

Surface Science Letters

Relationship between sliding acceleration of water droplets
and dynamic contact angles on hydrophobic surfacesMunetoshi Sakai ^{a,*}, Jeong-Hwan Song ^a, Naoya Yoshida ^{a,b}, Shunsuke Suzuki ^{a,c},
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Abstract

This study measured sliding acceleration of water droplets on hydrophobic solid surfaces and used expanding and contracting method to compare that value with dynamic contact angles. Sliding action of the droplet was classified into three motion categories: constant accelerated motion, constant velocity and stasis. Differences exist in the dependencies of contact radius and the injection–suction rate in dynamic contact angle hysteresis according to these categories. This method is an effective indicator of water droplets' sliding acceleration.

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1. Introduction

Technologies related to hydrophobic coatings are important for suppressing chemical reactions and bonding formation between water and solid surfaces. Such coatings have been adopted for various industrial uses including anti-wetting, anti-snow (or ice)-adherence, anti-rusting, and reduction of friction resistance [1–4].

The contact angle of water is used widely as a criterion for evaluation of surface hydrophobicity. However, recognition of the importance of dynamic hydrophobicity is growing in the glass, automobile, and electronics industries, among others. To date, the sliding angle (the critical angle at which a water droplet with a certain weight begins to slide

down an inclined plate) and contact angle hysteresis (the difference between receding contact angle and advancing contact angle) have been commonly employed as criteria for assessing the dynamic hydrophobicity of solid surfaces.

The sliding angle value does not include information on water-shedding properties such as sliding acceleration or velocity. Recently, information related to the speed at which the droplet can be removed from the surface at a certain tilt angle is becoming more important than that at the lowest tilt angle at which the droplet slides down [5]. Yoshida et al. evaluated sliding acceleration of water droplets on several hydrophobic polymer coatings; those results revealed that the order of sliding acceleration does not coincide with that of sliding angle [6,7].

Sliding acceleration is typically measured using a high-speed camera with a motion analysis system. Because of the expensive system requirements, fundamental understanding of the factors and their contribution to the overall sliding acceleration and velocity remain insufficient. For

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those reasons, development of a simple evaluation method is demanded. Sliding action of water droplets depends strongly on the interaction between the solid and water at the interface. It is expected that the interaction affects the dynamic contact angles obtained by expanding and contracting method. Through this study, we measured the contact angles using this method during motion. Subsequently, for three hydrophobic surfaces, we compared the obtained values with the sliding acceleration values of water droplets obtained from a high-speed camera system.

2. Experimental

2.1. Sample preparation

This study employed *octadecyltrimethoxysilane* (ODS, $\text{CH}_3(\text{CH}_2)_{17}\text{Si}(\text{OCH}_3)_3$; Sigma-Aldrich Co., Milwaukee, WI, USA) and *heptadecafluorodecyltrimethoxysilane* (FAS, $\text{CF}_3(\text{CF}_2)_7\text{CH}_2\text{CH}_2\text{Si}(\text{OCH}_3)_3$, TSL8233; Dow-Toshiba Silicone Co., Tokyo, Japan) as water-repellent agents. Water-saturated xylene (Wako Pure Chemical Industries Ltd., Tokyo, Japan) was used as the solvent. Both ODS and FAS were dissolved into the solvent (concentration of ODS or FAS in the solvent: 25 mM). A cleaned Si (100) wafer (Aki Corp., Miyagi, Japan) was immersed in the solution for 24 h (for ODS) or 2 weeks (for FAS). After soaking, the wafer was rinsed with methylene chloride, acetone, and water. Then it was dried at 80 °C. A commercial PTFE plate was also tested for comparison.

2.2. Evaluation of coatings

Surface roughness (R_a) was evaluated in a 5- μm square area using atomic force microscopy (AFM, MMAFM-2; Veeco Instruments, CA, USA) with a Si cantilever. The sessile drop method, using a contact angle meter (Dropmaster 500; Kyowa Interface Science Co. Ltd., Saitama, Japan), was used to measure the contact angles. The droplet mass for contact angle measurement was 3 mg. The contact angles were measured at five different points for each sample. The surface was blown with ionized air (Winstat BF-Z; Shishido Electrostatic Ltd., Tokyo, Japan) to eliminate static electricity on the surface before each measurement. A sliding angle measurement system (SA-20; Kyowa Interface Science Co. Ltd.) recorded the sliding angles of a 30-mg water droplet.

2.3. Measurement of dynamic contact angles by expanding and constricting method

Samples were set on the stage; then, a small water droplet of 4–6 μl was put on the surface. A needle (diameter: ≈ 1 mm, material: SUS) was inserted into the droplet. Injecting water at a constant rate from the needle expanded the droplet volume. The advancing contact angle during expansion was measured using a contact angle meter with a constant water injection or suction unit. When the drop-

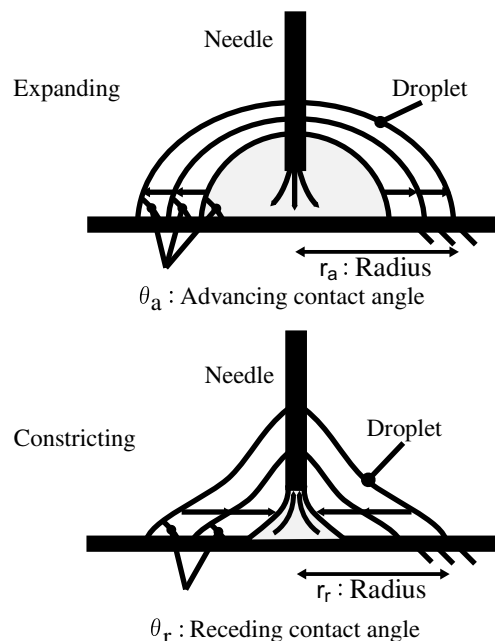


Fig. 1. Schematic illustration of the water droplet's expansion and constriction.

let mass reached a certain amount, the injection was stopped and the operation was switched to suction. Suctioning water through the needle then contracted the droplet volume. The receding contact angle during contraction was also measured (Fig. 1). Injection and suction rates of water were changed from 2 $\mu\text{l/s}$ to 16 $\mu\text{l/s}$. These dynamic contact angles were measured every 200 ms during injection and suction. The measuring period was 9400 ms (48 repetitions of injection and suction).

2.4. Sliding acceleration measurement

We evaluated the sliding acceleration of the droplet on the hydrophobic surface by analysis of recorded images that were taken using a high-speed digital camera. Using an automatic pipette, the 30 μl droplet was placed on the sample, which was tilted at 35°. When the pipette tip was pulled from the droplet, the droplet began to slide on the hydrophobic surface. Sequential photographs of the sliding action of the water droplet on the surface were taken every 4 ms using a high-speed digital camera system (512 PCI; Photron Corp., Tokyo, Japan). We estimated the sliding acceleration by measuring the sliding distance of the front edge of the contact line between the droplet and sample surface from the initial starting point using image analysis software (Dipp Macro; Ditect Co. Ltd., Tokyo, Japan).

3. Results and discussion

Respective contact angles, sliding angles, and surface roughness (R_a value) for the ODS sample, FAS sample and PTFE plate are 100.3°, 111.5°, and 124.0° for the contact angle; 9°, 47°, and 10° for the sliding angle; and 0.20 nm,

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