Sensors and Actuators B 213 (2015) 360–367

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Dynamic lateral adhesion force of water droplets on microstructured hydrophobic surfaces

Jae Min Lee, Seung-hwan Lee, Jong Soo Ko*

Graduate School of Mechanical Engineering, Pusan National University, Busandaehak-ro 63 Beon-gil, Geumjeong-gu, Busan 609-735, Republic of Korea

ARTICLE INFO

Article history:
Received 10 October 2014
Received in revised form 14 February 2015
Accepted 21 February 2015
Available online 27 February 2015

Keywords:
Lateral adhesion force
Contact angle
Hydrophobic
Superhydrophobic
Microstructure

ABSTRACT

This study investigates the change of the dynamic lateral adhesion forces of water droplets on microstructured surfaces by varying their hydrophobicities. While hydrophobic surfaces showed significant asymmetry in advancing-to-receding profiles, superhydrophobic surfaces did not. As a result, hydrophobic surfaces required greater moving forces at the moment of change of the moving direction than superhydrophobic surfaces. In addition, lateral adhesion forces measured from hydrophobic surfaces were much higher than those from superhydrophobic surfaces. In the present experimental conditions, water droplets did not roll on the surfaces with lateral adhesion forces larger than 21 mgf. These results support the possibility that the rolling ability of a water droplet on a surface can be evaluated by measuring the lateral adhesion force.

1. Introduction

Surface modification to achieve superhydrophobicity is a typical example of biomimetics [1–3]. The representative plant that has a superhydrophobic characteristic is the lotus. The surface of the lotus leaf is covered with microprotrusions, which are in turn covered in nanoprotrusions composed of hydrophobic epicuticular wax crystalloids, and the lotus leaf has superhydrophobic and self-cleaning characteristics [4]. These characteristics are also referred to as the lotus effect. Artificial realization of a nano–micro hierarchical topology is the key factor to achieve a superhydrophobic surface with a static contact angle greater than 150°, and numerous fabrication methods have been developed to date [5–9]. The rose petal is also covered with nano–micro hierarchical structures, showing a superhydrophobic surface. However, a water droplet on a petal does not roll; rather it is suspended when the petal is inverted [10]. As a result, the rose petal does not have a self-cleaning capability [11,12]. In short, the lotus leaf and the rose petal both show very high contact angles greater than 150° (superhydrophobic), but they show antithetic behavior with regard to the rolling of water droplets [13]. This indicates that it is not sufficient to predict the dynamic behavior of the water droplet on a superhydrophobic surface simply by measuring the contact angle.

To investigate the dynamic behavior of the water droplet on a surface, several methods for measuring dynamic contact angles have been developed, including the dynamic sessile drop method [14] and tilting plate method [15]. Through the measurement of dynamic contact angles, the contact angle hysteresis, defined as the difference between advancing and receding contact angles, can be obtained [16–18]. The contact angle hysteresis is an important physical parameter that affects the dynamic behavior of water droplets, such as rolling and collision. In practice, rolling-off of a water droplet and self-cleaning ability are determined by the level of contact angle hysteresis measured from a surface. The roll-off angle/contact angle hysteresis should be maintained at less than 10° to realize the lotus effect on a surface [19]. Assessing the contact angle hysteresis is an effective means to predict the dynamic behavior of a water droplet on a surface. However, this measurement method uses an optical subsystem to capture the profile of a moving water droplet. Because it relies on the captured image of a water droplet, the actual adhesion force between the surface and the water droplet cannot directly be obtained.

Recently, several approaches to measure normal and lateral adhesion forces have been reported. Atomic force microscopy (AFM), a representative approach for measuring normal adhesion force, has been used to measure the capillary bridging force of a liquid between the AFM tip and the substrate surface [20–26]. Although this method provides a quantitative means of measuring the adhesion force, the measurement area is limited to the submicroscopic level due to the usage of a nanoscale tip. It is therefore difficult to use the method with topographically-modified

---

* Corresponding author. Tel.: +82 51 510 2488; fax: +82 51 514 0685.
E-mail address: mems@pusan.ac.kr (J.S. Ko).

http://dx.doi.org/10.1016/j.snb.2015.02.101
0925-4005/

hydrophobic surfaces including a microstructured surface [25]. The most important approach to investigate static lateral adhesion forces to date is the tilted plate method [27–29]. This method involves gradual tilting of the plate and measuring the roll-off angle, followed by calculation of the static lateral adhesion forces from the relation to the projection of the gravitational force needed to initiate droplet movement. Although a useful way to measure the lateral adhesion forces, this method has several limitations. First, only "static" lateral adhesion forces can be obtained. Second, this method is valid only for sufficiently large droplets, because small droplets do not slide owing to insufficient gravity. Third, it does not directly measure the forces. Tadmor et al. [30] proposed a centrifuge method in which gravitation is replaced by a centrifugal force. The static lateral adhesion force of the small droplets can be measured by using a centrifugal adhesion balance (CAB) system. This method also measures the "static" lateral adhesion forces and does not directly measure the forces.

The capability of measuring a dynamic lateral adhesion force when a water droplet moves in the lateral direction along a surface would be very helpful to predict the dynamic behavior of a water droplet on a surface. In this study, we introduce a new approach to characterize surface properties: measuring the dynamic adhesion force of a surface and a water droplet that moves laterally to the surface. To verify the proposed measurement scheme, microstructured surfaces with different hydrophobicity are fabricated and characterized. In addition, the relationship of the lateral adhesion force and the rolling ability of a water droplet is discussed.

2. Measurement concept

The configuration of the measurement system is shown in Fig. 1. An H-shape probe has been devised to measure the dynamic lateral adhesion force between the water droplet and the substrate surface. The lower end of a rigid bar is attached to the center of the H-shape probe, while its upper end is locked onto the probe holder. The holder is connected to a very precise load cell, allowing the very small force acting at it to be measured. Two water droplets are attached to each probe disk. The probe disks are modified to be hydrophilic to give sufficient adhesion force between the water droplet and the probe disk surface. Two samples are attached to each moving plate, where the lateral movement is precisely controlled by the respective linear servo actuator. Two linear actuators are clamped onto the stage.

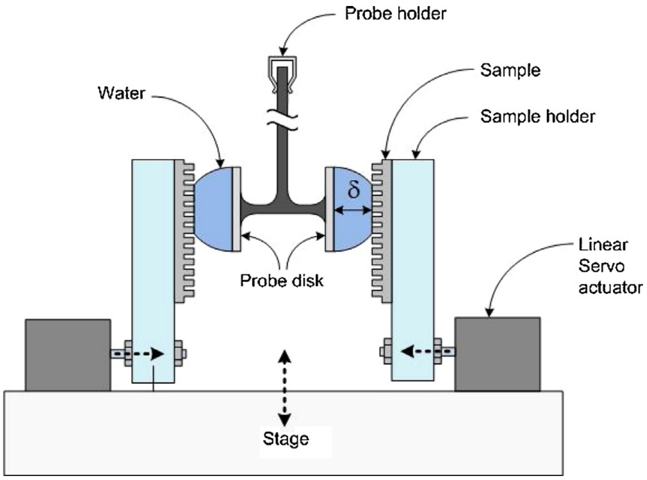

Fig. 1. Measurement scheme of dynamic lateral adhesion force of water droplets on microstructured sample surfaces. While the probe disk is fixed, the stage moves up and down.

After two water droplets are dispensed on each probe disk, the two sample holders simultaneously move to the center with the same velocity, and then stop when they reach a certain distance (δ) from the probe disks. The water droplets are constrained between the sample surfaces and the probe disks. The stage then moves downward and upward. During the whole measurement, the probe holders and the probe disks do not move. Briefly, while the probe does not move, the two moving plates move horizontally and then the stage moves vertically.

To continuously measure the dynamic lateral adhesion forces using the proposed measurement concept, the probe disk should hold the droplet and the droplet volume should remain constant during the measurement. Two necessary conditions should be satisfied to meet these requirements. First, the adhesion force of the probe disk and the droplet must be higher than that of the sample surface and the droplet. The probe disk surface thus should have strong hydrophilicity to endow a strong adhesion force between

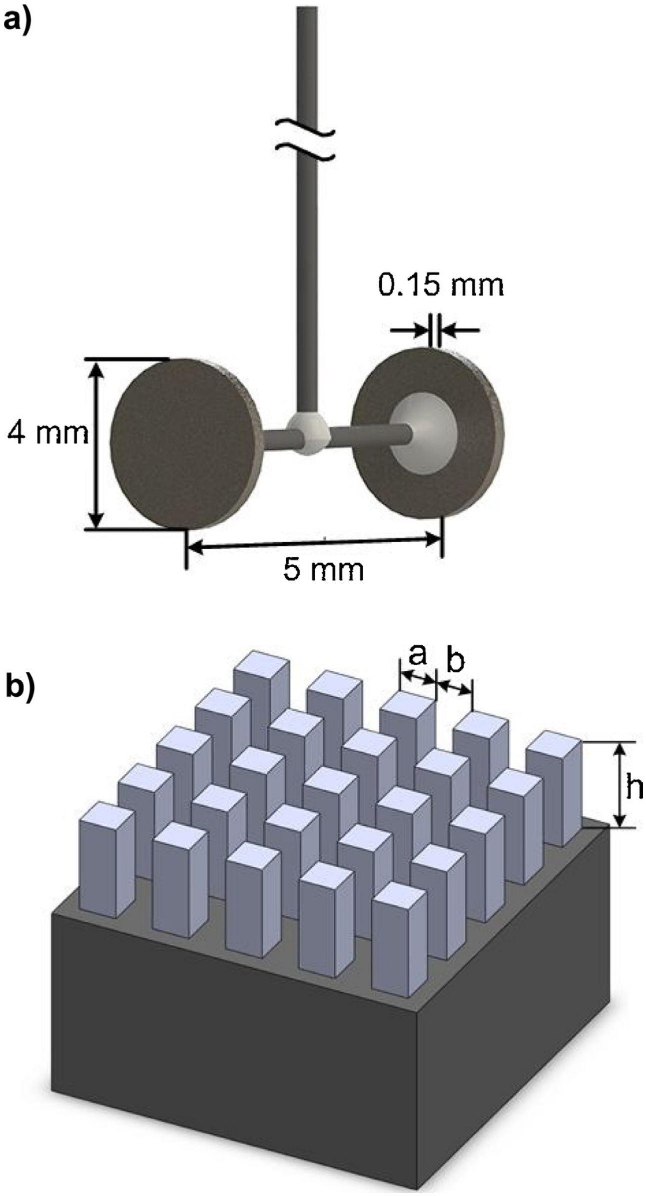

Fig. 2. Geometries of the designed probe disk (a) and microstructures that will be formed on a sample surface (b). *a*, *b*, and *h* denote pillar width, spacing between neighboring pillars, and height of the microstructures, respectively.