Drop Impact Study on Flexible Superhydrophobic Surface Containing Micro-Nano Hierarchical Structures

Abinash Tripathy, Girish Muralidharan, Amitava Pramanik, Prosenjit Sen

***Abstract*—**Superhydrophobic surfaces are abundant in nature. Several surfaces such as wings of butterfly, legs of water strider, feet of gecko and the lotus leaf show extreme water repellence behaviour. Self-cleaning, stain-free fabrics, spill-resistant protective wears, drag reduction in micro-fluidic devices etc. are few applications of superhydrophobic surfaces. In order to design robust superhydrophobic surface, it is important to understand the interaction of water with superhydrophobic surface textures. In this work, we report a simple coating method for creating large-scale flexible superhydrophobic paper surface. The surface consists of multiple layers of silanized zirconia microparticles decorated with zirconia nanoparticles. Water contact angle as high as 159 ± 1^0 and contact angle hysteresis less than 8^0 was observed. Drop impact studies on superhydrophobic paper surface were carried out by impinging water droplet and capturing its dynamics through high speed imaging. During the drop impact, the Weber number was varied from 20 to 80 by altering the impact velocity of the drop and the parameters such as contact time, normalized spread diameter were obtained. In contrast to earlier literature reports, we observed contact time to be dependent on impact velocity on superhydrophobic surface. Total contact time was split into two components as spread time and recoil time. The recoil time was found to be dependent on the impact velocity while the spread time on the surface did not show much variation with the impact velocity. Further, normalized spreading parameter was found to increase with increase in impact velocity.

***Keywords*—**Contact angle, contact angle hysteresis, contact time, superhydrophobic.

I. Introduction

UNDERSTANDING the dynamic behaviour of droplets impacting on solid surfaces is of great interest due to its various technological applications such as inkjet printing, spray painting, superhydrophobic coatings etc. [1]-[4]. In this context, high speed imaging has become an attractive tool to understand the drop impact at short time scales in the range of few milliseconds thereby enabling better design of such surfaces [5]. When drop impacts the solid surface, it was observed that drop undergoes various morphological transformation such as spreading, recoiling, and bouncing depending on the nature of substrate and the liquid [6]-[9]. The parameters such as contact time, maximum spread diameter, satellite drop formation, resonant frequency, oscillation dynamics etc. have become important parameters to fabricate surfaces with superior functional benefits. Richard et al. developed an expression for the contact time ($\tau = (\rho R^3/\gamma)^{1/2}$) on a non-wetting surface by performing the droplet impact experiments at different Weber numbers [9], [10]. They also showed the non-dependence of contact time on droplet impact velocity over a wide range of velocities. Okumura et al. could predict the maximal deformation and the contact time of an impacting droplet onto a superhydrophobic surface using scaling arguments [8]. In the same vein, Clanet et al. found scaling law ($D_{max}/D_0=We^{0.25}$) by balancing between gravity and the surface forces [7]. Another critical factor which affects the impinging behaviour is the flexible nature of the substrate. Most of the studies in the literature have been limited to rigid substrate [1]-[3], [5], [11]-[14].

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Thus, in this work, we report a simple, cost-effective method to fabricate large-scale, micro-nano structured flexible superhydrophobic surface. Superhydrophobic properties were studied through drop impact studies using high speed imaging. The contact time and normalized spreading parameter were measured for water droplet on the superhydrophobic surface. To unravel the critical parameters, we split the contact time into spread time and recoil time. Also, the normalized spreading parameter at different Weber number has been obtained from the experimental data.

II. Fabrication Method

In this work, flexible superhydrophobic surfaces are prepared using sol-gel technique. Two different sizes of Zirconia nanoparticles were used. First of all, 1 ml of 1H, 1H, 2H, 2H Octyltriethoxy silane was added to 40 ml of Ethanol. The solution was then stirred for 2 hours to ensure proper mixing. After that Zirconia microparticles (0.9 g, ~ 3 microns) was added to the solution and stirred for 30 minutes followed by the addition of Zirconia nanoparticles (0.4 g, ~ 180 nm). The solution was further stirred for one hour. Then the mixture was spread on paper using a syringe and the surface was allowed to dry in room temperature. Fig. 2 represents the representative FESEM image of hierarchical structures on the paper surface. After that, experiments were performed on the surface to characterize the surface.

III. Experimental Set Up

After the fabrication of the nano structured hierarchical surface, contact angle and contact angle hysteresis measurement were carried out using a Goniometer. A 10 µL drop of water was placed on the superhydrophobic hierarchical surface using a micro pipette and images of the droplets was captured using a CMOS camera. ImageJ software was used to calculate the contact angle from the captured image. For contact angle hysteresis, the Goniometric stage tilts the whole imaging setup capturing the tilt at which the droplet starts to move.

A high speed imaging set-up (Photron High Speed Camera) was used for the drop impact study of water droplet on the flexible superhydrophobic surface at 10000 fps (Fig. 3). 10 µL water droplets were allowed to fall on the superhydrophobic surface from five different heights (3.3 cm, 6.7 cm, 8 cm, 10 cm and 13.3 cm), thereby allowing to modulate the Weber number from 20 to 80. All the high speed imaging experiments were performed three times for confirming the repeatability and were carried out at room temperature. Vibration isolation table was used for all the experiments to protect them from external disturbances. Parameters like contact time of the droplet with the surface, normalized spreading parameter (D_{max}/D_0) of the droplet on the surface were calculated from the droplet bouncing experiments on the flexible superhydrophobic surface.

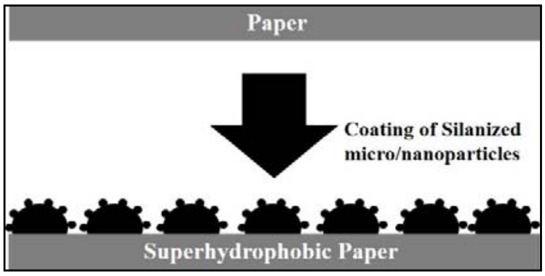

Fig. 1 Process flow of fabrication of superhydrophobic surface

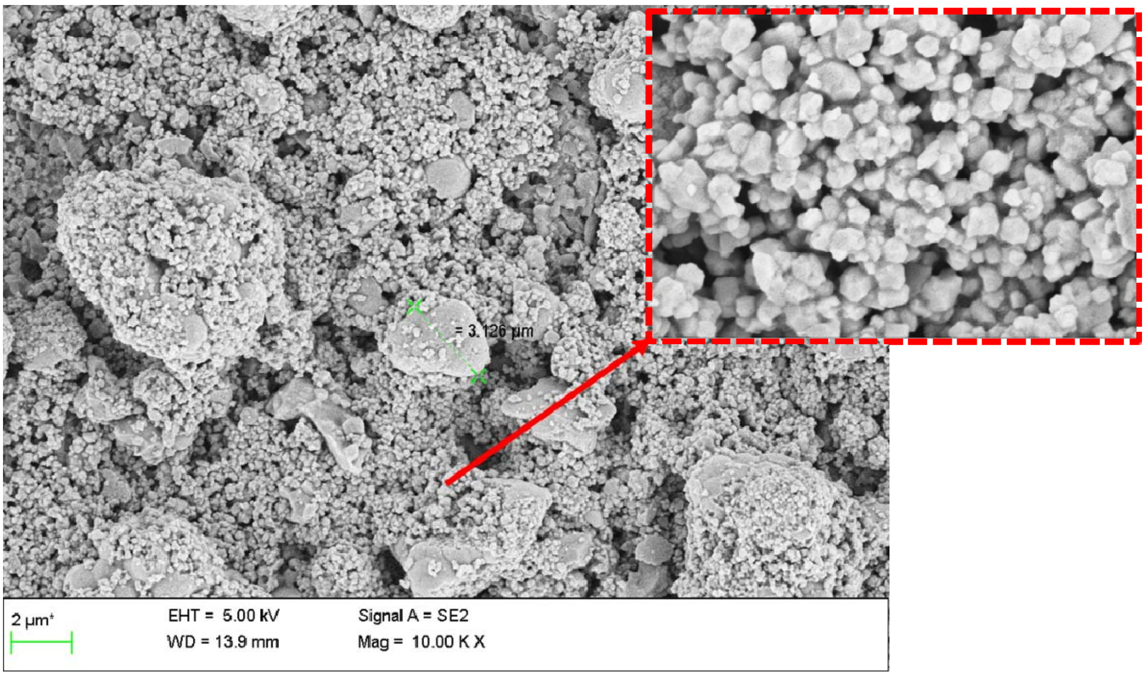

Fig. 2 Representative FESEM image of hierarchical superhydrophobic paper surface

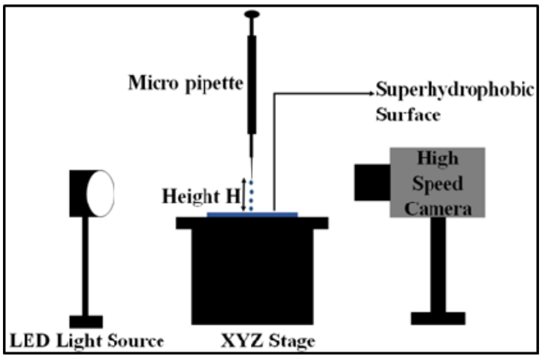

Fig. 3 High speed imaging setup for drop impact study

IV. Experimental Results

A. Contact Angle and Contact Angle Hysteresis Measurement

Contact angle and contact angle hysteresis has been measured on the superhydrophobic paper surface. A 10 µL water droplet was used for the measurement. On the superhydrophobic paper surface the contact angle was 159 ± 1^0 and contact angle hysteresis was less than 8^0. Measurements were carried out three times to ensure repeatability. Fig. 4 shows the image of a 10 µL water droplet on the superhydrophobic surface. ImageJ software was used to measure the contact angle from the captured image.

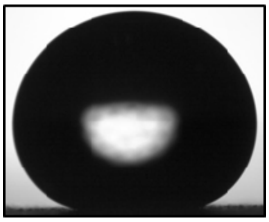

Fig. 4 Water droplet on superhydrophobic paper surface

B. Drop Impact Study on Flexible Superhydrophobic Surface

Using the high speed imaging setup drop impact experiments on the hierarchical superhydrophobic surface were carried out at five different Weber numbers ranging from 20 to 80. 10 µL water droplets were allowed to fall from different heights onto the flexible superhydrophobic surface and the droplet dynamics were captured at 10000 fps using the high speed imaging camera. Fig. 5 shows the snap shots of the water droplet on the superhydrophobic surface released from a height of 6.7 cm at various time points. D_0 is the diameter of the droplet just before the impact on the surface and D_{max} is the maximum spreading diameter of the droplet on the surface. The ratio of D_{max}/D_0 is defined as the normalized spreading diameter.

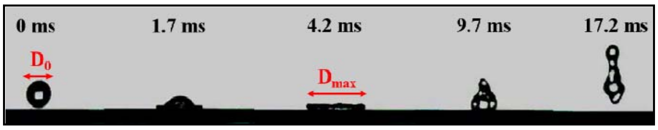

Fig. 5 Snapshot of water droplet bouncing on flexible superhydrophobic surface

After the drop impact experiments at different Weber numbers contact time was calculated for each case. Contact time is the time of contact of the droplet with the surface. Contact time was split in to two components as spread time and recoil time. Spread time is the time from the point of impact to the maximum spread condition and recoil time is defined as the time from the maximum spread to the final detachment (Fig. 6). Spread time did not show much variation with the increase in velocity while recoil time and contact time were found to be dependent on velocity and increased with the increase in velocity (Fig. 7).

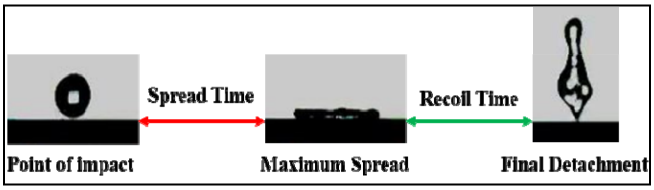

Fig. 6 Spread time and recoil time during drop impact on superhydrophobic surface

Also, we calculated the contact line width of the droplet from the point of maximum spread condition to the final detachment from the surface. A 4th order polynomial fit was performed to obtain the temporal evolution of the contact line velocity profile from the contact line width data. From Fig. 8 it is obvious that during the recoil phase of the droplet the contact line velocity first increases and attains a maximum. The excess interfacial energy driving the retracting contact line reduces and the contact line velocity decreases as the droplet approaches the spherical shape. And finally once the stretching droplet overcomes the stiction forces, the contact line velocity increases again till the final detachment.

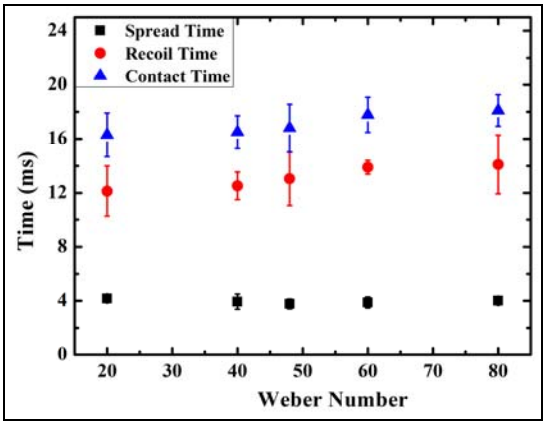

Fig. 7 Spread time, Recoil time and Contact time during drop impact

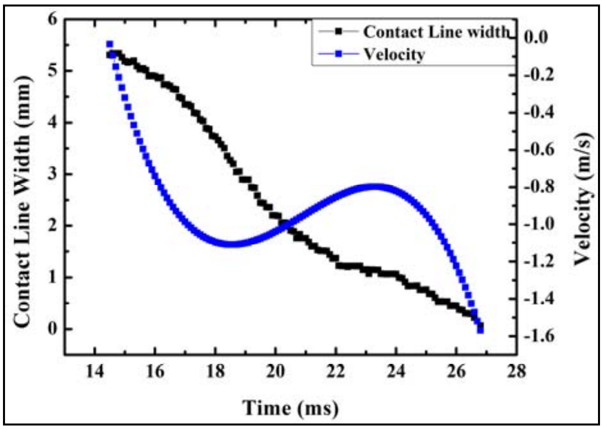

Fig. 8 Temporal evolution of contact Line width and contact line velocity of water droplet at Weber Number 40 during contact with the superhydrophobic surface

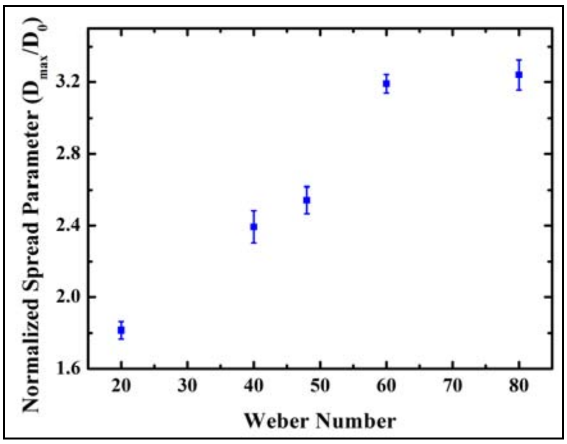

Fig. 9 Normalized spread parameter (D_{max}/D_0)

Fig. 9 shows the graphs between the normalized spread parameter ($R = D_{max}/D_0$) vs. Weber number on flexible superhydrophobic surface for water droplet. It has been observed that normalized spreading diameter R depends on the Weber number and an increase in velocity, increases the D_{max}.

V. Conclusion

A very effective method to fabricate hierarchical micro/nano structured superhydrophobic flexible surface has been presented in this paper. This method is a simple coating technique to fabricate surface with extreme water repellence ability. Also, it is a large area fabrication technique for superhydrophobic surfaces and other than paper the same coating can be applied on fabric, plastic, metals etc. to make them superhydrophobic. The contact time and normalized spreading parameter were measured for water droplet on the superhydrophobic surface. We observed that a velocity dependence of the recoil time and contact time and the spread time did not show variation with respect to velocity. Also, an increase in D_{max} was observed as we increased the impact velocity of the droplet.

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