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Research Article

Basic Evaluation for Dynamic Behavior of Waterdrop on Line-patterned Silicone Surface using Equation of Motion

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Abstract

Inspired by the water-repellent and self-cleaning properties of the lotus leaf in the natural world, artificial superhydrophobic surfaces have generated extensive attention in academia and industry. Hydrophobicity and the sliding behavior of waterdrops is a very important phenomenon in our daily life as well as in many industrial processes. However, the difference between these two phenomena is not well understood. This study was performed to predict movement of waterdrop on surfaces of silicone sheet and was focused on interface resistive forces between waterdrop and surfaces. Various hydrophobic sheets having different the waterdrop contact ratio (the ratio of the contact area between the waterdrop and the sheet) were prepared. And the relationships between the sliding angles, the sliding velocities and the surface structure were investigated. Equation of motion is used to calculate the interface resistive forces from the sliding angle and the sliding velocities. As the result of calculation, interface resistive forces between waterdrop and the surfaces are equivalent to force of the gravity. The interface resistive forces decrease with decreasing the waterdrop contact ratio. Sliding velocities seems to affect interface resistive forces. This research clarifies that sliding velocity and interface resistive forces are related to positive correlation by the waterdrop contact ratio. The relationship may help prediction of movement of drops on surfaces.

Keywords: Hydrophobicity; Surface topography; Interface resistive force; Sliding behavior of waterdrop; Sliding velocity; Equation of Motion

Introduction

In 1997, Barthlott [1] reported that taro leaves have fine irregularities, so the waterdrops on the surface can be made spherical. This phenomenon is called superhydrophobicity, and so the taro leaves can be cleaned with rainwater [2]. In order to evaluate the antifouling property, it is necessary to evaluate not only the water repellency of the surface but also the waterdrop removability (water-sliding property). There are many studies on water repellency [3-5], but water repellency is often unclear.

In addition to taro leaves, rose petals show superhydrophobicity. The waterdrop on the surface of the rose petal is spherical. But the waterdrop does not fall even if the petals are turned upside down [6].

When the surface is horizontal, the drop remains at equilibrium owing to the force balance between the weight of the drop (mg) and the normal reaction force (N) from the substrate. When the surface is tilted through an inclination angle (α), the drop changes shape and leans in the direction of the unbalanced component. Fig.1 (a) depicts the forces acting on a sessile drop on a real tilted surface. The equilibrium condition for this sessile drop is maintained by a force balance on the drop, given as follows:

$$mg \sin \alpha = F_r \# (1)$$

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Where m is the mass of the drop, α is the inclination angle of the solid surface and F_r is the magnitude of the total impeding force on the drop.

The study of the retention of liquid drops resting on inclined surfaces has been the subject of much research [7]. These authors determined that the $mg \sin \alpha$ is proportional to the difference between the cosines of the contact angles at the rear (receding) edge θ_R and at the front (advancing) edge θ_A of the drop. This difference is called contact angle hysteresis (CAH).

$$mg \sin \alpha = \kappa(\cos\theta_R - \cos\theta_A)\ \#\ (2)$$

Figure 1(b) depicts the receding edge and the advancing edge of the drop on the tilted surface. The shape of the drop on the tilted surface distorted, exhibiting advancing and receding contact angles.

Figure 2 depicts the contact area on a sessile drop on a solid surface. The study of the contact area between liquid drops and inclined surfaces has been also the subject of much research [8-10]. When F_r is estimated with a characteristic length, such as its contact-area diameter $2r$ (or width w), one obtains a size-independent parameter.

$$F_r = \kappa w \gamma_L (\cos\theta_R - \cos\theta_A)\ \#\ (3)$$

Where γ_L is the surface tension of the waterdrop.

There was some interesting research about sliding waterdrop. Reyssat et. al. [11] have shown that the waterdrop on an inclined superhydrophobic surface follows the law of free fall in the initial condition. Then the drop reaches terminal velocity, 100 to 1000 times larger than on a windowpane. They suggested that air friction limits the drop speed.

In a recent study [12], we have shown that the waterdrops on the surface of the silicone sheet slide at a constant velocity on any inclination. However, the velocity of the waterdrop was so slow. It is mean that the air friction was so small as to be ignorable as compared with the interface resistive force. This study's aim was performed to create a slid surface that can remove waterdrop on it. That was focused on the interface resistive forces between the waterdrops and surfaces. In this work, the relationship between the sliding velocity of the waterdrops on the silicone sheets with different groove structures and their interface resistive force was studied.

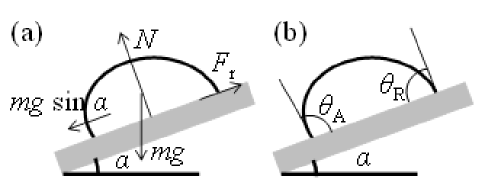

Figure 1: (a) Schematic depicting the forces acting on a drop and (b) shape of the drop on the critical inclination angle (α).

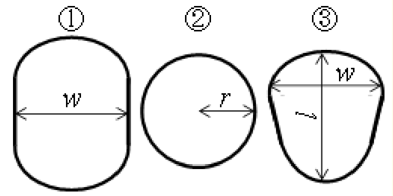

Figure 2: Plane view of liquid drops with contact lines having various shapes: (a) a circular drop, (b) a parallel-sided drop, and (c) a drop with front-to-back asymmetry.

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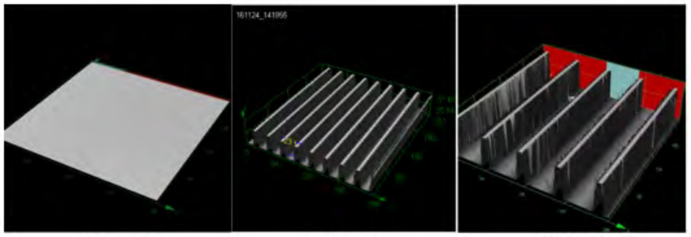
Materials and Methods

Various hydrophobic sheets having different the waterdrop contact ratio (the ratio of the contact area between the waterdrop and the sheet) were prepared. These waterdrops' contact ratios were 1/1, 1/3, and 1/6 (Fig. 3). The sliding angle was measured using an automatic sliding system (FTA1000, First Ten Angstroms Co. Ltd.) with a tilt speed of 0.5°/s. The waterdrops used for measurement of the sliding angle were 10 μl. The respective averages of five measurements were used as sliding angle data. The sliding behavior was measured using the FTA1000 with 10° tilt stage. The waterdrops used for measurement of the sliding behavior was 10μl. The moving distance of the waterdrops dropped on the stage was measured. The respective averages of three measurements were used as sliding distance data.



1/1 sheet 1/3 sheet 1/6 sheet

Figure 3: Laser scanning microscopy images of the various surfaces on silicone sheets.

Displacement of the waterdrops on the inclined silicone sheet was measured by contact angle meter (FTA1000, First Ten Angstroms, USA). The equation of motion for the waterdrops on the inclined silicone sheet is given by Eq. (4).

$$m\frac{d^2x}{dt^2} = mg\sin\alpha - \gamma\frac{dx}{dt} - F_r\#(4)$$

Where *m* is the mass of a waterdrop, g is the gravitational acceleration, γ is the air resistance coefficient. The interface resistive force F_r between the waterdrop and the inclined silicone sheet was calculated by this Eq. (4).

Eq. (5) and Eq. (6) are obtained by integrated Eq. (4) with respect to the displacement *x* and velocity *v* of the waterdrop.

$$x(t) = -\frac{m}{\gamma}\left\{v_0 - \frac{m}{\gamma}\left(g\sin\theta - \frac{F_r}{m}\right)\right\}e^{-\frac{\gamma}{m}t} + \frac{m}{\gamma}\left(g\sin\theta - \frac{F_r}{m}\right)t + \frac{m}{\gamma}\left\{v_0 - \frac{m}{\gamma}\left(g\sin\theta - \frac{F_r}{m}\right)\right\}\#(5)$$

$$v(t) = \left\{v_0 - \frac{m}{\gamma}\left(g\sin\theta - \frac{F_r}{m}\right)\right\}e^{-\frac{\gamma}{m}t} + \frac{m}{\gamma}\left(g\sin\theta - \frac{F_r}{m}\right)\#(6)$$

Where v_0 is the initial velocity. v_0 and *f* can be obtained by curve-fitting the displacement of the drop sliding on the sample measured using the least squares method in Eq. (5).

The sliding velocity *V* is determined by the limit value of the drop velocity *v*(*t*) such as following in Eq. (7).

$$V = \lim_{t\to\infty} v(t) = \frac{m}{\gamma}\left(g\sin\theta - \frac{F_r}{m}\right)\#(7)$$

Results and Discussion

The relationships between the sliding angles, the sliding velocities and the surface structure were investigated. Equation of motion is used to calculate the interface resistive forces from the sliding angle (Fig. 4(a)) and the sliding velocities (Fig. 4(b)). As the result of the calculation, interface resistive forces between waterdrop and the surfaces are equivalent to force of the gravity.

The interface resistive forces decrease with decreasing the waterdrop contact ratio. Sliding velocities seem to affect interface resistive forces. This research clarifies that sliding velocity and interface resistive forces are related to a positive correlation by the waterdrop contact ratio (Fig. 4(b)).

The interface resistive force F is proportional to the sliding velocity *V* to the δ power (0 < δ <1). δ means a material parameter. The relationship between *V* and *F* can be expressed by the following equation (8) to (10). The solid lines in Fig (4) are shown as equations (8) to (10), respectively.

$$F_{r,1/1} = \kappa w_{1/1}\, V^{0.14} \,\#\, (4)$$
$$F_{r,1/3} = 1/3\, \kappa w_{1/3}\, V^{0.14} \,\#\, (4)$$
$$F_{r,1/6} = 1/6\, \kappa w_{1/6}\, V^{0.14} \,\#\, (4)$$

Where W is measured as the width of the contour of each inclined contact surface. The δ on the silicone surface is considered to be 0.14. It is considered that a more detailed examination is necessary. The interface resistive forces decrease with decreasing the waterdrop the contact ratio. The cause of the decrease in force is considered to be the decrease in contact area. The relationship may help predict of movement of drops on surfaces.

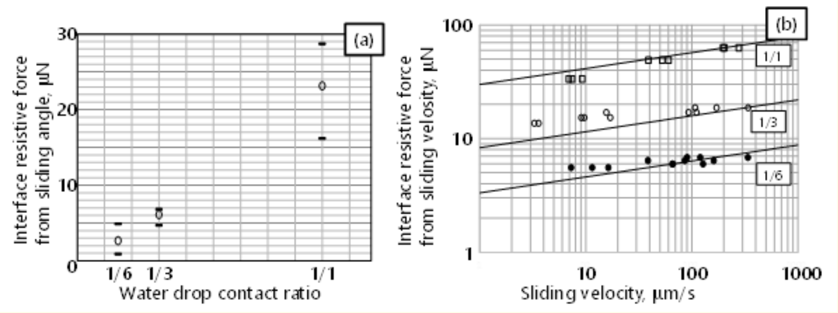


Figure 4: Interface resistive force between the waterdrop and the various sheets calculating from (a) the sliding angles and (b) the sliding velocities.

Conclusion

In order to understand the sliding behavior of waterdrops, we developed a silicone sheet with the surface topography. The interface resistive forces decrease with decreasing the waterdrop contact ratio. This research clarifies that sliding velocity and interface resistive forces are related to a positive correlation by the waterdrop contact ratio.

Acknowledgements

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References

1. Barthlott W., et al. "Purity of the sacred lotus, or escape from contamination in biological surfaces". Planta 202.1 (1997): 1-8.
2. Milles S., et al. "Characterization of self-cleaning properties on supercoefficientc aluminum surfaces fabricated by direct laser writing and direct laser interface patterning". Appl. Surf. Sci 524 (2020): 146518.
3. Young T. "An Essay on the cohesion of Fluids". Philosophical Transactions of the Royal Society of London 95 (1805): 65-87.
4. Wenzel RN. "Resistance of Solid Surfaces to Wetting by Water". Ind. Eng. Chem 28.9 (1936): 988-994.
5. Cassie ABD., et al. "Wettability of Porous Surface". Trans. Faraday Soc 40 (1944): 546-551.
6. Feng L., et al. "Petal Effect: A Superhydrophobic State with High Adhesive Force". Langmuir 24.8 (2008): 4114-4119.
7. Furmidge CGL. "Studies at Phase Interfaces I. The Sliding of Liquid Drops on Solid Surfaces and a Theory for Spray Retention". J. Colloid Sci 17.4 (1962): 309-324.
8. Extrand CW and Kumagai Y. "Liquid Drops on an Inclined Plane: The Relation between Contact Angles, Drop Shape, and Retentive Force". J. Colloid Interface Sci 170.2 (1995): 515-521.

9. ElSherbini AI., et al. “Retention forces and contact angles for critical liquid drops on non-horizontal surfaces”. J. Colloid & Interface Sci 299 (2006): 841-849.
10. CW Extrand. “Remodeling of Super-hydrophobic Surfaces”. Langmuir 32.34 (2016): 8608-8612.
11. Reyssat M., et al. “Dynamical superhydrophobicity”. Faraday Discussions 146 (2010): 19-33.
12. Yanagisawa K., et al. “Evaluation for Sliding Behavior of Water Droplets on Surface of VGCF Composited Silicone sheet”. Trans. GIGAKU 7.1 (2020): 07005-1-07005-7.

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