered wedge structure): Stretching was reduced, but the droplet fractured at $\sim T = 300$ ms, leaving residue corresponding to roughly half of its original volume (Figure 6b). With a slightly higher WCA and a notably lower CAH than Sample 1, the surface lay in a Cassie–Wenzel transitional state, with adhesion moderate enough to retain part of the kinetic energy but insufficient for complete rebound.

(3) Sample 3 (WCA = 158.0°, CAH = 3.7° on the engineered wedge structure): The droplet underwent reversible, spindle-shaped stretching, and by $T = 300$ ms the main body had fully rebounded, leaving only minimal residue (Figure 6c). With a high WCA and the lowest CAH, the surface adopted a Cassie-dominated mixed state, in which a small effective solid–liquid contact area and low adhesion force produced near-ideal bouncing.

Together these results show that CAH influences dynamic adhesion far more strongly than the WCA. Although Samples 1 and 2 differ by only 0.5° in the WCA, lowering the CAH from 39.1° to 25.8° shifted the outcome from “significant residue” to “half-volume residue”; the larger CAH gap between Samples 2 and 3 (25.8° vs. 3.7°) further improved it to “minimal residue”. CAH is thus the key parameter governing dynamic droplet detachment—and the residue level in particular—on hydrophobic surfaces.

To confirm that this CAH–adhesion trend is not an artifact of narrow sample selection, three additional configurations (Samples 4–6) were tested across a wider CAH range (10.9°–74°), with WCAs clustered near 140–142°. All six followed the same monotonic trend: lower CAH yielded more complete rebound and less residue, regardless of the WCA. Notably, Samples 4 and 5 differed by only 0.2° in the WCA but 39.3° in CAH, and the lower-CAH sample showed markedly less residue—mirroring the Sample 1/2

comparison. These results confirm that CAH, rather than the WCA, governs dynamic detachment.

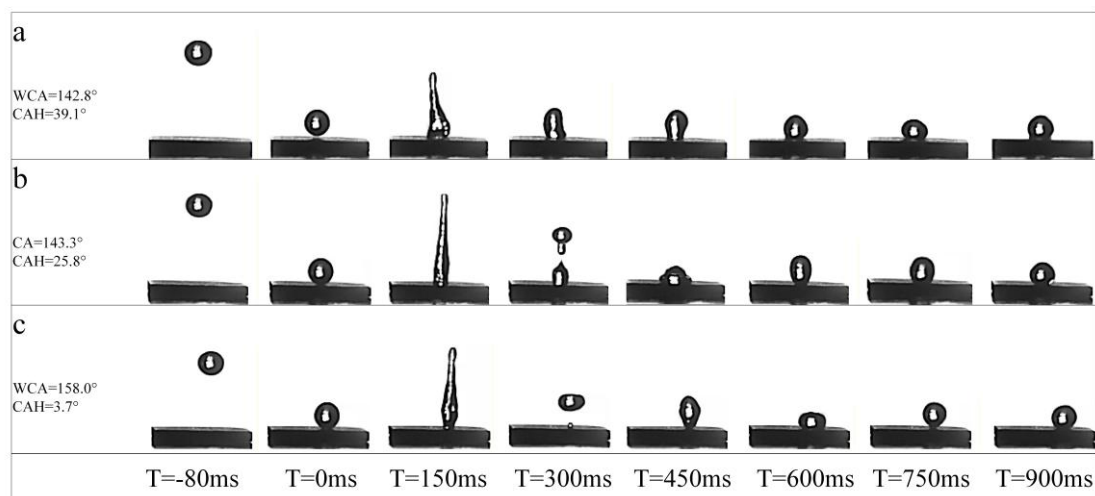


Figure 6. Snapshots of dynamic water droplet behavior with different CAH. (a) Dynamic behavior of Sample 1 (CAH = 39.1°). (b) Dynamic behavior of Sample 2 (CAH = 25.8°). (c) Dynamic behavior of Sample 3 (CAH = 3.7°).

3.3. Statistical Quantification of Multi-Parameter Impacts on Wettability

3.3.1. Main Effect

The results obtained from the full-factorial linear model and Type III sum-of-squares decomposition (Section 2.3) are summarized in Tables 1 and 2.

Tables 1 and 2 show that all four main effects on both the WCA and CAH attain $p < 0.001$, indicating high statistical significance. Ranked by contribution ratio, the relative importance for the WCA is laser power (34.69%) > scanning pitch (24.08%) > scanning speed (10.06%) > spot diameter (9.52%); for CAH it is laser power (33.68%) > scanning pitch (32.26%) > scanning speed (21.68%) > spot diameter (3.20%).

Both rankings place laser power first. A notable contrast, however, is that scanning pitch contributes 32.26% to CAH—essentially comparable to laser power and substantially higher than its WCA share. This statistically corroborates Section 3.2: CAH is highly sensitive to groove continuity and three-phase contact-line pinning, which scanning pitch directly governs.

Table 1. Full factorial ANOVA results for WCA.

Effect type	Source of variation	Sum of squares	df	F-value	p-value	Contribution ratio (%)	Significance
Main effect	P	1368.1	2	69.61	<0.001	34.69	Highly significant
Main effect	S	949.8	2	48.33	<0.001	24.08	Highly significant
Main effect	V	396.6	2	20.18	<0.001	10.06	Highly significant

Main effect	D	375.4	2	19.10	<0.001	9.52	Highly significant
Two-way interaction	P × D	122.1	4	3.11	0.024	3.10	Significant
Two-way interaction	D × S	108.5	4	2.76	0.038	2.75	Significant
Two-way interaction	P × S	80.8	4	2.06	0.102	2.05	Marginally significant
Two-way interaction	V × S	25.8	4	0.66	0.623	0.65	Not significant
Two-way interaction	P × V	22.9	4	0.58	0.678	0.58	Not significant
Two-way interaction	D × V	22.5	4	0.57	0.685	0.57	Not significant
Residual	Random error	471.7	48	—	—	11.96	—
Total	—	3944.2	80	—	—	100.00	—

Note: P = laser power; S = scanning pitch; V = scanning speed; D = spot diameter (used throughout).

Table 2. Full factorial ANOVA results for CAH.

Effect Type	Source of Variation	Sum of Squares	df	F-value	p-value	Contribution ratio (%)	Significance
Main effect	P	23871.94	2	249.97	<0.001	33.68	Highly significant
Main effect	S	22868.98	2	239.47	<0.001	32.26	Highly significant
Main effect	V	15371.25	2	160.95	<0.001	21.68	Highly significant
Main effect	D	2270.88	2	23.78	<0.001	3.20	Highly significant

Two-way interaction	$V \times S$	2108.48	4	11.04	<0.001	2.97	Highly significant
Two-way interaction	$P \times S$	765.46	4	4.01	0.007	1.08	Significant
Two-way interaction	$P \times V$	646.12	4	3.38	0.016	0.91	Significant
Two-way interaction	$D \times S$	406.32	4	2.13	0.092	0.57	Marginally significant
Two-way interaction	$P \times D$	179.92	4	0.94	0.448	0.25	Not significant
Two-way interaction	$D \times V$	104.08	4	0.54	0.704	0.15	Not significant
Residual	Random error	2291.91	48	—	—	3.23	—
Total	—	70885.34	80	—	—	100.00	—

3.3.2. Two-Way Interaction Effects and Coupling Mechanisms

The statistically significant two-way interactions are interpreted below via the interaction-effect-value matrices, with synergistic enhancement and mutual suppression identified.

(1) Significant interactions affecting WCA

For the WCA, two significant interactions ($P \times D$, $D \times S$) are obtained, with effect-value matrices in Tables 3 and 4.

The $P \times D$ term reflects a trade-off between energy input and energy-density distribution. At 10 W, increasing the spot diameter to 40 μm produces synergistic enhancement (+2.1°), raising the WCA via favorable coupling; at 14 W, the same change turns into mutual suppression (−2.1°), offsetting the high-power benefit and potentially inducing thermal damage that lowers the WCA (Table 3).

The $D \times S$ term governs the independence and integrity of the topography. A small spot (10 μm) paired with a large pitch (130 μm) yields synergistic enhancement (+1.6°), preserving independent deep grooves; conversely, a large spot (40 μm) with a large pitch (130 μm) yields mutual suppression (−2.0°), consistent with the heat-accumulation-induced groove remelting discussed in Section 3.2 (Table 4).

(2) Significant interactions affecting CAH

CAH is more sensitive to parameter coupling: three significant interactions ($V \times S$, $P \times S$, $P \times V$) emerge, with effect-value matrices in Tables 5–7.

The $V \times S$ term dominates among CAH interactions. At low speed (100 mm/s) with small pitch (70 μm), the effect is −9.5°, indicating that the coupling lowers CAH; at high speed (300 mm/s) with small pitch, it becomes +5.6°, indicating that the coupling raises CAH (Table 5).

For $P \times S$, decreasing pitch shifts the effect from positive to negative at 10 W (+0.5 → −2.2) and from negative to positive at 14 W (−0.2 → +1.9); at 12 W the values remain near zero across all pitches (Table 6).

For $P \times V$, the effect is negative for low- P /low- V (-1.8°) and high- P /high- V (-1.0°)—the coupling lowering CAH—and positive for low- P /high- V ($+1.2^\circ$) and high- P /low- V ($+1.6^\circ$)—the coupling raising CAH (Table 7).

(3) Comparison of WCA and CAH interaction mechanisms

The significant WCA interactions cluster around spot-diameter combinations ($P \times D$, $D \times S$), whereas the CAH interactions cluster around energy-input combinations ($V \times S$, $P \times S$, $P \times V$). CAH involves at least three significant interactions— $V \times S$ being highly significant—and is therefore more sensitive to coupling, making it the preferred core target for regulating dynamic droplet behavior. This contrast indicates that static and quasi-static wetting properties exhibit distinct sensitivity patterns to parameter coupling, and quantitatively distinguishing the two provides a reference for targeted process optimization.

Table 3. Interaction effect value matrix of $P \times D$ for WCA (unit: $^\circ$).

$P \backslash D$	10 μm	20 μm	40 μm
10 W	−1.1	−1.0	+2.1
12 W	−0.1	0.0	+0.1
14 W	+1.1	+1.0	−2.1

Table 4. Interaction effect value matrix of $D \times S$ for WCA (unit: $^\circ$).

$D \backslash S$	70 μm	100 μm	130 μm
10 μm	−1.9	+0.3	+1.6
20 μm	−0.2	0.0	+0.2
40 μm	+2.1	−0.1	−2.0

Table 5. Interaction effect value matrix of $V \times S$ for CAH (unit: $^\circ$).

$V \backslash S$	70 μm	100 μm	130 μm
100 mm/s	−9.5	+4.7	+4.8
200 mm/s	+3.9	+0.8	−4.7
300 mm/s	+5.6	−5.5	−0.1

Table 6. Interaction effect value matrix of $P \times S$ for CAH (unit: $^\circ$).

$P \backslash S$	70 μm	100 μm	130 μm
10 W	−2.2	+1.7	+0.5

12 W	+0.3	0.0	−0.3
14 W	+1.9	−1.7	−0.2

Table 7. Interaction effect value matrix of $P \times V$ for CAH (unit: °).

P\V	100 mm/s	200 mm/s	300 mm/s
10 W	−1.8	+0.6	+1.2
12 W	+0.2	0.0	−0.2
14 W	+1.6	−0.6	−1.0

Physically, these interaction patterns can be rationalized by the competition between per-track energy density and inter-track heat accumulation. For $V \times S$, low V (100 mm/s) combined with small pitch (70 μm) supplies excess per-spot energy, producing continuous, deep grooves that suppress three-phase contact-line pinning (CAH effect -9.5°); at high V (300 mm/s) with the same small pitch, low per-spot energy density yields shallow grooves with weak air entrapment, allowing droplet penetration into the grooves and enhancing solid–liquid adhesion (CAH effect $+5.6^\circ$). For $P \times S$, high P (14 W) with small pitch (70 μm) can drive excessive inter-track heat accumulation and edge remelting, as exemplified in Figure 2(d1–d3), increasing morphological heterogeneity and pinning (CAH effect $+1.9^\circ$), whereas low P (10 W) with the same small pitch yields dense, uniform grooves that suppress pinning (CAH effect -2.2°). These sign reversals are consistent with the groove morphologies in Figure 2(b1–b6) and (d1–d3) and the CAH trends in Figure 5. Although a full three-dimensional groove quantification is deferred to future work, the sign and magnitude of the interaction terms are consistent with the observed changes in groove geometry.

Notably, the quantitative contribution ratios in Tables 1–7 are specific to LPBF GH3536 within the studied nanosecond laser window and are not universal constants. Yet three qualitative mechanistic trends remain generalizable to laser texturing of comparable metallic systems. First, laser power stays dominant, rooted in energy-density-controlled ablation that governs groove geometry. Second, scanning pitch disproportionately affects CAH over the WCA, due to the material-independent nature of three-phase contact-line pinning. Third, interaction patterns differ: the WCA is driven mainly by spot-diameter couplings, while CAH is dominated by energy-input couplings, reflecting their respective reliance on gross roughness and local contact-line heterogeneity. While absolute effect magnitudes shift with an alloy’s ablation threshold, thermal conductivity and native oxide properties, the mechanistic hierarchy of parameter importance transfers across similar laser-textured metal surfaces.

4. Conclusions

To address the challenge of precisely controlling the surface wettability of additively manufactured metal components, this work systematically examined how laser processing parameters influence the surface morphology, static/quasi-static wettability, and dynamic droplet behavior of LPBF-fabricated GH3536 nickel-based superalloy. By integrating full-factorial experiments, multi-scale characterization, and ANOVA, a clear “laser parameters–surface morphology–wetting behavior” relationship was established,

offering practical guidelines for the controllable fabrication of wettability-tunable metallic surfaces. The main conclusions are as follows:

(a) A clear mapping among laser processing, surface morphology, and wettability is established. Within parameter sets that maintain stable micro-groove morphology, increasing laser power, decreasing scanning speed, or reducing spot diameter all promote micro-grooves of higher aspect ratio, enhancing roughness and air entrapment, raising the WCA, and lowering the CAH.

(b) CAH is identified as the key parameter governing dynamic droplet bouncing. By comparing surfaces with similar WCAs but markedly different CAHs, CAH is shown to influence dynamic behavior (bouncing and detachment) far more strongly than the WCA, confirming that minimizing CAH through process optimization is essential for low-adhesion, easy-shedding hydrophobic surfaces.

(c) Parameter mismatch can reverse surface performance: uncoordinated adjustments trigger heat accumulation that remelts grooves, erodes the micro-/nano-structures, and degrades wettability. Achieving stable hydrophobicity therefore requires precise multi-parameter matching to prevent thermal damage.

(d) The main and two-way interaction effects on wettability were quantified. Laser power is the primary factor for both the WCA and CAH, while scanning pitch contributes to CAH almost as much as laser power. Significant WCA interactions involve mainly spot-diameter combinations, whereas significant CAH interactions involve mainly energy-input combinations—indicating distinct sensitivities of the two wetting properties to parameter coupling.

In contrast to prior studies focused on configuration optimization for specific anti-icing performance, this work probes the more fundamental and general mechanisms of wettability regulation. It provides concrete process guidance for functional micro-textures on additively manufactured superalloy surfaces and, more importantly, clarifies the dominant role of CAH in dynamic wetting behavior, shifting surface design from static “hydrophobicity” to dynamic “adhesion control”. Although motivated by the practical needs of wedge-shaped structures on aviation intake temperature sensors, the conclusions also provide theoretical guidance for applications requiring rapid droplet shedding, anti-icing, and self-cleaning.

Three limitations of this work should be acknowledged. First, the established process–wettability mapping is specific to unidirectional parallel grooves on LPBF GH3536. For other common surface geometries (e.g., micropillar arrays, dimples, and cross-hatched meshes), differences in contact-line configuration and air-pocket connectivity may yield distinct parameter sensitivity rankings, though the ANOVA-based analytical framework remains transferable. Second, the quantitative contribution ratios are bounded by GH3536’s thermophysical properties and the particularities of the laser texturing process. For other alloy systems or non-laser surface modification methods (e.g., chemical etching and plasma texturing), the absolute effect magnitudes will differ accordingly, yet the ANOVA-based analytical framework remains broadly applicable as a reference. Third, all wettability measurements were conducted under standard ambient static conditions on FAS-17 organosilane-modified surfaces. While such surfaces maintain stable hydrophobicity during long-term static storage, their durability under harsh service conditions (abrasion, erosion, and high-shear flow) remains unevaluated. Notably, the laser-fabricated groove topography is an intrinsic substrate feature with far higher mechanical robustness than the overlying organic monolayer; after mild wear, hydrophobicity can be restored simply by re-fluorination without re-fabricating the microstructures.

Future work could investigate the wettability evolution and long-term durability of these laser-structured surfaces in extreme environments (e.g., low temperature, high

pressure, or corrosive media). Building on established protocols for laser-textured metallic surfaces [22,40], systematic cross-sectional SEM imaging will be performed to quantitatively resolve groove depth, width, and aspect ratio, and thereby establish the geometry–wetting correlations that top-view SEM alone cannot provide. In addition, machine-learning methods will be incorporated to enable intelligent prediction and inverse design of surface morphology and performance.

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