

High-Speed Imagery Analysis of Droplet Impact on Van der Waals and Non-Van der Waals Soft-Textured Oil-Infused Surfaces.

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ABSTRACT

This study investigates the impact of surface functionalization, oil coating, and oil absorption on droplet impact behavior on textured polydimethylsiloxane (PDMS) substrates. The textured surfaces were fabricated with square micro-posts having spacings of 5 and 20 microns. The PDMS samples were functionalized with octadecyltrichlorosilane (OTS) to improve water repellency. Following this, the surfaces were either coated with or allowed to absorb two different lubricants: silicone oil (SO-5cSt) and hexadecane. We performed detailed wetting measurements on both untreated and OTS-functionalized substrates. These measurements provided useful insights into how water and lubricants were retained and distributed under static conditions. High-speed imaging was used to capture droplet impact across a range of Weber numbers. On SO-5cSt-absorbed substrates, droplets consistently showed complete rebound at all Weber numbers, regardless of post spacing. This robust rebound was attributed to the oil's ability to fill the gaps between the posts through capillary action, while also forming a stable lubricating layer above the texture. This thin oil film reduced friction between the droplet and the surface, enabling the droplet to retain sufficient energy for complete rebound. In contrast, hexadecane-absorbed substrates displayed different dynamics. At low Weber numbers, only partial rebound was observed, while at intermediate values, droplets rebounded completely. However, droplets no longer rebounded at higher Weber numbers and remained deposited. Repeated droplet impacts further demonstrated that hexadecane-infused surfaces gradually lost oil from the textured gaps, resulting in a decline in rebound performance over time. This effect was not observed with SO-5cSt, underscoring the importance of lubricant affinity and stability.

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1. Introduction

The interaction of liquid droplets with solid surfaces has fascinated scientists and engineers since Worthington's pioneering observations in 1876.¹ It began as a curiosity about the complex, crown-like shapes produced upon impact, and has evolved into a critical research area with wide-ranging technological implications.¹ Droplet impact dynamics, including spreading, retraction, rebound, and breakup, directly influence processes such as agricultural spraying, spray cooling, surface coating, inkjet printing, combustion, and even forensic investigations^{2–6}. When a droplet strikes a rigid surface, it undergoes deformation, entrains a thin air pocket, and, at sufficiently high impact velocities, produces splashing that may either form a crown (corona splashing) or eject secondary droplets directly from the spreading lamella (prompt splashing).^{7–11} The distinction between these splashing modes has significant implications in fields where the trajectory and size distribution of satellite droplets determine system efficiency and safety, such as fuel combustion^{10,12,13} and the transmission of pathogens.¹⁴

Despite decades of study, the physics governing droplet impact remains incomplete, as modern high-speed imaging continues to reveal unanticipated features of this seemingly simple yet complex phenomenon. Surface design has emerged as a powerful tool to tune droplet dynamics. Superhydrophobic surfaces, which trap air in their textured microstructures, have long been studied for their water-repellent properties.^{7,15–17} However, these surfaces suffer from practical limitations, as the air layer is highly unstable and susceptible to collapse during impact, under pressure, or in the presence of surface defects. Inspired by the *Nepenthes* pitcher plant, lubricant-infused surfaces (LIS) have been introduced as robust alternatives, where a lubricating oil film replaces air pockets.¹⁸ These surfaces offer ultra-low contact angle hysteresis, mechanical self-healing, pressure stability, and resistance to fouling or icing, making them highly attractive for real-world applications.^{18–25} Since the early 2000s, researchers have drawn inspiration from nature, particularly from superhydrophobic surfaces like those found on lotus leaves and rose petals, to fabricate similar surfaces using various polymers and patterning techniques. With the successful biomimicry of these textured non-wetting surfaces, studies explored their static and dynamic wettability characteristics. When gently placed on a micropatterned surface, a water droplet typically settles into either the Cassie–Baxter or Wenzel wetting state. Traditionally, studies have focused on how droplets interact statically with textured surfaces, particularly how they penetrate surface features. Patankar^{26,27} developed a theoretical framework to describe how liquids infiltrate the gaps

between micropillars. Building on this, Nonomura et al.²⁸ used high-speed imaging to capture the moment a water droplet entered a pore on a silicone surface.

One early investigation by Yong Chae Jung and Bharat Bhushan²⁹ focused on how droplet impact velocity affects wetting behavior on micro- and nanopatterned surfaces. In their study, the researchers examined droplet impacts on various surfaces with different wettabilities, including silicon micropillars, carbon nanotube (MWCNT) arrays, and nanopatterned PMMA surfaces. They observed that higher impact velocities on silicon micropillars and PMMA surfaces caused a transition from a non-wetting (Cassie–Baxter) state to a wetting (Wenzel) state, where the droplet stuck to the surface. In contrast, the MWCNT surface allowed the droplet to bounce off even at higher velocities. Based on these observations, the authors proposed a predictive model that relates this transition to surface geometry and liquid properties, enabling the estimation of the critical impact velocity at which a droplet will adhere. These findings are essential for designing superhydrophobic surfaces that retain water-repellent behavior under real-world, dynamic conditions. In a similar study, Ying-Song Yu et al.³⁰ conducted droplet impact experiments on PDMS surfaces with post-arrays of varying solid fractions. The results showed that surfaces with lower solid fractions allowed droplet rebound only at lower impact velocities. When the Weber number exceeded a critical threshold, a transition from the Cassie–Baxter to the Wenzel wetting state was observed. A predictive model was developed to capture this behavior, and the maximum spreading was found to follow a $We^{0.25}$ scaling law. In a follow-up study^{31,32}, he investigated droplet impact on PDMS surfaces with varying solid fractions, featuring microgrooves and different post spacings and shapes. The key finding was that the solid fraction significantly influences droplet bouncing dynamics, affecting both rebound behaviour and wetting transitions.

Researchers have fabricated a variety of soft, textured surfaces using materials such as PDMS and PMMA to study droplet impact behaviour.³³ They examined how these parameters influence droplet dynamics by varying surface features, solid fraction, and wettability. Smooth PDMS surfaces, when infused with lubricant, have also been studied for their wettability, particularly in applications aimed at preventing anti-icing and biofouling.^{33–35} Several studies have highlighted that oil absorption in PDMS leads to different bouncing phenomena.³⁶ However, only a few investigations have explored the combined effects of solid fraction, softness, and the effect of coating and absorption of different lubricants in the porous soft surface on static and dynamic wettability.

In this study, we prepared PDMS surfaces with square post textures having post spacings of 5 μm and 20 μm . We then examined how surface treatment and lubrication methods influence droplet interaction with these textured PDMS surfaces. Two lubricants, silicone oil (SO-5cSt) and hexadecane, were applied either as a surface coating or absorbed into the substrate. Using high-speed imaging and contact angle measurements, we tracked the spreading, retraction, and rebound of droplets under a wide range of impact conditions. This study provides a clear understanding of how texture, surface chemistry, and lubricant type affect droplet impact dynamics across different Weber numbers. The findings demonstrate a simple approach to designing SLIP surfaces with strong water repellency, which could be useful for applications in droplet handling, self-cleaning, and microfluidic devices.

2. Experimental Section

Sample preparation and surface characterization

Microtextured silicon surfaces with 10 μm square posts, interpost spacings of 5 μm and 20 μm , and heights of 10 μm were fabricated using a standard photolithographic process.³⁷ the microtextured PDMS surfaces were fabricated using a soft lithography process from these microtextured silicon surfaces.^{38,39} The soft-textured surfaces were prepared using PDMS (Sylgard 184, Dow Corning, Wiesbaden, Germany). The commercially available liquid PDMS was mixed with a curing agent in a 10:1 ratio (PDMS to curing agent)⁴⁰. The detailed fabrication process of textured PDMS from textured silicon surface is explained in the supporting information.) These soft-textured PDMS surfaces were functionalized using octadecyltrichlorosilane (OTS, Sigma-Aldrich) via a liquid phase deposition method³⁷ (explained in the supporting information). This treatment imparted non-polar, low-surface-energy characteristics to the surface, significantly affecting lubricant retention and droplet interaction behavior.^{30,41–47} According to contact angle measurements, OTS reports⁴⁸ a free surface energy of 26mN /m².

The choice of lubricant is essential for obtaining stable LIS. The lubricant must be immiscible with water and have a similar viscosity to that of the impacting liquid, i.e $\mu_{oil} \approx \mu_{water}$. In addition, the lubricant should have a suitable affinity for binding to the surface. In this study, we selected two lubricants, one with a higher affinity for the OTS & PDMS surface and the other with a lower affinity. LIS formed with lubricants of higher surface affinity are referred to as Van der Waals SLIPs (VdW SLIP), while those with lower affinity are termed non-Van der Waals SLIPs (nVdW SLIP). The affinity of a lubricant for the OTS surface was

assessed by measuring its equilibrium contact angle (Eq. CA) on the OTS-functionalized PDMS surface. For strong affinity, the Eq. CA must remain below 5° , confirming stable wetting of the lubricant on the surface.⁴⁹ We measured Eq.CA and contact angle hysteresis (CAH) of SO-5cSt and Hexadecane on the OTS-coated smooth PDMS surfaces in the air and DI water environment using a Ramé-Hart Model 500-U1 Advanced Goniometer. Thus, we chose two lubricants that fit our criteria: SO-5cSt and hexadecane.

The post spacing on the textured surface is another crucial parameter for stability. The stability of the SLIPs can be considered based on the advancing and receding contact angles (shown) and the critical contact angle of the textured surface (as shown in Supplementary Information, Tables S2 and S3). The supporting information provides detailed explanations of the measurement and calculation of the above parameter. It's important to note that if the receding angle is greater than the critical contact angle, $\theta_{rec,os(a)} > \theta_c$, then the lubricant film won't spontaneously spread onto the textured surface,⁴⁹ i.e., the textured surface is unstable for that particular lubricant. However, when $\theta_{rec,os(a)} < \theta_c$, the lubricant film spreads onto the textured surface, and the impregnating liquid film remains stable.⁴⁹ Thus, to have a stable SLIPs configuration when coated with lubricant, we chose the 5 μ m and 20 μ m post spacing sample. Further to check the lubricant's affinity toward the surface, we determine the Hamaker constant using combining rules (Shown in supplementary material). The effective Hamaker constant quantitatively measures the VdW forces between surfaces, which is crucial for predicting the stability and behaviour of thin films.

The samples were coated with lubricant by dipping them into a reservoir and then withdrawing them at a controlled speed (V) to maintain a ($Ca = \mu_o V / \gamma_{oa}$) capillary number of 10^{-5} . This method ensured a uniform lubricant layer without leaving excess oil on the surface. In this equation, μ_o is the dynamic viscosity and γ_{oa} is the surface tension of the lubricant. By keeping the capillary number constant at 10^{-5} , the withdrawal speed (V) was adjusted to achieve the same lubricant thickness despite differences in viscosity. For both SO-5cSt and hexadecane, the withdrawal speed was selected based on the capillary number to ensure a consistent oil thickness across all experiments. In this manner, microtextured surfaces with varying post spacings were functionalized with OTS and subsequently coated with the two lubricants, resulting in vdW and nvdW LIS, as illustrated in Figure 1. Four textured PDMS-OTS samples coated with lubricants, i.e., PDMS-OTS_(5 μ m)(SO-5cSt-coated), PDMS-OTS_(20 μ m)(SO-5cSt-coated), PDMS-OTS_(5 μ m)(Hexa-coated), and PDMS-OTS_(20 μ m)(Hexa-coated). It has been observed that

when the textured PDMS surfaces are dip-coated with both lubricants, a stable configuration is formed, i.e., the oil is retained between the microtextures. This was confirmed through microscopic imaging and theoretical calculations.⁴⁹ However, over time, the lubricant trapped between consecutive microtextures gradually gets absorbed into the PDMS matrix due to the material's inherent porosity.^{19,50,51} This absorption leads to slight surface deformation, trapping the oil within the PDMS elastomer.^{42,52,53} Thus, to check the effect of absorption on the wettability and droplet impact, we added one more sample set in which the textured PDMS surface was absorbed into the lubricant.

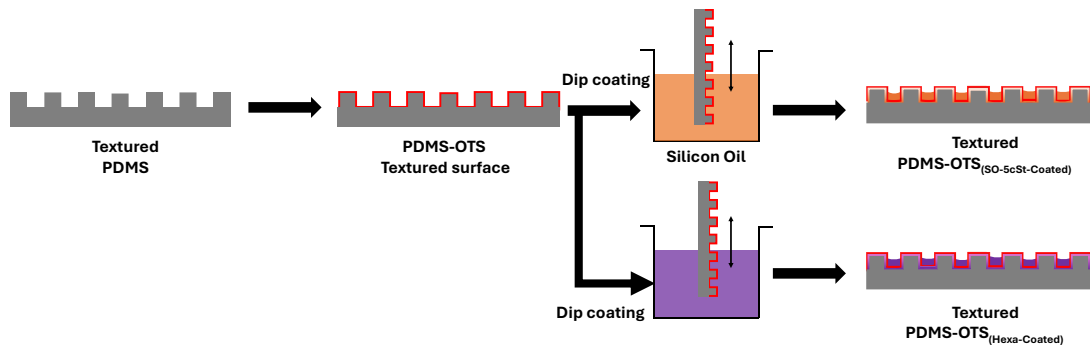


Figure 1. Schematic representation of the fabrication of textured PDMS-OTS when coated with SO-5cSt and hexadecane lubricant.

For the absorbed textured PDMS, the lubricant was allowed to absorb into the PDMS to study the effect of a bulk oil phase. The textured PDMS surfaces were immersed in the oils (SO-5cst and hexadecane) for the absorption samples and left to soak for 24 hours.³⁹ Thus, four textured PDMS-OTS samples were absorbed with lubricants, as shown in Figure 2. i.e., PDMS-OTS(5 μ m)(SO-5cSt-Absorb), PDMS-OTS(20 μ m)(SO-5cSt-Absorb), PDMS-OTS(5 μ m)(Hexa-Absorb), and PDMS-OTS(20 μ m)(Hexa-Absorb). Before the droplet impact tests, the oil-absorbed samples were recoated with lubricant to ensure a uniform oil layer on the surface.⁵⁴ To assess the formation of a thin layer on the surface.

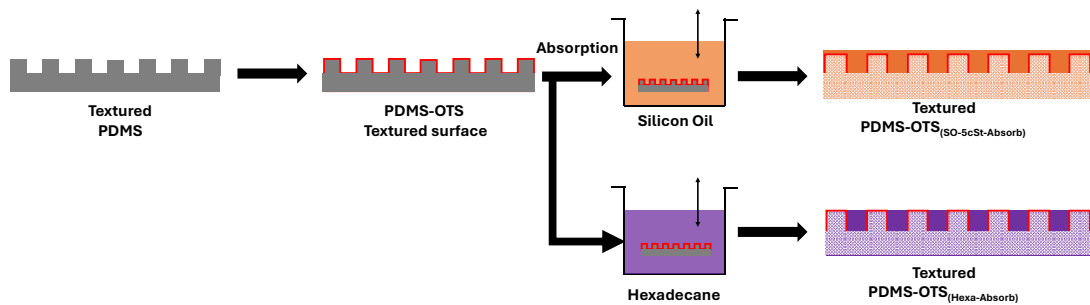


Figure 2. Schematic representation of the fabrication of textured PDMS-OTS when absorbed with SO-5cSt and hexadecane lubricant.

Droplet Impact Setup

Droplet impact experiments were carried out by placing the samples on a flat metal surface. Droplets with a diameter of 2.8 mm were produced from the tip of a Teflon-coated needle connected to a syringe pump, which was operated at an infusion rate of 1 ml/hr using a Harvard Apparatus syringe pump. The impact velocity (V_i) of the droplets was controlled by varying the fall height between 4 and 70 cm, giving velocities from 0.88 to 3.70 m/s. Initial tests showed distinct droplet behaviors within this velocity range. Based on these observations, four Weber numbers (We) were chosen: 28, 63, 127, and 245, covering a broad range from low to high values. The Weber number, defined as $We = (\rho D V_i^2 / \sigma)$, represents the ratio of inertial to surface tension forces, where σ is the surface tension, ρ is the water density, and D is the droplet diameter. Droplet impact dynamics were recorded from the side using a Phantom VEO 410 high-speed camera at a resolution of 1280×720 and a frame rate of 5000 frames per second. A high-intensity light source was positioned behind the substrate, ensuring that the light, substrate, and camera were aligned on the same optical axis, as illustrated in Figure 3. Video analysis was performed with MATLAB, while ImageJ was used to extract data from images representing different stages of droplet impact. In total, 250 videos were captured and analyzed to improve the accuracy of droplet impact measurements.

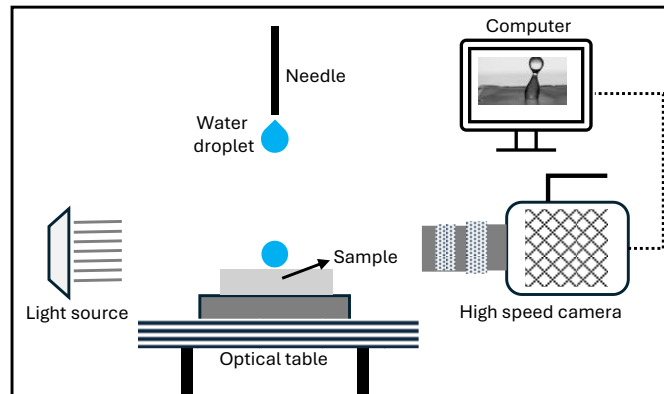


Figure 3. Schematic diagram of droplet impact setup.

3. Results and Discussions

Stability and Surface Wettability

The stability of the oil infused in the textured PDMS surface can be explained through a thermodynamic framework, considering the interfacial energies at distinct interfaces. There are twelve possible configurations within a four-phase system where oil impregnation occurs.⁴⁹ This thermodynamic framework allows us to predict which of these 12 states will be stable for a droplet, oil, and substrate. In our previous study by the same authors,¹⁸ we extensively

discussed the existence of four stable states, building upon those findings and considering contact angle measurements in the present case, both Hexadecane and SO-5cSt will exhibit stable configurations in air and water environments for post spacings of 5 μm and 20 μm .

Figure 4 illustrates the measured contact angle hysteresis (CAH) for PDMS-OTS surfaces under different configurations. Figure 4. (a) shows CAH values for textured PDMS-OTS substrates with post spacings of 5 μm and 20 μm . An apparent increase in CAH was observed with increasing spacing. This trend can be attributed to the reduced solid fraction at larger spacings, which enhances contact line pinning due to the collapse of air pockets and the increased exposure of the underlying substrate to water movement. In 5 μm post spacing, an air layer is present beneath the water droplets (Cassie-Baxter state), which ultimately leads to reduced CAH. The increase in the post spacing strongly influences the wetting behavior of textured surfaces. The square posts at 20 μm spacing result in a Wenzel state, where water penetrates between the constituent posts and replaces the trapped air. This causes more pronounced contact line distortion during droplet advancement and recession, leading to higher contact angle hysteresis. Figure 4(b) shows the CAH for the same surfaces coated with two lubricants, SO-5cSt and hexadecane. In the cases of 5 μm post spacing, there is not much significant change in the CAH. This is because the air layer underneath the droplet in the uncoated case is now replaced by Lubricating oil. In coated samples, lubricant infusion significantly reduces CAH, particularly on the 20 μm textured surface. This occurs because the infused oil fills the post spacing, reducing contact line pinning and thereby lowering CAH compared to the uncoated 20 μm PDMS surface.

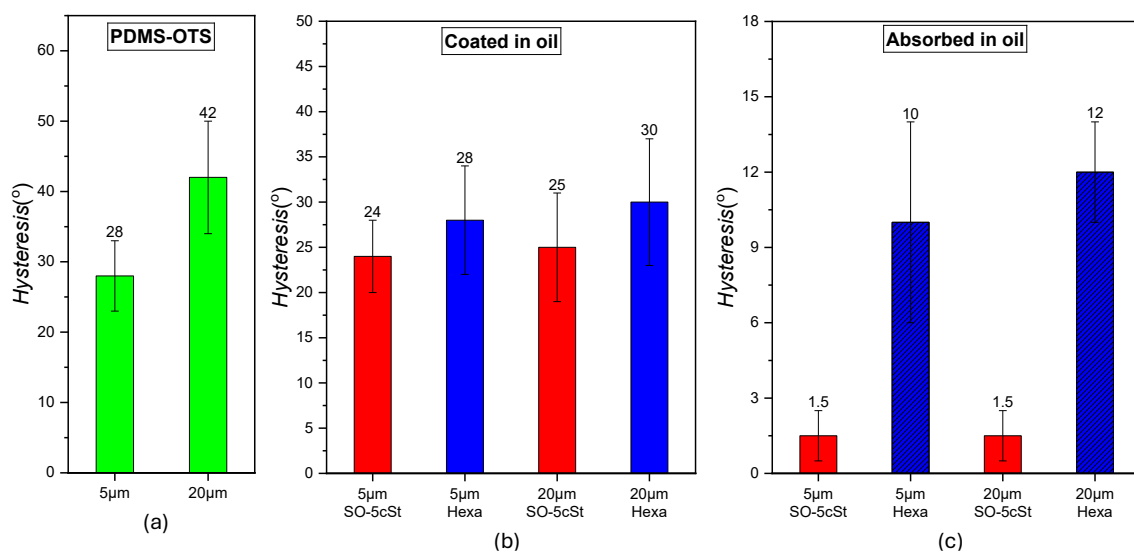


Figure 4. Summary of contact angle hysteresis data for 5 and 20 μm post spacing for (a) PDMS-OTS samples, (b) PDMS-OTS samples coated with different lubricants, and (c) PDMS-OTS samples absorbed with different lubricants. Error bars indicate the standard deviation from ten independent measurements.

Silicone oil-coated surfaces with 5 and 20 μm post spacing exhibit only a very slight decrease in CAH compared to hexadecane-coated samples. This behavior arises from the chemical similarity between silicone oil and PDMS, which promotes a stronger affinity. However, this affinity does not significantly influence the wettability of the textured PDMS surface when coated with different lubricants. This is because of the porous nature of PDMS, where the lubricant on the top of the posts is rapidly absorbed into the matrix, exposing the OTS-functionalized tops directly to air. In contrast, the space between the posts acts as micro-reservoirs that retain oil for longer. Although the oil in these gaps also gradually absorbs into the PDMS, the confined geometry delays this process, leaving a thin lubricant film within the valleys as seen in Figure 5, which illustrates oil distribution on the textured PDMS-OTS surfaces after coating. This uneven absorption results in a hybrid wetting state, where the droplet experiences a mix of lubricated and exposed regions during impact or spreading. This diminishes the overall lubricating efficiency and results in larger CAH. To summarise the CAH trends observed for the coated samples: $\text{PDMS-OTS}_{(20\mu\text{m})} > \text{PDMS-OTS}_{(5\mu\text{m})} > \text{PDMS-OTS}_{(20\mu\text{m})(\text{Hexa-coated})} > \text{PDMS-OTS}_{(5\mu\text{m})(\text{Hexa-coated})}$, $\text{PDMS-OTS}_{(20\mu\text{m})(\text{SO-5cSt-coated})} > \text{PDMS-OTS}_{(5\mu\text{m})(\text{SO-5cSt-coated})}$.

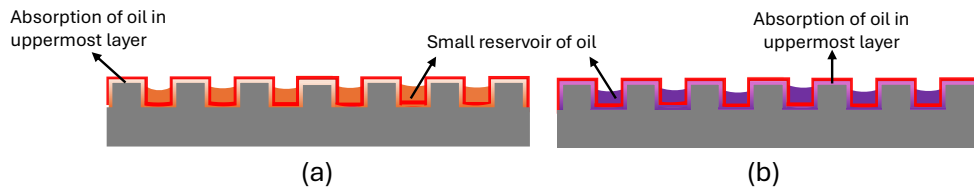


Figure 5. Schematic showing the lubricant distribution on OTS-functionalized textured PDMS surfaces: (a) SO-5cSt (orange) and (b) Hexadecane (purple). The red line indicates the OTS-functionalized layer on the textures.

The CAH measurements for textured PDMS-OTS samples absorbed with lubricant revealed interesting trends, as shown in Figure 4(c). The SO-5cSt absorbed PDMS-OTS samples for 5 and 20 μm post-spacing; both, i.e., ($\text{PDMS-OTS}_{(5\mu\text{m})(\text{SO-5cSt-Absorb})}$ and ($\text{PDMS-OTS}_{(20\mu\text{m})(\text{SO-5cSt-Absorb})}$) surfaces exhibited significantly lower CAH values. This behavior can be attributed to the complete absorption of low-viscosity oil into the substrate and the oil being trapped between the posts due to capillary force. This forms a thin lubricant film at the surface (Figure 6(a)). This continuous oil film reduces the solid-water interfacial interaction, resulting in lower CAH. In contrast, the CAH values for textured PDMS-OTS samples for 5 and 20 μm post-spacing absorbed with hexadecane, i.e., for $\text{PDMS-OTS}_{(5\mu\text{m})(\text{Hexa-Absorb})}$, PDMS-

OTS_(20μm)(Hexa-Absorb) are significantly higher than those observed for SO-5cSt absorbed samples. This increased CAH can be attributed to the absence of a stable thin lubricant film at the surface.²⁵ However, the oil present between the posts gives sufficient lubrication to the water droplet. Thus, the CAH of textured PDMS-OTS absorbed in hexadecane has a lower CAH when compared with the textured PDMS-OTS sample coated with hexadecane (see Figure 4(b&c)). To summarise the CAH trends observed for the lubricant absorbed samples: PDMS-OTS_(20μm) > PDMS-OTS_(5μm) > PDMS-OTS_(5μm)(Hexa-Absorb) > PDMS-OTS_(20μm)(Hexa-Absorb), PDMS-OTS_(5μm)(SO-5cSt-Absorb) > PDMS-OTS_(20μm)(SO-5cSt-Absorb).

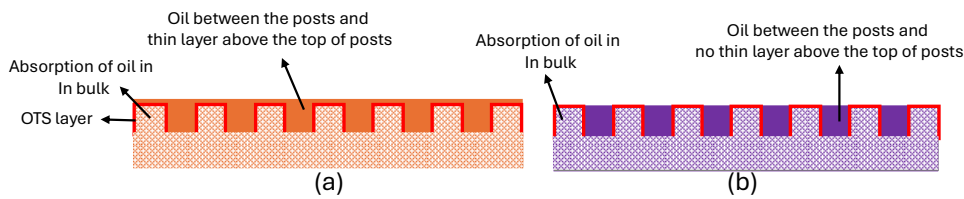


Figure 6. Schematic showing the lubricant absorption into OTS-functionalized textured PDMS (a) SO-5 cSt (orange) and (b) Hexadecane (purple). The red line indicates the OTS-functionalized top layer, while the shaded region represents oil absorbed into the PDMS matrix.

The above Figure 6 illustrates lubricant distribution after 24 hours of absorption into the textured PDMS-OTS surface. During this period, oil is absorbed into the porous PDMS matrix until it reaches its saturation limit. For the SO-5cSt lubricant (left), the oil can penetrate deeply and uniformly into the entire PDMS matrix, including the textured region and the top surface. This results in forming a stable and continuous thin lubricating film, known as a SLIPS (Slippery Liquid-Infused Porous Surface), supported by the oil's favorable interaction with the PDMS-OTS. Consequently, SO-5cSt is present both in the texture grooves and on the tops of the posts, creating a uniformly lubricated surface that remains stable in both air and water environments. In contrast, for hexadecane (Figure 6(b)), although bulk absorption into the matrix occurs over 24 hours, the lack of a strong interaction with PDMS-OTS inhibits thin film formation on the top surface. Instead, the oil remains primarily within the grooves between posts, forming a stable but localized reservoir of lubricant. The top surface of the posts (PDMS-OTS) remains exposed to air due to insufficient film formation. This results in a hybrid wetting state during droplet interaction, where the droplet partially contacts the exposed solid, i.e., PDMS-OTS, and partially interacts with the lubricated grooves. The theoretical calculation, wettability measurements, and CAH analysis supported such behavior.

Effect of Lubricant on Droplet Impact Dynamics

Before analyzing droplet impact dynamics on textured PDMS-OTS surfaces coated or absorbed with SO-5cSt and hexadecane, it is essential to understand the baseline behavior first. This involves studying droplet impact on textured PDMS-OTS surfaces without any lubricant. Such a comparison provides critical insight into the role of lubricant in altering wetting, spreading, and rebound behavior. Figure 7(a and b) illustrates droplet impact on OTS functionalized PDMS surfaces with 5 and 20 μm post spacing at different Weber numbers, respectively. For 5 μm spacing, a complete rebound is observed at lower Weber numbers, as the droplet cannot overcome the high capillary pressure and remains in the Cassie-Baxter state. At higher Weber numbers, partial rebound occurs due to water penetrating the texture.

In contrast, droplets exhibit complete deposition on the 20 μm surface even at lower Weber numbers. The larger post spacing reduces the capillary barrier, allowing the droplet to enter the texture and transition toward a Wenzel state. This leads to greater energy dissipation and suppresses rebound. As a result, kinetic energy is insufficient to support rebound. These trends underscore the crucial role of texture spacing in determining the wetting state and its influence on the outcome. The theoretical explanation for this is provided in the Supporting Information. These results are consistent with previous research on droplet impact on textured surfaces.^{18,30–32,55,56}

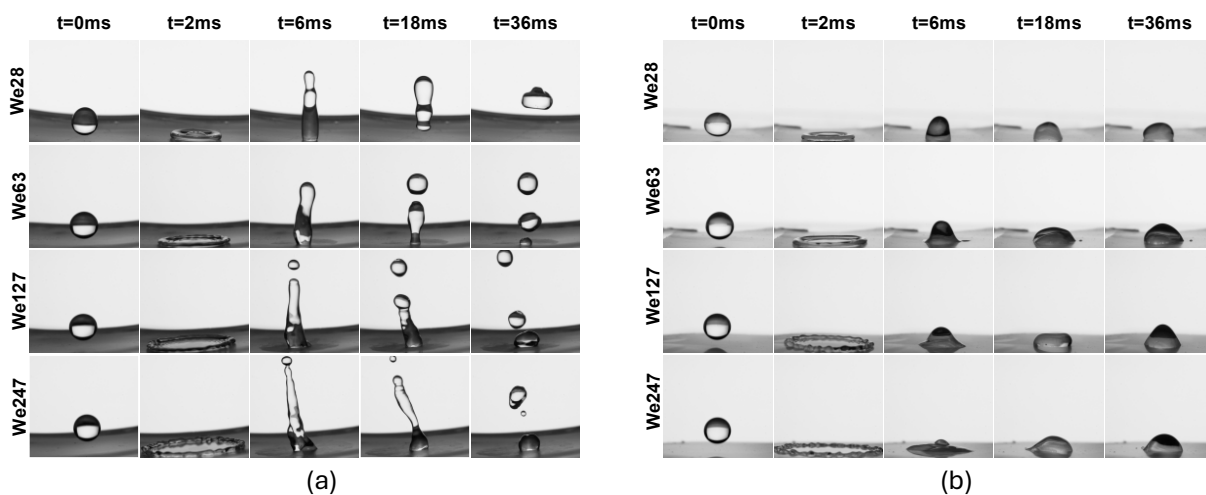


Figure 7 Time-resolved images showing droplet impact dynamics on textured PDMS-OTS surfaces with (a) 5 μm and (b) 20 μm post spacing across varying Weber numbers.

Textured PDMS-OTS Coated with Lubricant

In our previous study, we coated textured silicone surfaces with silicone oil and hexadecane to create Van der Waals and non-Van der Waals liquid-infused surfaces. When applying the same approach to textured PDMS surfaces, it was initially expected that the lubricant would remain trapped between adjacent micro-posts, forming stable reservoirs similar to those in conventional liquid-infused surfaces. However, observations from an optical microscope, contact angle measurements, and droplet impact experiments showed that the oil was retained between the posts for only a limited time. This behavior can be attributed to the intrinsic porosity of PDMS, which enables the lubricant to gradually absorb into its upper layer. This reduces the amount of oil between the posts, as shown in Figure 5. Such absorption has been reported previously and is consistent with the well-recognized porous characteristics of PDMS^{39,41,57}. As a result, the top surface of the microstructures remains predominantly exposed to air, giving rise to a heterogeneous wetting regime where both solid-air and liquid-oil interactions coexist. Figure 8 and Figure 9 illustrate the temporal evolution of droplet impact dynamics on textured PDMS surfaces functionalized with OTS (Textured PDMS-OTS) and subsequently coated with different lubricants for 5 and 20 μm post spacing, respectively.

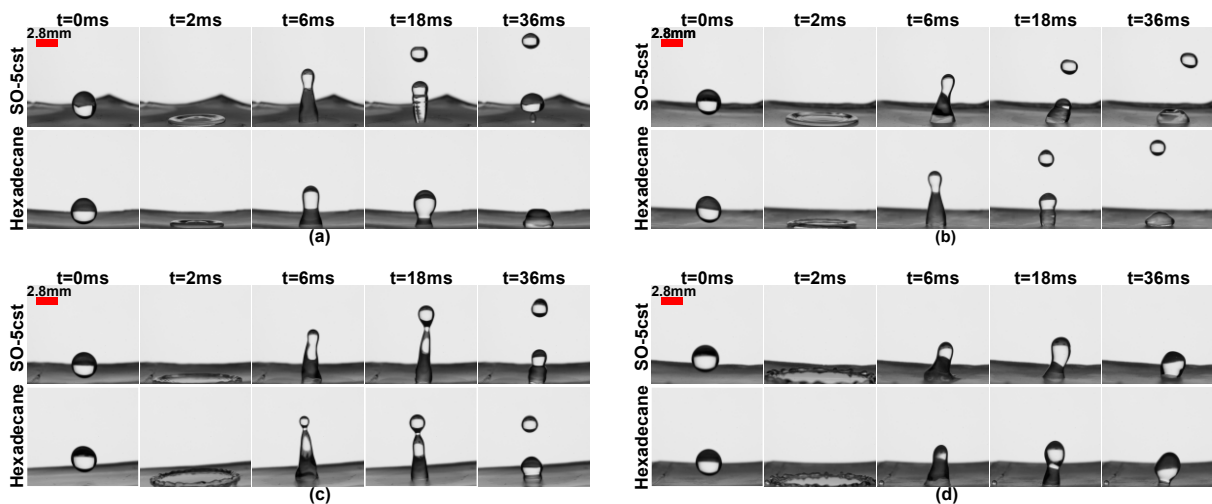


Figure 8. Droplet impact on textured PDMS-OTS samples with post spacing of 5 μm when coated with a different oil at the different Weber numbers (a) $We = 28$, (b) $We = 63$, (c) $We = 127$, (d) $We = 247$.

Figure 8 illustrates the droplet impact dynamics on the post spacing of 5 μm for the range of Weber numbers. At a lower Weber number ($We = 28$), Figure 8 (a) distinct differences in droplet behavior are observed between uncoated PDMS-OTS textured surfaces (Figure 7 ($We=28$)) and those coated with lubricants such as SO-5cSt or hexadecane. During the impact, due to heterogeneous wetting, oil reservoirs within the gaps offer localized viscous damping,

while the exposed micro post tops hinder the spreading. This asymmetric surface condition introduces drag and resistance to the droplet's lateral motion during the spreading and retraction phases, ultimately suppressing the recoil and resulting in partial rebound. In contrast, on the uncoated PDMS-OTS surface for $5\mu\text{m}$ (Figure 7(a)), characterized by a trapped air cushion between the microstructures. Since the droplet lacks sufficient kinetic energy at low Weber numbers to penetrate the texture, it predominantly interacts with the air layer, enabling near-frictionless retraction and complete rebound.

At intermediate $We = 63$ and 127 , Figure 8(b and c), both lubricants. This partially allows the droplet to infiltrate the textured structure. Interestingly, the bouncing behavior on lubricant-coated surfaces becomes qualitatively similar to that observed on uncoated PDMS-OTS surfaces (see Figure 7(a)). However, the degree of rebound, characterized by reduced rebound height and spreading diameter, remains lower. This behavior can be attributed to enhanced viscous dissipation from the droplet's contact with the residual oil in the textured gaps. The lubricant provides additional resistance to the recoiling lamellae, thus damping the rebound. At higher Weber numbers, $5\mu\text{m}$ particles coated with SO-5cSt lubricant partially enter the texture and push out some of the oil from the gaps. This results in additional energy loss due to viscous resistance. As a result, the droplet does stick and can not slide back, showing no rebound. Similarly, in hexadecane-coated PDMS-OTS surfaces, the bouncing behavior is not different, as hexadecane exhibits a comparatively weaker affinity for the PDMS-OTS matrix due to lower van der Waals interaction. When a droplet impacts the hexadecane-coated surface, the kinetic energy drives the water into the texture, rapidly displacing the weakly bound hexadecane. As the droplet penetrates and displaces the oil, it directly interacts with the solid PDMS-OTS substrate. This increases adhesion and energy dissipation, causing the droplet to complete deposition rather than partial rebound, which was observed in an uncoated PDMS-OTS $5\mu\text{m}$ textured surface (see Figure 7). Thus, the PDMS-OTS $5\mu\text{m}$ textured surface coated with hexadecane and SO-5cSt behaves like an unlubricated hydrophobic substrate under high Weber number impacts.

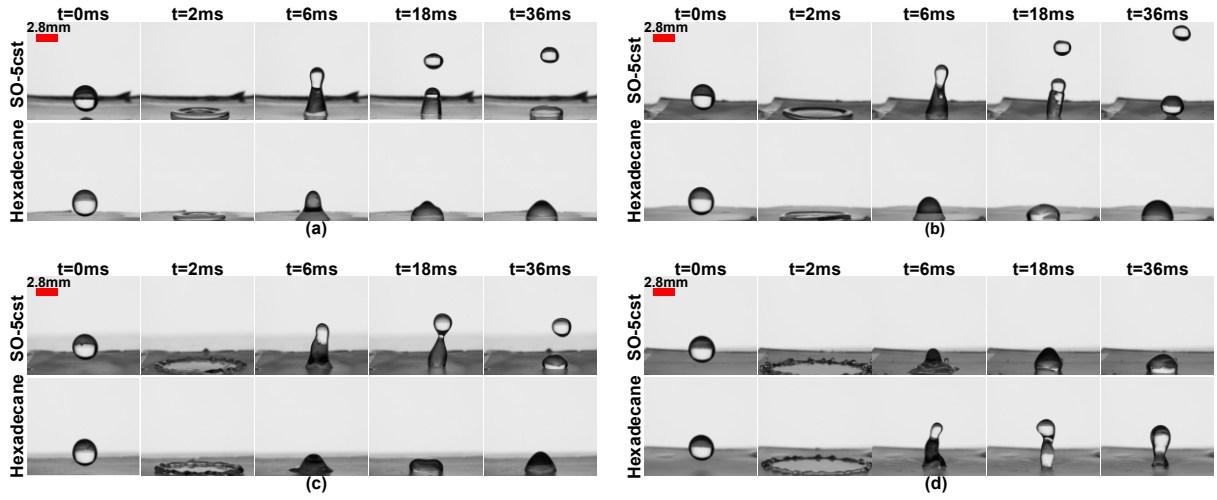


Figure 9. Droplet impact on textured PDMS-OTS samples with post spacing of $20\mu\text{m}$ when coated with a different oil at the different Weber numbers (a) $We = 28$, (b) $We = 63$, (c) $We = 127$, (d) $We = 247$.

Figure 9 illustrates the droplet impact behavior on $20\mu\text{m}$ textured PDMS-OTS surfaces coated with SO-5cSt and hexadecane lubricants. For the SO-5cSt-coated surface, the partial rebound was consistently observed across the entire range of Weber numbers, except at higher Weber numbers. This behavior can be attributed to the droplet penetrating the textured surface during impact and displacing the excess lubricant stored in the texture gaps. However, a residual oil film remains at the interface, preventing direct contact between the water and the PDMS-OTS substrate, thereby enabling partial rebound. However, at higher Weber numbers, this residual oil layer is also removed, resulting in complete adhesion of the water droplet to PDMS-OTS and no rebound.

The droplet impact resulted in complete deposition on the hexadecane-coated $20\mu\text{m}$ textured PDMS-OTS surface. During impact, the droplet easily displaced the loosely bound hexadecane from the texture gaps, leading to direct water contact with the PDMS-OTS surface. Since the inherent stickiness of PDMS-OTS dominates in the absence of an oil barrier layer, the droplet adheres and does not rebound, similar to its behavior on the uncoated PDMS-OTS surface (see Figure 7(b)). These observations underscore the crucial influence of both lubricant type and micro-post spacing on droplet impact behavior over textured, oil-absorbing PDMS surfaces. The ability of the lubricant to form a stable film and its retention within the textured matrix directly affect the spreading, rebound, and deposition outcomes. The distinct responses observed with SO-5cSt and hexadecane highlight how variations in oil retention and film stability influence the overall impact dynamics, driven by the interaction between the lubricant and the porous PDMS substrate.

Textured PDMS-OTS Absorbed with Lubricant

To investigate the effect of droplet impact dynamics on lubricant-absorbed PDMS-OTS surfaces, samples were prepared by allowing the substrates to uptake SO-5cSt silicone oil and hexadecane, respectively, following the protocol described in the experimental section. Water droplet impact experiments on the SO-5cSt absorbed textured PDMS-OTS surface revealed a complete rebound across the full range of Weber numbers tested for both micro post spacings of 5 μm and 20 μm , as shown in the top row of Figure 10 and 12. This rebound behavior indicates that this absorbed SO-5cSt oil forms a stable lubricating layer that spreads evenly over the top of the square post and within the microstructured gaps between posts, enhancing surface uniformity and stability. The layer of oil on the top of the square post is sufficiently thick to avoid exposing bare PDMS-OTS, yet thin enough to prevent significant viscous drag on the impacting droplet. As a result, the surface presents a low-adhesion, low-friction interface that facilitates efficient droplet rebound by reducing both contact line pinning and viscous dissipation. At higher Weber numbers, particularly around $We \approx 230$, an additional dynamic behavior was observed during the droplet retraction phase for 5 μm and 20 μm post-spacing samples infused with SO-5cSt (see Figure 10(d) for $We = 247$). Following the initial spreading phase, as the droplet retracts, instabilities form near the rim at its maximum spread diameter. These manifest as several thin, thread-like filaments emerging around the perimeter of the droplet. Eventually, the filaments rupture, leading to the ejection of tiny satellite droplets that momentarily surround the main droplet. This phenomenon is likely a result of the high retraction speed at elevated Weber numbers, where inertial forces dominate over capillary forces. The instability may also arise from complex interactions at the three-phase boundary involving air, water, and the thin surface-absorbed oil layer, particularly at the rim where the interface curvature and local velocity gradients are highest.

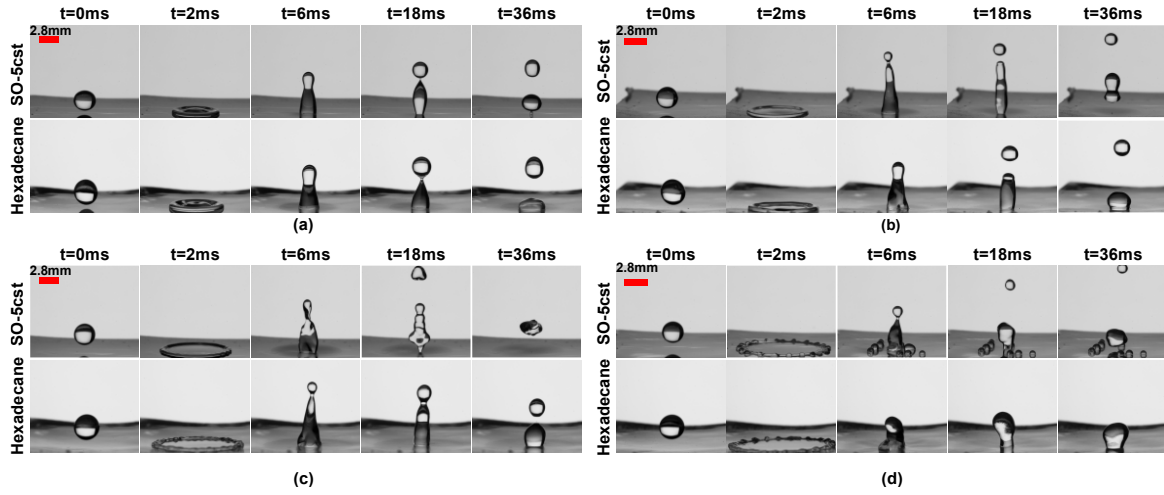


Figure 10. Droplet impact on textured PDMS-OTS samples with post spacing of $5\mu\text{m}$ when absorbed with a different oil at the different Weber numbers (a) $We = 28$, (b) $We = 63$, (c) $We = 127$, (d) $We = 247$.

Despite this transient rim instability, the droplet retains sufficient momentum and coherence to completely recoil from the surface at high-impact velocities in both post-spacing cases. The ability of the surface to support such rebound, even after rim fragmentation, highlights the strong compatibility and interaction between the SO-5cSt lubricant and the OTS-functionalized PDMS. The oil is not visibly displaced or removed during impact, suggesting that the lubricant layer remains stable and intact throughout the process. The oil absorbed into the bulk of the PDMS contributes to maintaining a continuous, slippery interface that resists water adhesion even under high kinetic energy conditions. These results collectively indicate a strong intermolecular affinity between SO-5cSt oil, OTS, and the PDMS-OTS substrate, which contributes to the stable retention of the lubricant and enhances the surface's anti-wetting performance.

For textured PDMS-OTS surfaces absorbed with hexadecane (See Figures 11 and 12 bottom row), different impact dynamics were observed, including complete rebound, partial rebound, and no rebound, depending on the Weber number and post spacing. At a post spacing of $5\mu\text{m}$ (Figure 11), where the solid fraction is high and no stable thin film forms over the square micro-posts (For hexadecane), droplets exhibited partial rebound at lower and intermediate Weber numbers. This suggests that the available kinetic energy was insufficient to overcome the inherent adhesive forces of the PDMS-OTS surface, leading to the partial rebound of the water droplet. However, at a higher Weber number ($We \approx 247$), the droplet sticks to the surface entirely. This non-rebounding behavior can be attributed to the weak affinity between hexadecane and the PDMS-OTS substrate. Unlike SO-5cSt, which has stronger van der Waals interactions with PDMS-OTS, hexadecane does not form a robust

lubricant film. During high-speed impacts, this weak interaction allows the water droplet to displace the hexadecane from the textured valleys and penetrate the gaps between posts, resulting in direct contact with the solid substrate. This solid-water contact enhances droplet pinning and adhesion, effectively suppressing rebound and resulting in complete deposition.

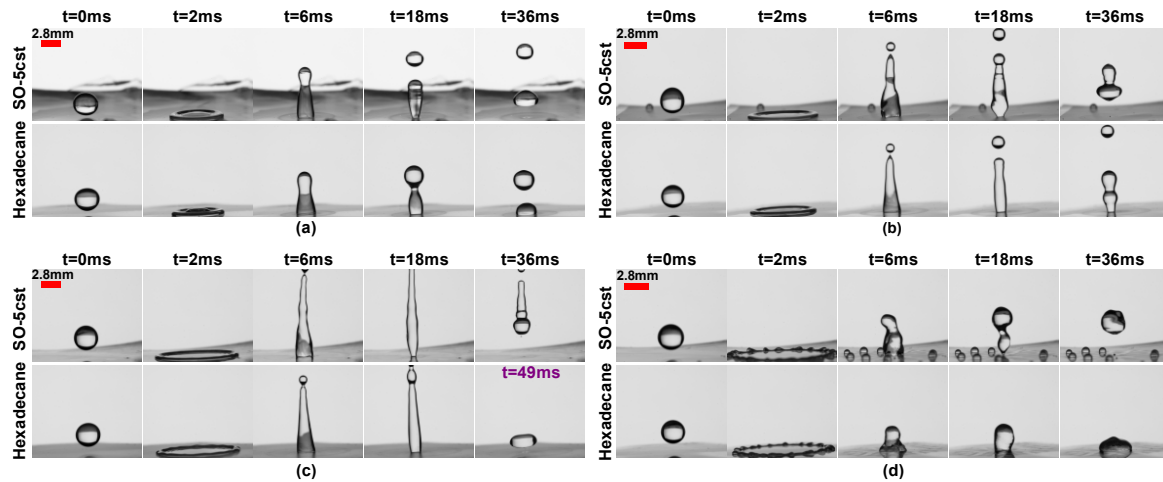


Figure 11. Droplet impact on textured PDMS-OTS samples with post spacing of $20\mu\text{m}$ when coated with a different oil at the different Weber numbers (a) $We = 28$, (b) $We = 63$, (c) $We = 127$, (d) $We = 247$.

Figure 12 shows a distinct trend in bouncing behaviour, ranging from partial to complete rebound, and no rebound was observed for the $20\mu\text{m}$ post-spacing when absorbed in the hexadecane. At low Weber numbers, droplets exhibited partial rebound due to insufficient kinetic energy to overcome surface adhesion, see Figure 11 (a). The complete rebound was observed in the intermediate Weber number range ($We \approx 63\text{--}127$), Figure 11 (b and c). This is primarily attributed to the lower solid fraction of the $20\mu\text{m}$ texture, which reduces the contact area and enables easier droplet recovery. The oil, absorbed mainly into the porous PDMS matrix, also leaves minimal resistance at the top surface, allowing for efficient recoil. However, droplets impacting hexadecane-coated surfaces exhibited complete deposition at higher Weber numbers Figure 11(d). This is due to the weak affinity of hexadecane for the PDMS-OTS surface, which allows the lubricant to be displaced during impact, resulting in direct contact between the textured substrate and water. The enhanced pinning and adhesion at high-impact velocities suppress rebound, leading to complete droplet deposition.

Influence of Weber Number on Drop Impact Dynamics

The Weber number, which summarises the influence of impact velocity relative to surface tension, is crucial in determining droplet impact dynamics. A series of experiments was conducted across a range of Weber numbers to investigate its effect, with a focus on how it

governs the spreading and retraction behavior of impacting droplets. Figure 7, Figure 8, Figure 10, and Figure 11 present sequential time-lapse images that capture the stages of droplet deformation and rebound on surfaces with 5 μ m and 20 μ m post spacings, each functionalized with OTS and subsequently coated with either SO-5cSt or hexadecane. One of the most common methods for analyzing the Weber number's influence is monitoring the droplet's maximum spreading diameter. As depicted in Figure 12 and

Figure 13. This diameter increases consistently with a rising Weber number for all surface types studied.

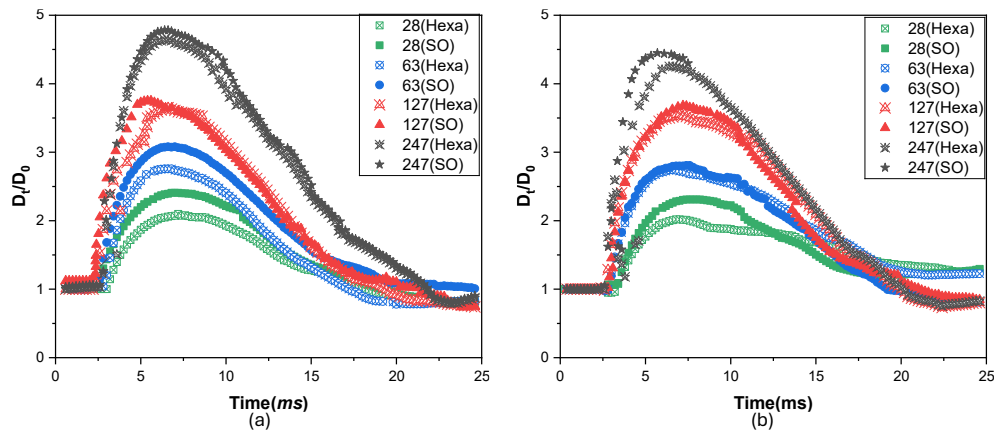


Figure 12. Time development of the diameters of the hitting droplet lamellas for the two different surfaces of PDMS-OTS (a) 5 μ m and (b) 20 μ m post spacing when coated with SO-5cSt and hexadecane for different Weber numbers.

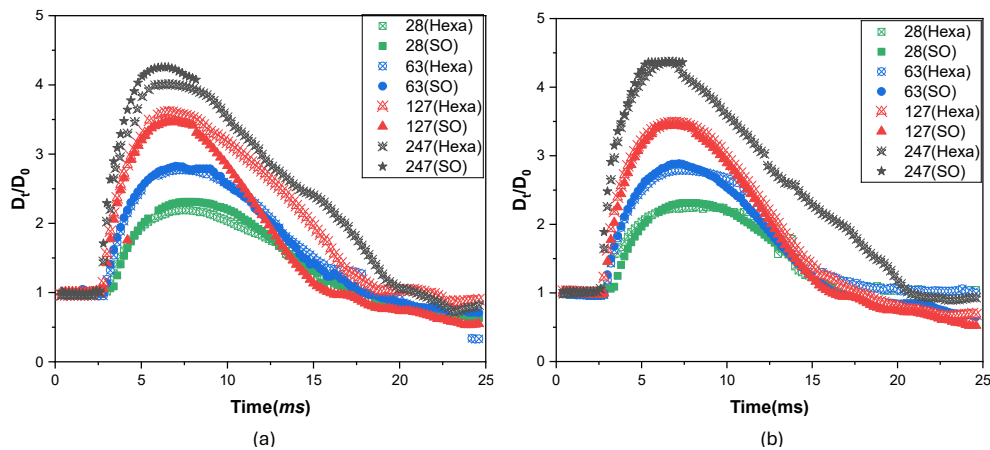


Figure 13. Time development of the diameters of the hitting droplet lamellas for the two different surfaces of PDMS-OTS (a) 5 μ m and (b) 20 μ m post spacing when absorbed with SO-5cSt and hexadecane for different Weber numbers.

Although this behaviour aligns with established findings in droplet dynamics, its interpretation on lubricant-coated textured surfaces warrants further analysis using a scaling-

based approach. The dynamic contact angle at the three-phase composite interface strongly influences the spreading behaviour of droplets on textured PDMS-OTS surfaces coated and absorbed with lubricants. These experimental surfaces possess low solid fractions, making the composite interface prone to disruption under dynamic conditions such as impact. This results in a transition from the Cassie-Baxter to the Wenzel wetting state, increasing the solid-liquid contact area and thus enhancing viscous dissipation, significantly affecting droplet spreading. To quantify spreading, the non-dimensional maximum spreading factor, this model predicts that the maximum spreading factor β_{max} scales with the Weber number as $\beta_{max} \sim We^{\frac{1}{4}}$, which has been reported in experiments^{58–60} for the low-viscosity liquids.⁷ Kim et al.¹²⁶ highlighted that the scaling law for maximum spreading can differ between superhydrophobic surfaces and LIS. Specifically, for LIS, the scaling is expressed, $\beta_{max} = \left[1 + \left(\frac{t}{h}\right) \left(\frac{\mu_w}{\mu_o}\right)\right]^{0.5} We^{\frac{1}{4}}$, where t is the oil film thickness, and h is the thickness of the maximum spreading droplet. small viscous-oil correction that only becomes important when the oil layer is a non-negligible fraction of the pancake thickness (i.e. $\left(\frac{t}{h}\right)$ or when μ_o is much smaller than μ_w). In our case $t \ll h$ and μ_o is comparable to or larger than μ_w , so the prefactor ≈ 1 . Thus the for the SLIPs and LIS with less thickness and low viscosity oil fall on the same slope $We^{\frac{1}{4}}$. The maximum spreading factor follows a power-law relationship with the Weber number, expressed as $\beta_{max} \sim We^{\alpha}$. When the graph was plotted according to the experimental data, On textured PDMS-OTS when coated or absorbed with lubricant surfaces, the maximum spreading of the droplet results in good agreement with the corresponding slope with a value of $\alpha \approx 0.30$ (Shown in) $\beta_{max} \sim We^{\frac{1}{4}}$ ^{15,61,62}. The exponent values obtained in our study agree with those reported in previous experimental studies.^{15,61,62}

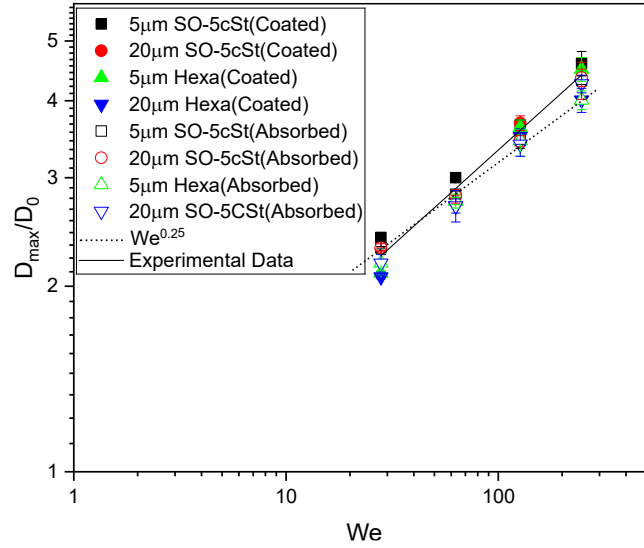


Figure 14. Normalized maximum spreading diameter $D_{\max}/D_0$ as a function of the Weber number. Error bars indicate the standard deviation based on four independent measurements.

Effect of Texture

An important observation was made when comparing textured PDMS-OTS samples prepared using two different lubricant application methods. In the coated samples, the lubricant (e.g., SO-5cSt or hexadecane) was initially coated on the surface, but the lubricant gradually soaked into the PDMS matrix over time. This process left behind a sufficient quantity of oil retained between the micro-posts, which facilitated droplet mobility and promoted different bouncing regimes after impact. On the other hand, in the samples that were allowed to absorb lubricant overnight, the oil was more uniformly distributed, not only retained between the posts but also absorbed into the bulk of the PDMS-OTS substrate. This dual retention led to a more stable lubricating environment, reducing interfacial friction and enhancing droplet mobility. Notably, even hexadecane-infused samples, which typically exhibit weaker surface affinity, demonstrated reduced frictional resistance when prepared via absorption due to the presence of lubricant in both the bulk and inter-post regions.

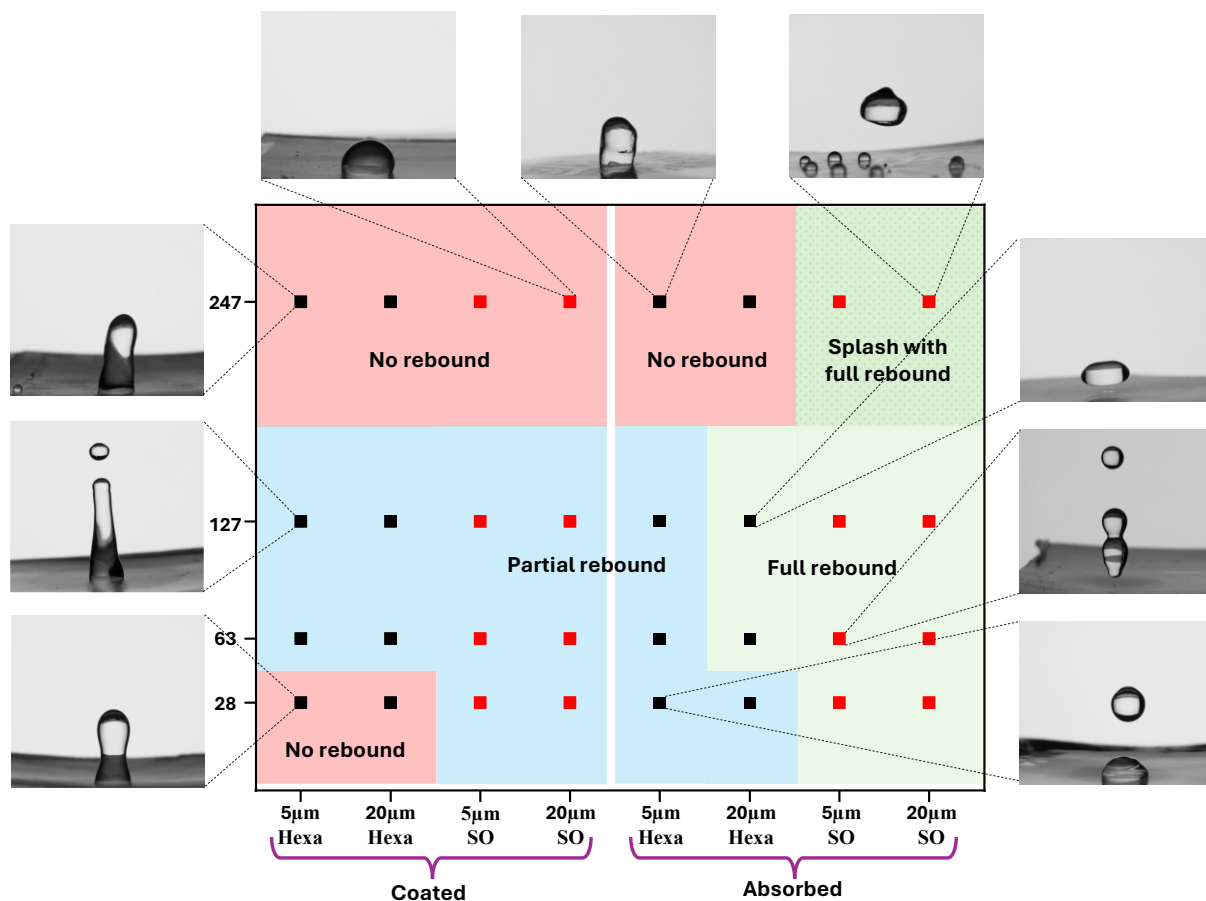


Figure 15. Schematic regime map of the outcome of drop impact at the end of the receding cycle for textured PDMS-OTS surface 5 and 20μm when coated and absorbed (separately) with So-5cSt (red square) and hexadecane (black square).

Figure 15. Presents the regime map summarizing the droplet impact outcomes across 5 and 20μm post-spacings of textured PDMS-OTS surfaces, either coated or absorbed with SO-5cSt and hexadecane lubricants, across the entire range of Weber numbers. The map categorizes the impact behaviours, deposition, partial rebound, and full rebound across a range of Weber numbers and surface treatments. It highlights how surface textures and the nature of lubricant incorporation (coating vs. absorption) influence droplet dynamics. This difference in oil distribution also influences the classification of the surfaces in terms of their lubrication mechanism. For instance, when SO-5cSt oil is absorbed into the textured PDMS-OTS surface, it forms a thin, stable film that coats not only the interstitial regions but also the top surfaces of the micro-posts. This creates a continuous, low-friction boundary layer that resembles a Van der Waals-type SLIPS (Slippery Liquid-Infused Porous Surface), where the droplet interacts with a homogeneous lubricant interface, minimizing contact line pinning. In contrast, when hexadecane is used, the absorbed oil remains primarily within the texture and does not rise to

coat the tops of the microstructures. As a result, the droplet partially contacts the bare PDMS-OTS surface during impact, forming a type of SLIPS that can be classified as non-Van der Waals. Such surfaces provide reduced lubricating coverage, allowing for stronger droplet-substrate interactions and increasing the likelihood of partial rebound or pinning.

The observed behaviors of complete rebound, partial rebound, or no rebound surfaces can be understood using the concepts of wetting and anti-wetting pressures⁶³. Earlier studies on droplet impact dynamics describe the dynamic pressure is given by $P_D = \frac{1}{2}\rho v^2$ with density ρ of water and velocity v of impact, If the droplet displaces the lubricant from the spacing between posts, this pressure is counteracted by the capillary pressure, expressed as $P_c = \frac{\sigma_{ow} \cos \theta_{(os)w}}{D_{post}}$, where σ_{ow} interfacial tension between oil and water, $\theta_{(os)w}$ contact angle of oil and water in the environment, and D_{post} post spacing of the sample. By equating the above to the equation, $\frac{1}{2}\rho v^2 \sim \frac{\sigma_{ow} \cos \theta_{(os)w}}{D_{post}}$. We get the critical velocity $v \sim \sqrt{\frac{\sigma_{ow} \cos \theta_{(os)w}}{\rho D_{post}}}$ at which droplet replaces the oil present in the post. This velocity represents the threshold above which the droplet displaces the lubricant within the post array. Consequently, when the actual impact velocity exceeds this critical value, the droplet adheres to the surface, resulting in either partial rebound or complete suppression of rebound. The calculated critical velocities corresponding to different post spacings are provided in the table below.

Table 1. The critical velocities with corresponding Weber numbers for VdW SLIPs and nVdW SLIPs were determined only for the lubricant absorbed samples for various post-spacings.

Post spacing	Critical velocity (nVdW SLIPs)	Critical velocity (VdW SLIPs)
5 μm	3.07m/s $\sim$ (We-300)	2.87m/s $\sim$ (We-280)
20 μm	1.53m/s $\sim$ (We- 75)	1.43m/s $\sim$ (We-73)

The droplet impact results show that on 20 μm post-spacing samples at a Weber number of 127 for SO-5cSt, both hexadecane-absorbed surfaces demonstrated complete droplet rebound. This result confirms that, regardless of the lubricant used at moderate impact velocities, both types of surfaces can momentarily provide a sufficiently lubricated interface to support full recoil. Repeated droplet impact tests were performed at the exact sample locations to check the oil retention capacity of the textured surfaces. It has been observed that this approach highlights that sustained impacts influence lubricant stability within the surface texture. When droplets impacted SO-5 cSt-infused soft textured PDMS surfaces, a complete rebound was observed up to 17-20 repeated impact cycles, after which it transitioned to a partial

rebound. In contrast, this transition occurred much earlier, after just 4-8 cycles on hexadecane-absorbed PDMS-OTS textured samples. Repeated droplet impact tests were also performed on 20 μm silicon-wafer-based LIS surfaces infused with the same oils to examine the role of oil retention without absorption. On SO-5cSt-infused silicon surfaces, a complete rebound was maintained for up to 6-8 cycles before shifting to a partial rebound. However, the transition occurred after only 2-3 impacts with hexadecane-infused silicon surfaces. These results demonstrate that the bulk absorption of lubricant into the porous PDMS structure significantly enhances oil retention, resulting in more sustained droplet rebound performance for both lubricants.

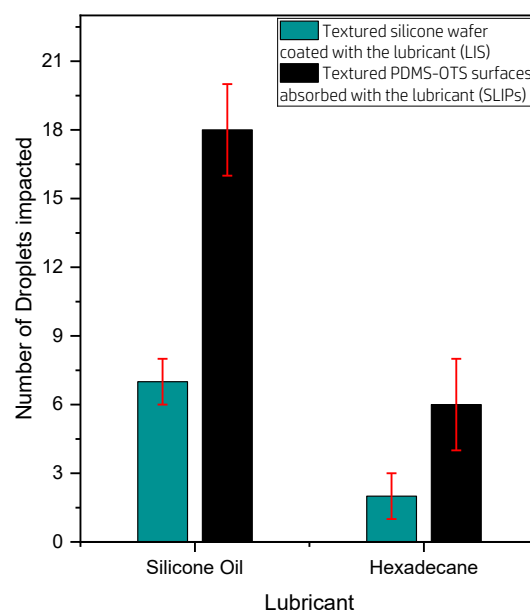


Figure 16. Number of droplet impacts sustained before the transition from full rebound to partial rebound on 20 μm post-patterned samples coated with different oils for two cases: PDMS and silicon wafer substrate.

4. Conclusion

In this study, the effect of surface texture on droplet impact dynamics is investigated by fabricating PDMS surfaces with square micropost arrays having post spacings of 5 μm and 20 μm using soft lithography. These textured surfaces were then functionalized with OTS to enhance their non-wettability. Following functionalization, the samples were either coated with or allowed to absorb two different lubricants, SO-5cSt silicone oil and hexadecane, for 24 hours. Wettability measurements were conducted on all samples, and droplet impact experiments were performed at various Weber numbers (28, 63, 127, and 247) to assess the influence of texture, surface chemistry, and lubricant interaction on impact behavior. The droplet impact behaviour on textured PDMS surfaces showed only minor differences between

the unfunctionalized samples (Textured PDMS) and the OTS-functionalized samples (Textured PDMS-OTS) in terms of bouncing behaviour. However, significant changes in droplet bouncing behaviour were observed when the OTS-functionalized PDMS textured surfaces were coated with lubricants. The type of lubricant and the spacing between the posts played a crucial role in determining whether the droplet rebounded, partially rebounded, or adhered to the surface.

When the textured PDMS-OTS surfaces were absorbed with lubricants, apparent differences in rebound behaviour were noted. For example, surfaces absorbed with SO-5cSt showed complete rebound across all Weber numbers for both the post spacings, indicating stable lubricant retention and a continuous oil layer at the surface. In contrast, hexadecane-absorbed surfaces showed variable behaviour depending on both the post spacing and the Weber number, with a partial rebound at a lower Weber number and no rebound at higher Weber numbers for the same 5 μm post spacing. This phenomenon was explained based on the balance between impact and capillary pressures. Durability was also assessed by repeating droplet impacts. It was observed that surfaces with SO-5cSt or hexadecane absorbed into the textured PDMS maintained rebound for more cycles than solid textured silicon wafers. This demonstrates that the ability of PDMS to retain oil internally helps preserve its droplet-repelling properties over repeated impacts. This study highlights how surface texture, chemical treatment, and internal oil absorption can significantly influence droplet rebound behaviour. These insights are helpful in developing surfaces for applications such as biofouling, anti-microbial coatings, and anti-icing.

Supporting Information

See the supporting information for the details of the experiment and results. It is divided into sections: 1. Fabrication on Textured PDMS Surface, 2. Results of Wettability Measurements and Friction Calculation, 3. Stability and Thermodynamic framework, 4. FESEM Images of Textured silicon and PDMS surfaces, 7. Experimental critical We for the transition in bouncing phenomena.

Conflicts of Interest

There are no conflicts to declare.

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Author Approval

All authors have approved the final version of the manuscript.

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Supporting Information

High-speed imagery analysis of droplet impact on Van der Waals and non-Van der Waals soft textured oil-infused surface.

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1. Fabrication on Textured PDMS Surface.

To prepare textured PDMS samples for droplet impact experiments, we first fabricated microtextured silicon surfaces with 10 μm square posts, interpost spacings of 5 and 20 μm , and a height of 10 μm using standard lithography. Silicon wafers were coated with Shipley S1818 photoresist and exposed to 405 nm UV light through a chrome mask (Advanced Reproductions Corporation). The photoresist was developed in a 1:1 mixture of DI water and Microdev solution (Dow Chemicals). Etching was performed to a depth of 10 μm using an inductively coupled plasma reactor (Surface Technology Systems). Surface profiles were measured with an optical profiler (CCI HD, Taylor Hobson). Residual photoresist was removed using a piranha solution (3:1 sulfuric acid to hydrogen peroxide).

Polydimethylsiloxane (PDMS) is a flexible polymer widely used for fabricating microstructures due to its ease of moulding. In this study, soft surfaces were prepared using PDMS (Sylgard 184, Dow Corning, Wiesbaden, Germany). Liquid PDMS was mixed with a curing agent in a 10:1 ratio (PDMS to curing agent) using a mechanical stirrer for 5 minutes.⁴⁰ This process introduced air bubbles, which were removed by placing the mixture under vacuum for 30 minutes.³⁹ The degassed PDMS was then used to prepare textured PDMS surfaces through a soft lithography process.³⁸ For textured surfaces, the degassed PDMS was poured onto silicon wafers coated with a fluorosilane layer. The wafers were placed inside a custom mold, and the PDMS was cured at room temperature for 24 hours to form a negative mold of the textured surface. The cured PDMS mold was then coated with a fluorosilane layer to prevent sticking. A fresh batch of degassed PDMS was poured onto this mold and cured under the same conditions. Once removed, the PDMS formed a positive mold that reproduced the original textured silicon surface. This method enabled clean replication and easy demolding of

PDMS layers, which were later used in droplet impact studies. A schematic of the preparation process is shown in Figure S1.

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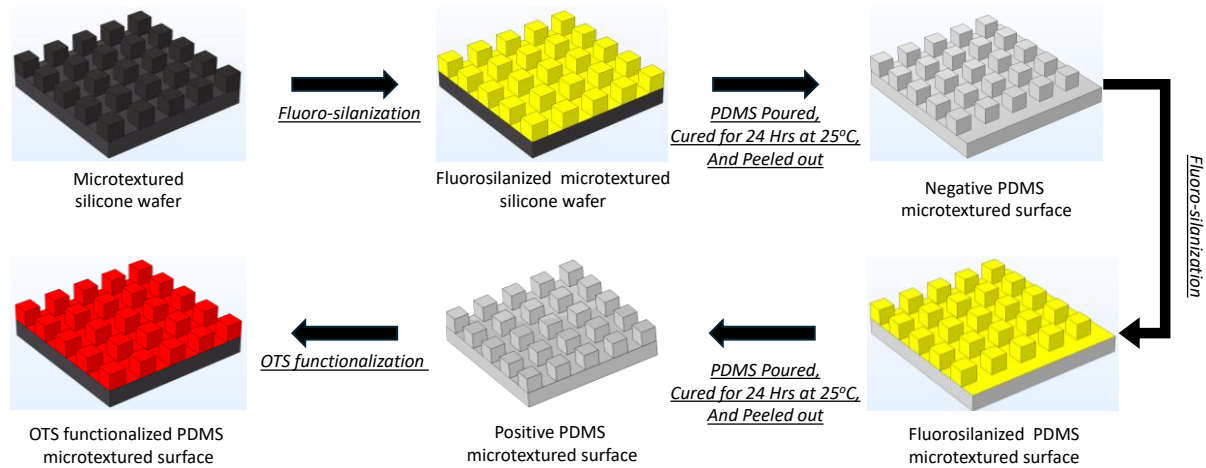


Figure S1.The schematic diagram outlines the procedures for preparing textured PDMS for droplet impact tests.

• OTS Functionalization.

Before functionalization, the samples were plasma cleaned for 2 minutes to activate the surface. A reactive solution was prepared by mixing 75 mL of toluene with 250 μL of octadecyltrichlorosilane (OTS). Separately, a water-in-toluene emulsion was made by combining 325 μL of deionized water (resistivity 18.2 $\text{M}\Omega$, Millipore) with 50 mL of toluene, followed by high-energy probe sonication (750 W, Sonics) for 90 seconds. This emulsion was then added to the OTS–toluene solution and further mixed using bath sonication (Branson) for 2 minutes to ensure uniformity. The samples were immersed in the silanization solution for at least 20 minutes. After functionalization, they were rinsed thoroughly with acetone and isopropanol to remove unreacted OTS and byproducts.³⁷

Table S2. Physical Properties of Lubricant.

	SO-5cSt	Hexadecane
Kinematic viscosity (<i>cSt</i>)	5	4.3
Specific gravity	0.91	0.71
Dynamic viscosity(<i>mPa-s</i>)	4.57	3.06
Surface tension (<i>mN/m</i>)	19.7	27.47

2. Results of Wettability Measurements

After sample preparation, wettability measurements were performed. All samples were mounted on a goniometer (Rame Hart, Model 500) to measure equilibrium, advancing, and receding contact angles, as well as droplet roll-off angles. A monochrome video camera attached to the goniometer was used to capture droplet images. Deionized (DI) water droplets of 8 μ L volume were placed vertically on the test surfaces for contact angle measurements. Ten measurements were taken for each sample type, covering five different locations per sample.⁶⁴ Experiments were carried out at 24 °C and 75% relative humidity. Contact angle hysteresis (CAH) was determined using the drop volume-change method.⁶⁴ A needle was positioned near the surface to add water gradually until the advancing contact angle was reached, just before the three-phase contact line (TPCL) moved forward. The receding contact angle was recorded during suction when the TPCL began to retract. CAH was calculated as the difference between the advancing and receding angles. Droplet roll-off angles were measured by placing a sessile droplet on the surface and tilting the goniometer stage until the droplet rolled off. The tilt angle at this point was recorded as the roll-off angle.

Table S2. Wettability measurements for water of Textured PDMS-OTS 5 and 20 μ m samples coated with SO-5cSt and hexadecane lubricant, respectively. All measurements are in Degrees(°).

	5 μ m		20 μ m	
	Hexadecane	SO-5cSt	Hexadecane	SO-5cSt
	PDMS-OTS	PDMS-OTS	PDMS-OTS	PDMS-OTS
Functionalization				
Eq. CA	122 $\pm$ 1	120 $\pm$ 1	119 $\pm$ 3	113 $\pm$ 3
Advancing CA	124 $\pm$ 2	142 $\pm$ 2	121 $\pm$ 3	114 $\pm$ 3
Receding CA	96 $\pm$ 2	118 $\pm$ 2	91 $\pm$ 4	89 $\pm$ 3
CAH	28 $\pm$ 4	24 $\pm$ 4	30 $\pm$ 7	25 $\pm$ 6

Table S3. Wettability measurements for water of Textured PDMS-OTS 5 and 20 μ m samples absorbed with SO-5cSt and hexadecane lubricant, respectively. All measurements are in Degrees(°).

	5 μ m		20 μ m	
	Hexadecane	SO-5cSt	Hexadecane	SO-5cSt
	PDMS-OTS	PDMS-OTS	PDMS-OTS	PDMS-OTS
Functionalization				
Eq. CA	89 $\pm$ 1	90 $\pm$ 1	85 $\pm$ 7	92 $\pm$ 1

Advancing CA	92±2	91 ± 0.5	92±1	93±0.5
Receding CA	82±2	89.5±0.5	80±1	91.5 ± 0.5
CAH	10±4	1.5 ± 1	12 ± 2	1.5 ± 1

Table S4. Wettability of measurements of water, SO-5cSt, and hexadecane on smooth PDMS-OTS samples, in air and water environments, respectively. All measurements are in Degrees(°).

Liquid	$Eq. CA_{(a)}$	$\theta_{adv, OS(a)}$	$\theta_{rec, OS(a)}$	$Eq. CA_{(w)}$	$\theta_{adv, OS(w)}$	$\theta_{rec, OS(w)}$
Water	113±4	112±1.5	97±2.5	NA	NA	NA
Silicone Oil(5cSt)	1 ± 0.5	4 ± 2		30 ± 2	36 ± 2	5 ± 4
Hexadecane	41 ± 4	45 ± 4		33 ± 6	36 ± 3	25 ± 3

3. Stability and Thermodynamic framework.

Figure S2. Shows the 3D structure of the square post-spacing sample. The Figure S3(1). The dimensions of the post spacing are given, where a = the size of the post, b = the distance between two consecutive posts (post spacing), and h = the height of the post. The mathematical representation as a*b*h. Our experiment uses two different post spacings: i.e., b = 5, and 20 μ m. Figure S2 (2) shows solid fraction ϕ (the ratio of emerged surface area to projected surface area). The solid fraction can be calculated by $\phi = a^2/(a + b)^2$. Another important geometric parameter for calculating the critical contact angle is the ratio of the total area (Figure S2(3)) to the projected surface area, given by $r = 1 + 4ah/(a + b)$. Table S1. Shows ϕ and r value for the different post-spacing.

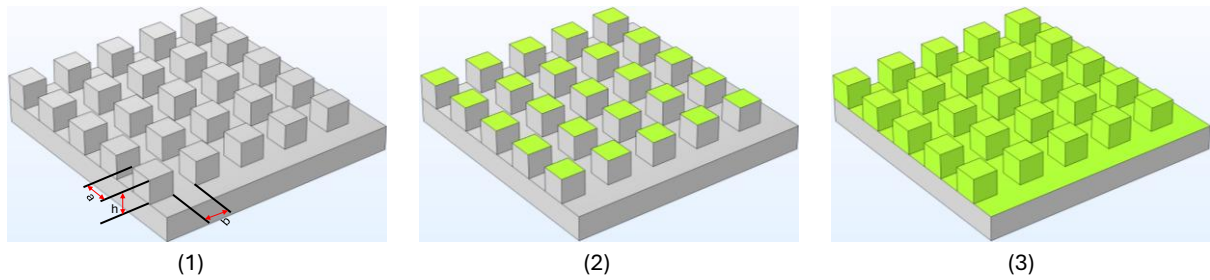


Figure S2. Schematic representation of square post-textured surface (1), Dimensions (2), Solid fraction (3),
Total area

Table S5. In the case of square posts with width a , edge-to-edge spacing b , and height h , $\varphi = a^2/(a + b)^2$ and $r = 1 + 4ah/(a + b)^2$ Texture parameters b , r , and critical contact angles θ_c defined by $\theta_c = \cos^{-1} ((1-\varphi)/(r - \varphi))$.

A schematic representation of a square post-textured surface is given in Figure S2.

Post spacing(b)(μm)	r	φ	θ_c ($^\circ$)
5	2.778	0.444	76.229
20	1.444	0.111	48.191

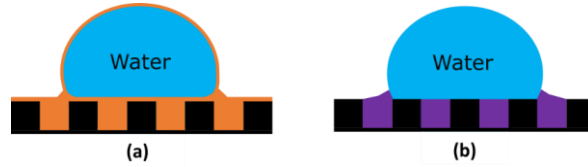


Figure S3. Schematic diagram of a liquid droplet placed on a textured surface impregnated with a lubricant that (a) cloaking of the oil (Orange colour represents SO-5cst), (b) non-cloaking the oil around the water droplet (purple colour represents hexadecane).

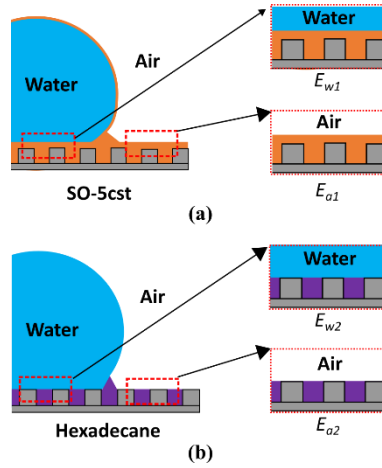


Table S6. The total interface energies per unit area are calculated for the above configuration (Figure S3.) by summing the individual interfacial energy contributions. Equivalent requirements for the stability of each configuration are provided in the next column.

Total interfacial energy per unit area accordingly to Figure S5	Equivalent criteria		
$E_{w1} = \gamma_{wo} + r\gamma_{os} \text{ (SO-5cst)}$	$E_{w1} < E_{w2}$	$S_{os(w)} \geq 0$	$\theta_{os(w)} = 0$
$E_{a1} = \gamma_{oa} + r\gamma_{os} \text{ (SO-5cst)}$	$E_{a1} < E_{a2}$	$S_{os(a)} \geq 0$	$\theta_{os(a)} = 0$
$E_{w2} = (r - \varphi)\gamma_{os} + \varphi\gamma_{sw} + (1 - \varphi)\gamma_{ow} \text{ (Hexadecane)}$	$E_{w2} < E_{w1}$	$-\gamma_{ow} \left(\frac{r-1}{r-\varphi} \right) < S_{os(w)} < 0$	$\theta_{os(w)} > 0 > \theta_c$
$E_{a2} = (r - \varphi)\gamma_{os} + \varphi\gamma_{sa} + (1 - \varphi)\gamma_{oa} \text{ (Hexadecane)}$	$E_{a2} < E_{a1}$	$-\gamma_{oa} \left(\frac{r-1}{r-\varphi} \right) < S_{os(a)} < 0$	$\theta_{os(a)} > 0 > \theta_c$

Consider the interaction between the fluid and substrate, where the substrate is PDMS, and the fluid is oil. Let h represent the thickness of the oil layer, d_1 the thickness of the PDMS

layer, and d_0 the distance between the two interfaces and the Hamaker constant is denoted by A . The total interaction between the substrate and fluid can be written as,

$$\begin{aligned}
 G_{system}^{lw} &= G_{film}^{lw} + G_{substrate}^{lw} + G_{interface}^{lw} \\
 &= C_2 - \frac{A_{22}}{12\pi h^2} + C_2 - \frac{A_{22}}{12\pi d_1^2} - \frac{A_{12}}{12\pi} \left[\frac{1}{d_0^2} - \frac{1}{(d_0 + h)^2} \right] \\
 &= C_E - \frac{A_{22}}{12\pi h^2} + \frac{A_{12}}{12\pi h^2} \\
 \therefore G_{system}^{lw} &\sim -\frac{A_E}{12\pi h^2}
 \end{aligned}$$

Where $A_E = \text{Effective hamaker constant} = A_{22} - A_{12}$

This $A_{12} = \sqrt{A_{11}A_{22}}$ form the combining relations⁶⁵

Where, $A_{22} = 24\pi d_0^2 \gamma_2^{lw}$ form the combining relation⁶⁵

Given

$\gamma_{2(SO5cst)}^{lw} = \text{Silicon oil } 5cSt = 0.0197 \text{ N/m}^2$, $\gamma_{2(hexa)}^{lw} = \text{Hexadecane} = 0.027 \text{ N/m}^2$,
 $d_0 = 0.165 \text{ nm}$

Table S7. Data for the effective Hamaker constant in (10^{-20} J).

	A_{22}	$A_{11}(\text{PDMS})$	$A_{12} = \sqrt{A_{11}A_{22}}$	$A_E (\times 10^{-20} \text{ J})$
Silicon oil	4.04	4.4	4.21	-0.1801 ± 0.150
Hexadecane	5.64	4.4	4.98	0.66 ± 0.08

4. FESEM Images of Textured PDMS

The FESEM images reveal a well-defined microtextured morphology formed on the PDMS surface (Figure S9). The surface shows uniform and periodic microstructures with minimal defects, confirming accurate replication from the mold. At higher magnifications, fine cracks are observed on the surface. These cracks arise due to the thin ($\sim 5 \text{ nm}$) conductive gold coating applied to prevent charging during imaging. Overall, the microtextures are clearly captured, confirming the structural integrity of the patterned PDMS surface.

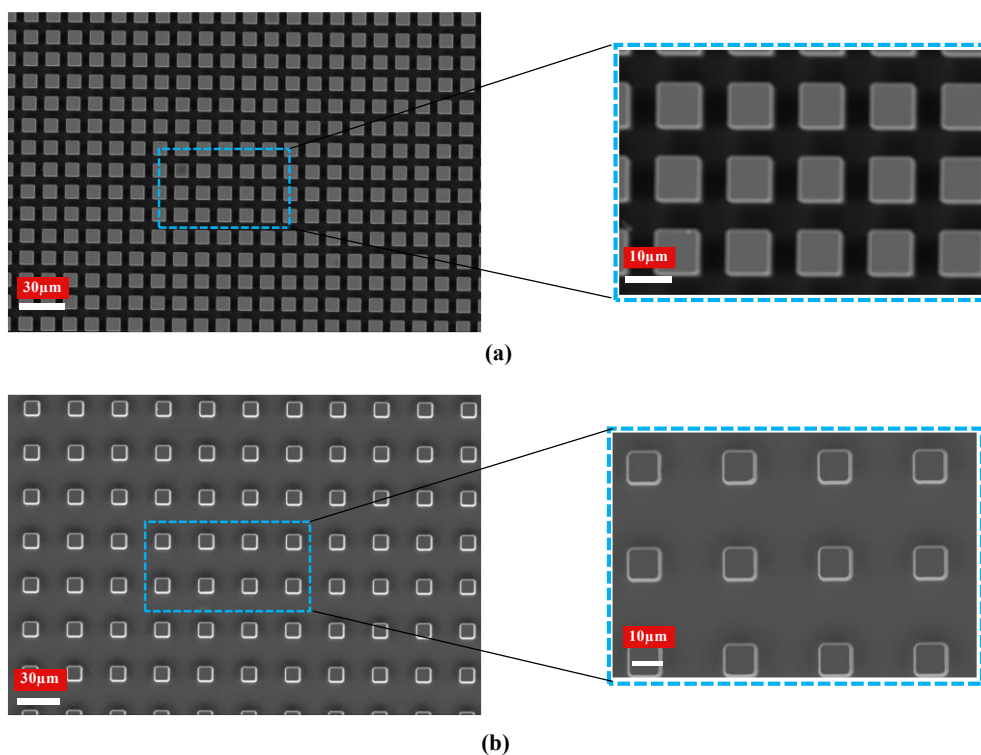


Figure S4. FESEM images of textured silicone wafer at two different magnifications: ((a) 5 μm , and (b) 20 μm post spacing samples, respectively.

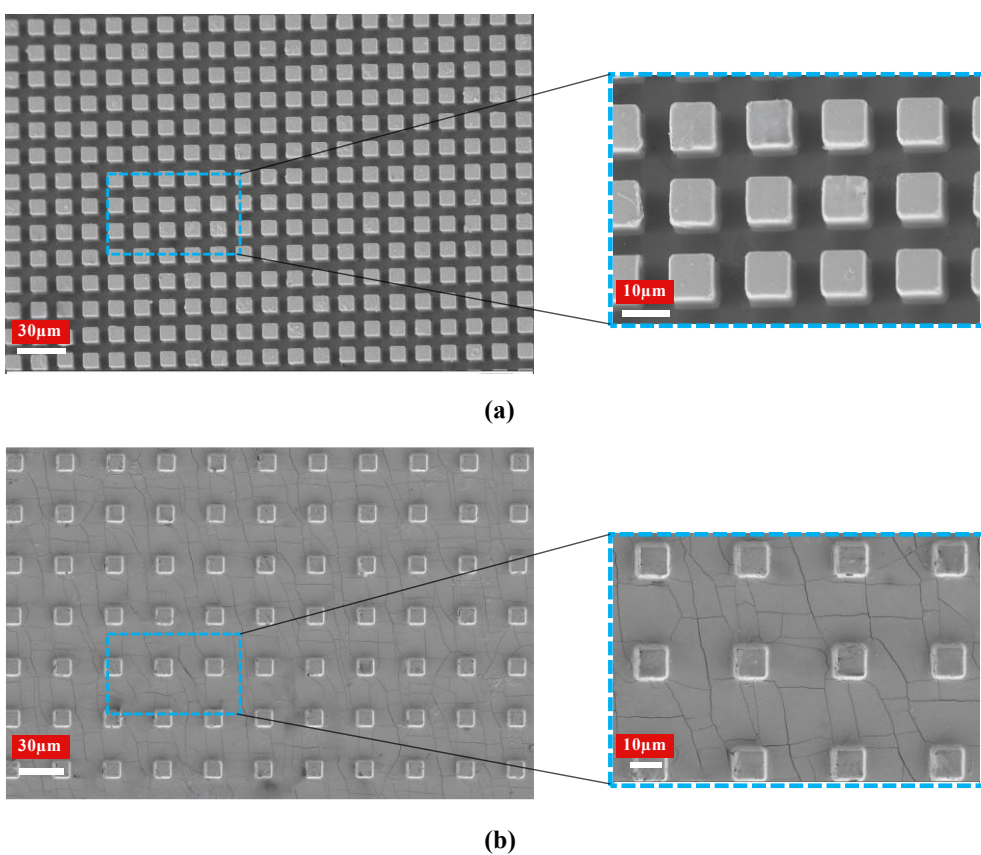


Figure S5. FESEM images of textured PDMS at two different magnifications: (a) 5 μm , and (b) 20 μm post spacing samples, respectively.

5. Experimental critical We for the transition in bouncing phenomena

To determine the experimental critical (threshold) value, we conducted a series of experiments with Weber numbers of 28, 63, 127, and 247. We conducted experiments with the Weber number in small intervals (~ 10) to determine the nearest experimental critical value for various transitions, ranging from no rebound to partial rebound, as the Weber number increased. Table S7. Shows the values.

Table S8. The experimental critical values for the transition from one outcome to another.

Sr. no	Samples	Threshold/critical We	Outcomes
1	PDMS-OTS 5 μ m	-	Always No Rebound
2	PDMS-OTS 20 μ m	We > ~ 80	Always No Rebound
Coated with Lubricant			
3	PDMS-OTS (SO-5cSt) 5 μ m	We ~ 220	Partial Rebound $\rightarrow$ No Rebound
4	PDMS-OTS (Hexa) 5 μ m	We ~ 40	No Rebound $\rightarrow$ Partial Rebound
		We ~ 210	Partial Rebound $\rightarrow$ No Rebound
5	PDMS-OTS (SO-5cSt) 20 μ m	We ~ 220	Partial Rebound $\rightarrow$ No Rebound
6	PDMS-OTS (Hexa) 20 μ m	We ~ 40	No Rebound $\rightarrow$ Partial Rebound
		We ~ 210	Partial Rebound $\rightarrow$ No Rebound
Absorbed with Lubricant			
7	PDMS-OTS (SO-5cSt) 5 μ m	We > 15-20	Always Rebound
8	PDMS-OTS (Hexa) 5 μ m	We ~ 230	Partial Rebound $\rightarrow$ No Rebound
9	PDMS-OTS (SO-5cSt) 20 μ m	We > $\sim 15-20$	Always Rebound
10	PDMS-OTS (Hexa) 20 μ m	We ~ 30	Partial Rebound $\rightarrow$ Full rebound
		We ~ 230	Full rebound $\rightarrow$ No Rebound

Calculation and explanation for wetting and anti-wetting pressure on textured PDMS-OTS surface.

The wetting states of impinging droplets are determined by the relative magnitudes of wetting and anti-wetting pressures⁶³:

- P_{EWH} is produced during the contact stage when the droplet impacts the textured surface.
- A total wetting state occurs when P_{EWH} exceeds P_D and P_C , i.e ($P_{EWH} > P_D > P_C$), allowing water to penetrate during both the contact and spreading stages.

- A partial wetting state is observed when P_{EWH} is greater than P_C but less than P_D , i.e ($P_{EWH} > P_C > P_D$), leading to water penetration only during the contact stage.
- A total nonwetting state arises when P_C exceeds both P_{EWH} and P_D , i.e ($P_C > P_{EWH} > P_D$), causing the structure to resist wetting throughout both stages.

$$\text{Dynamic/kinetic pressure} = P_D = \frac{1}{2} \rho v^2$$

$$\text{Effective hammer pressure of water} = P_{EWH} = 0.2 \rho C v$$

$$\text{Capillary pressure} = P_C = -2\sqrt{2} \gamma_{LV} \cos \frac{\theta_A}{B}$$

Where, ρ Density, v impact velocity, C velocity of sound in water=1497m/s, γ_{LV} Interfacial tension of water in air=0.072 N/m, θ_A is advancing the contact angle of water on a smooth PDMS-OTS coated surface, and D is post-sapping.

Table S9. Shows the calculated values of (a) dynamic, effective hammering pressure for the particular velocity and (b) capillary pressure for the corresponding post-spacing (Measuring units are Pascal p).

(a)			(b)	
V(m/s)~(We)	Dynamic pressure	Hammering pressure	Post spacing	Capillary pressure
	P_D	P_{EWH}		P_C
0.88 (28)	387.2	263472	5 μ m	18658.56
1.32 (63)	871.2	395208	20 μ m	4664.64
1.88 (127)	1767.2	562872		
2.61 (247)	3406.05	781434		

Effect of abdoberd lubricant in textured PDMS-OTS surface on droplet impact.

$$\text{Kinetic pressure } P_D = \frac{1}{2} \rho v^2 \quad \text{Eq. 1}$$

$$\text{Capillary pressure } P_C = \frac{\sigma_{ow} \cos \theta_{(os)w}}{\rho D_{post}} \quad \text{Eq. 2}$$

Equating Eq. 1 and Eq. 2, We get

$$\text{Critical velocity } v \sim \sqrt{\frac{\sigma_{ow} \cos \theta_{(os)w}}{\rho D_{post}}}$$

Table S10. Shows the interfacial tension at the oil-water phase and the equilibrium contact angle of oil-solid in water.

Parameters	Hexadecane	SO5cst
σ_{ow}	0.051 (N/m)	0.043(N/m)
$\theta_{(os)w}$	33 $\pm$ 4 (°)	30 $\pm$ 1 (°)

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