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ORIGINAL RESEARCH ARTICLE

Enhancing industrial resource efficiency through droplet impact optimization: Micro/Nanotextured and Lubricant-Infused surfaces for SDG 9.4

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ABSTRACT

Proper control of the droplet impact mechanism is very crucial in enhancing efficient use of resources in a variety of industrial practices such as spray cooling, anti-icing systems, and surface coating processes. To determine how droplet impingement occurred over time, the current study focuses on the investigation of such a process on micro- and micro/nanotextured and lubricant-infused surfaces (LIS). The visualization of impact events at different Weber numbers (We = 2~200) was carried out by means of high-speed imaging. Microelectromechanical systems (MEMS) fabrication techniques were applied to realize precise surface engineering. The findings show a significant increase in the droplet deposition and the accompanying inhibition of splashing, which directly provides a benefit on resources utilization and process stability. When connecting results to SDG 9.4 that suggests upgrading the existing industrial infrastructure by aiming to achieve the high degree of resource-use efficiency, the given study emphasizes that the most breakthrough surface engineering mechanisms hold great potential to transform sustainable industrial processes.

Keywords: Droplet impact; Micro/Nanotextured surfaces; Lubricant-Infused surfaces; industrial sustainability; SDG 9.4; energy efficiency

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1. Introduction

The impact of droplets on solid surfaces is a common occurrence that has been researched for centuries and is still of practical significance[1]. The droplet impact study necessitates the consideration of several crucial parameters, including impact velocity, surface tension, liquid viscosity, density, and surface wetting characteristics. Droplet impact behaviour varies and goes through a transition from spreading, retraction, deposition, rebounding, and receding breakup depending on these surface conditions. A droplet splashing incident may happen at very high impact velocities. Inkjet printing, spray cooling, surface coating, internal combustion engines, anti-icing, and many other industrial applications depend on droplet impact. The Weber number is a significant dimensionless number that has been introduced in the literature and governs the drop impact phenomenon [2-3]. It can be stated as,

$$We = \rho_L D_o V^2 / \sigma_{LV} \quad (1)$$

Where ρ_L, D_o, σ_{LV} and V_o indicates the liquid density (kg/m^3), droplet initial diameter (m), surface tension (N/m) at liquid-air interface and droplet impact velocity (m/s) respectively.

Additionally, droplet impact phenomena for hierarchically textured surfaces, both micro- and micro/nano-, is studied [4-8]. These surfaces, with contact angles of $\theta > 90°$ and $\theta > 150°$, respectively, were named hydrophobic and super-hydrophobic surfaces. Their high hydrophobicity has earned them the reputation of being self-cleaning surfaces. Bouncing phenomena is seen at low impact velocities when droplets impact these surfaces. Even though super-hydrophobic surfaces don't wet, they can still lose their super-hydrophobicity when drops hit them, evaporate, or squeeze them (a process known as the Cassie-Wenzel wetting transition). In order to prevent these issues and preserve the surface's non-wetting properties, some researchers have developed lubricant-infused surfaces (LIS)[9-15]. It was shown that the dynamics of drop impact on these surfaces are primarily influenced by the surface tension and viscosity of the lubricant oil. We have provided a qualitative description of the comparison between droplet impact dynamics on micro- and micro/nano-textures, as well as lubricant-infused surfaces (LIS) with micro/nano-textures, based on these background studies. It was found that the Weber number and these surface properties affect the droplet impact behaviour. Droplet impact behaviour on micro and nano textures with LIS, in particular, exhibits three distinct impact events prior to breakup: partial rebound, complete rebound, and deposition. Furthermore, we have looked into how LIS affects splashing through droplet breakup. When LIS was used instead of just micro- and micro/nano-textured surfaces, delayed droplet splashing was seen. It might happen as a result of the droplet's energy dissipating as a result of lubricant shear friction on the LIS surface. Nanoparticles/nanofluids have diversified applications and they can be very important for the nanostructures too.[16-18]

2. Materials and methods

Using the MEMS (Micro-Electro-Mechanical-Systems) technique, we have created three distinct substrate types: micro-, micro/nano, and lubricant-infused surfaces with micro-nano textures. We used dry etching and traditional photolithography to create micrometre scaled textures. Additionally, the black silicon technique was used to create textures with nanoscale scales[19-20]. Following the fabrication process, the substrates were thoroughly cleaned by using piranha solution and oxygen plasma to get rid of all passivation. The substrates were cleaned and then baked for 24 hours in a vacuum oven. The surfaces were coated using the Self-Assembled Monolayer (SAM) technique to achieve the hydrophobic property. The substrates were dipped in HDFS (HeptaDecaFluoro-1, 1, 2, 2-tetrahydro-decyltrichloroSilane) and n-hexane solution for a full day during the SAM coating process. Subsequently, the substrates were dried using a nitrogen cannon and rinsed with HFE-7100. A sample image of a micro- or nano-textured surface is displayed in **Figure 1**. The micro-pillars have diameters (d), spacings (S) and heights (h), of 50 µm, 48 µm, and 22 µm, respectively. Additionally, in order to prepare the LIS, we first completely wet the micro/nano-textured surface with Krytox GPL-101 (ν = 17 cSt) lubricant. After that, the surface was left slanted for a full day in order to eliminate any remaining oil and create a consistent oil layer. It is estimated that the lubricant's thickness is comparable to the height of the nano-textures (6µm) because it fully penetrates and stays at the space between them. Prior to and following SAM coating, the static contact angle (SCA) on a flat silicon surface was measured to be 64° and 120°. On a flat silicon surface with lubricant applied, the SCA was 70°. Additionally, as shown in **Figure 2**, the prepared micro, micro/nano-textured, and lubricant-infused surfaces had static contact angles of 150°, 168°, and 131°, respectively.

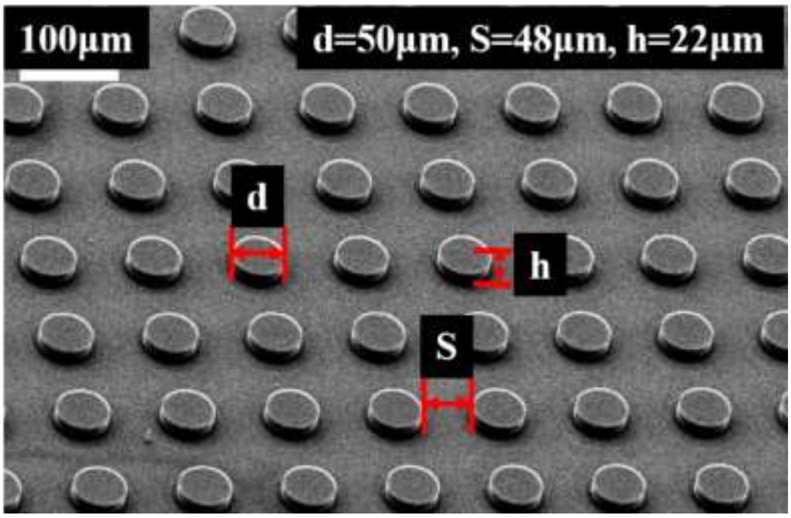

Figure 1. Micro/nano-textured surface image captured by a scanning electron microscope (SEM)

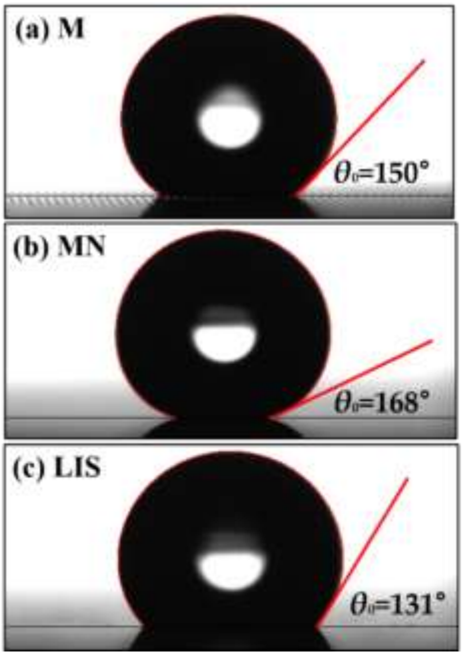

Figure 2. Measured contact angles on (a) Micro (M) (b) Micro/Nano-textured surfaces (MN) and (c) lubricant infused surfaces with Micro/Nano-textures (LIS).

3. Experimental facility

A high-speed camera (IDT Motion Studio), a syringe pump (Chemyx Fusion 200) with a needle, and a light source make up the experimental setup as shown in the **Figure 3**. First, the syringe pump was used to create a distilled water droplet (D_o = 2.3 ± 0.05 mm), which was then impacted onto the prepared substrate using a needle. Vertical variations in impact heights were made following each impact condition. With a high-speed camera operating at 8000 frames per second, the impact event was photographed and documented. Background light came from a source of light. The computer was linked to every device. At least three repetitions of each experimental condition were conducted. Ultimately, impact velocities were computed at every impact height using the high-speed camera's sequential image processing analysis. The primary control parameter in this experiment is the Weber number, which for distilled water droplets is between 2 ~ 200. The surface tension of droplets is 0.072 N/m, and the droplet impact velocity ranges from $0.42 < V_o < 2.64$ m/s.

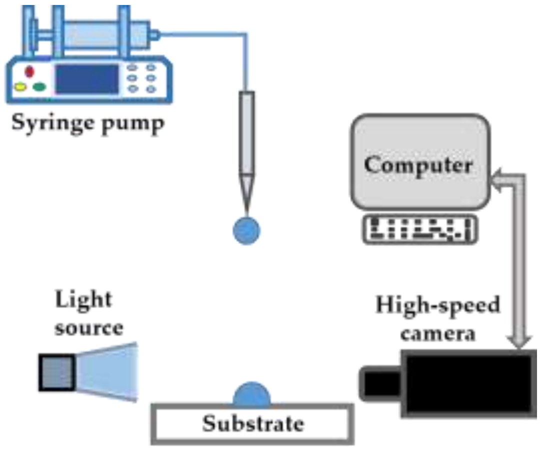

Figure 3. Schematic of experimental facility

4. Results and discussions

4.1. Effects of droplet collision

The first experiments involved lubricant-infused surfaces, micro, and nano-textured surfaces with varying impact velocities and, consequently, Weber numbers. With varying surface characteristics, **Figure 4** displays the impact event map in detail for each surface with the same micro-pillar geometry (*d*=50μm, *s*=48μm, and *h*=22μm). Six distinct droplet impact behaviours have been observed, varying in *We* number and contingent upon surface characteristics. The deposition, full rebound, partial rebound, singular jet, receding breakup, and splash are examples of these behaviours. Droplet impact behaviour changes from "complete rebound" to "partial rebound" and from "receding breakup" to "splash" on micro-textured surface (M). On the other hand, it changes from "complete rebound" to "partial rebound" and from "receding breakup" to "splash" on a micro/nano-textured surface (MN). Furthermore, lubricant-infused surfaces with micro/nanotextures (LIS) exhibit a variable impact behaviour, changing from "deposition" to "single jet" and "partial rebound" to "deposition" once more to "receding breakup" and ultimately "splash."

Figure 4 depicts the overall droplet impact behaviours with variations in Weber numbers on three different types of surfaces (M, MN, and LIS). We'll talk about this impact behaviour in more detail later. Additionally, **Figure 5 (a-f)** displays the captured images for various drop impact behaviours from the initial impact to the final event with the change in time. The droplet in deposition process (a) spreads out, retracts, and stays attached to the surface the entire time without breaking up or rebounding. Due to the drop's kinetic energy, the liquid in the complete and partial rebound cases (b and c) jumped up during retraction after the droplet had first spread out on the surface. Complete rebound occurs when a whole drop disappears from the surface in such circumstances. Partial rebound, on the other hand, occurs when some droplets separate from the main droplet and a portion of the droplet remains on the surface. The literature which is outside the purview of this study, explains how the wetting (water hammer and dynamic) and anti-wetting (capillary) pressures on the textured surfaces can be responsible for the deposition, partial rebound and complete rebound behaviours[21]. Later, at low Weber numbers, a singular jet (d) is typically formed. At *We* = 13, we have witnessed the singular jet event in this instance. When a drop impacts the surface in this instance, a sizable air bubble is trapped beneath the impacting droplet at a very low *We* number. The nature of singularities may be responsible for the air bubble's singular existence. Subsequently, this air bubble breaks down during the droplet's deformation, resulting in the jet formation. A prior study of singular jets and bubbles in drop impact provides a detailed explanation of how the excitation of capillary waves and collapse of the air cavity on the surface lead to the formation of singular jets [22]. Furthermore, when a drop impacts and spreads entirely across the surface, but leaves behind a few tiny droplets during the retraction process, it is known as the receding breakup phenomenon (e). The photos that were taken during this breakup incident are displayed in **Figure 5(e)**. Lastly, when a droplet impacts a surface with a very high impact velocity and a high *We* number, the prompt splash (f) phenomenon is seen. The current study's observation of splashing phenomena is defined by the formation of droplets at the spreading droplet's moving contact line as a result of surface characteristics. **Figure 4** displays all of the splashing *We* numbers for each surface condition.

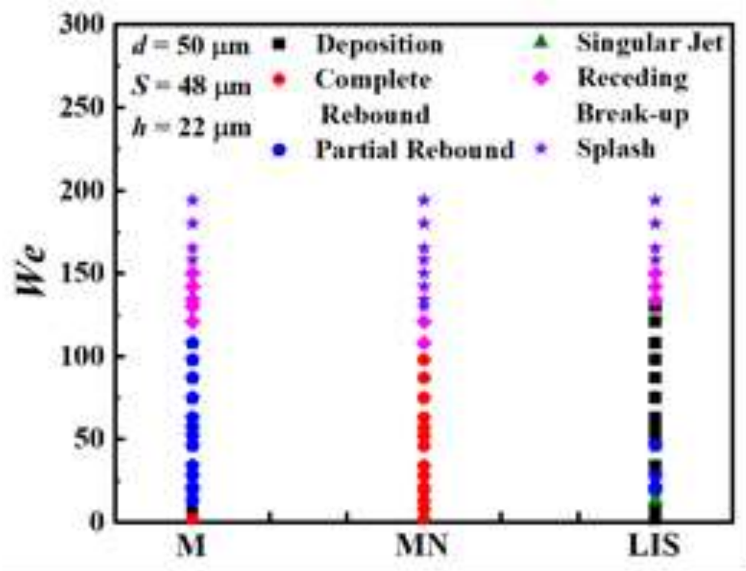

Figure 4. Droplet impact behaviours with a change in Weber number on three distinct types of surfaces (M, MN, and LIS).

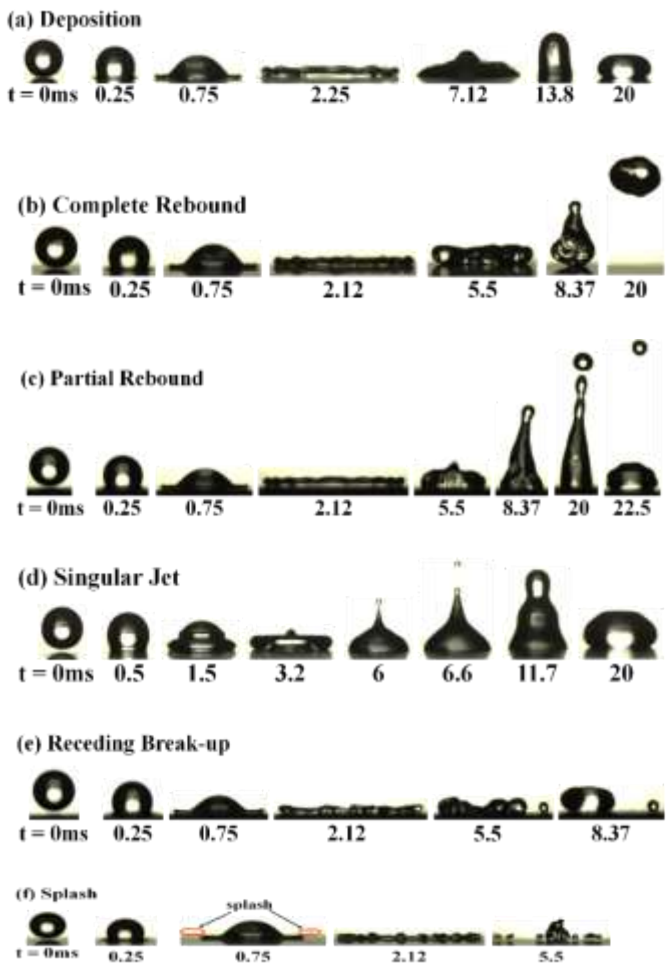

Figure 5. The droplet impact scenarios on prepared surfaces are visualized in the following ways: (a) *We*_LIS = 76; (b) *We*_MN = 74; (c) *We*_M = 78; (d) *We*_LIS = 16; (e) *We*_M = 128; and (f) *We*_MN = 122.

4.2. Impact of Weber number and surface features

Six impact behaviours in total were noted in the current study on three different types of surfaces, as indicated in **Figure 4**, as previously mentioned in the section. It is now necessary to make clear how surface features and Weber number impact droplet impact behaviour. The findings presented in **Figure 4** indicate that the primary parameter responsible for the variation in droplet impact behaviour on each surface is the Weber number, which is defined as the ratio of kinetic energy to surface energy. It has been noted that raising the Weber number and consequently, the impact velocity on each surface, encourages the droplet breaking up and splashing phenomena. Thus, the drop impact phenomenon on each surface is the topic of discussion here.

On a surface with Microtexturing (M): When the Weber number increases from $We > 10$, the impact behaviour changes to a partial rebound event. However, at very small $We < 10$, the droplet is observed to be completely rebounded. The high and low receding contact angles of the droplet, respectively, determine the rebounding behaviour. Furthermore, droplet forms receding breakup and splashing events at $We = 123$ and 158, respectively, are formed as the Weber number increases continuously. This demonstrates how the transition of droplet impact behavior is strongly influenced by an increase in impact velocity and consequently Weber number.

Concerning a surface with Micro/Mano textures (MN): Droplet impact behaviour in these kinds of micro/nano-textured surfaces primarily goes through a full rebound scenario. It has been shown in the literature that a high receding contact angle on the non-wetting surface is the cause of this behaviour. Next, a droplet experiences a receding breakup and splashing event at high $We = 108$ and 130. Droplet breakup was found to occur earlier on micro/nano-textured surfaces than on micro-textured surfaces alone. Thus, we speculate that the existence of nano-textures may be the cause of this instability at the spreading droplet's edge since the high capillary pressure prevented the liquid from penetrating the nanostructures, causing an earlier breakup. The literature provided an explanation for such breakup events [4].

On a surface infused with lubricant and featuring Micro/Nanotextures (LIS): We used a low viscosity 17 cSt, Krytox GPL-101 lubricant in the current investigation. Since this lubricant was applied on a surface with micro- and nano-texturing, both the viscosity of the lubricant and the surface morphology may have an impact on droplet impact behaviour. The different impact events on the LIS, including deposition, singular jet, partial rebound, receding breakup, and splash, are depicted in **Figure 4**. Because of the viscosity of the lubricant oil reducing the droplet's retraction velocity, droplet impact behaviour on the LIS mostly demonstrates deposition events which could lower the droplet's kinetic energy during the retraction process, making the droplet less energetic to rebound. Furthermore, partial rebound events do occasionally happen on LIS. This could happen as a result of oil being moved by droplet impact, which could be affected by surface morphology [9]. Thus, in certain situations, a droplet may partially rebound as a result of the textured surface effect. Ultimately, splashing events on LIS and receding breakup events happened at $We = 165$ and 134, respectively. These Weber number values are significantly greater than those of micro- and micro/nano-textured surfaces. This demonstrates how LIS's droplet breakup event occurs more slowly than it does on other textured surfaces. The theory was that since the lubricant's shear friction causes the droplet energy to dissipate during the droplet impact process on the LIS, the delay in the droplet breakup event on the LIS may be caused by viscous dissipation.

5. Conclusions

This paper presents a qualitative description of droplet impact behaviour on surfaces that are micro- and micro/nano-textured, as well as lubricant-infused surfaces that have micro/nano-textures. The following conclusions are supported by the results:

1. On the prepared surfaces, a total of six drop impact behaviours were seen: splash, deposition, singular jet, receding breakup, full rebound, and partial rebound.
2. The change in drop impact behaviour was effectively influenced by surface properties and Weber number. Retraction's effect on the receding contact angle can result in partial or complete rebound on surfaces with micro- and nano-textured coatings, respectively. On the other hand, it primarily displays the drop deposition event on LIS, which could have resulted from a decrease in retraction velocity caused by the viscosity of the lubricant oil. The droplet breakup and splash event on every surface are promoted by the constant increase in the Weber number.
3. Furthermore, LIS droplet breakup phenomena occurs later than on micro- and micro/nano-textured surfaces. The viscous effect on the LIS is to blame for this. Additionally, the presence of nanostructures on the micro/nano-textured surface causes early droplet breakup by causing instability at the edge of the spreading droplet, which in turn causes droplet breakup.

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Conflict of interest

The authors declare there is no conflict of interest.

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