Design of Quick-Dry Surface Using Structured Surface^{*}

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Abstract

This paper discusses the design of surface microstructures for quick drying. The structures produced in this study were arrays of micropillars with different sizes and pitches fabricated by photolithography. It was found that the sliding angle decreased with an increase in the pitch of the pillars. Hence, droplets could be removed easily. However, the evaporation time increased significantly. To achieve a balance between the evaporation time and the sliding angle, a reticular pattern consisting of pillars and flat areas was designed and tested. The evaporation time became shorter than the fully arrayed surface on this pattern, while the sliding angle could not be made small. The evaporation time became shorter than the fully arrayed surface on this pattern, while the sliding angle could not be made small.

Key words: Structured Surface, Wettability, Quick Dry, Sliding Angle, Evaporation

1. Introduction

A textured surface or a structured surface can be used for various purposes, e.g., to control wettability and friction and to produce an antireflective surface. Wettability can be controlled to produce a superhydrophobic surface, reduce flow resistance, etc. ⁽¹⁾⁻⁽⁵⁾. Quick-dry performance, which is achieved by controlling wettability, of materials used to produce windshields of vehicles, tiles for bathroom floors, etc., must be high. However, the design method to obtain a quick-dry surface has not yet been developed since various issues should be taken into account such as wetting, spreading, evaporation, etc..

Two parameters, namely, the sliding angle and the evaporation time, can be used to evaluate the quick-dry performance. The sliding angle is the angle at which a droplet begins to slide down an inclined surface. The smaller the sliding angle, the easier it is to remove droplets from the surface. The evaporation time is the time taken by droplets to evaporate from the surface. It can be estimated by measuring the decrease in the mass of droplets with time. A superhydrophobic surface has a small sliding angle ⁽⁶⁾; however, in this case, the evaporation time is long since the surface area of droplets is small ⁽⁷⁾.

In this study, we prepared a structured surface that consisted of an array of pillars of different sizes and pitches and we produced an appropriate design of a microstructured surface for quick drying.

2. Basics of wettability

Figure 1 (a) shows the cross section of a droplet on a surface. The radius of the droplet is smaller than the capillary length described below. The contact angle θ takes a specific value that is suitable for balancing three interfacial tensions. It can be given by Young's equation as follows ⁽⁸⁾:

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$$\cos \theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \quad (1)$$

where γ_{SV} , γ_{SL} , and γ_{LV} are the interfacial tensions per unit area of the solid-vapor, solid-liquid, and liquid-vapor interfaces, respectively. These tensions are determined by a combination of liquid, vapor, and solid materials used.

When an external force (e.g., gravity force) is applied, θ changes to balance the external force, as shown in Fig. 1 (b). Thus, the contact angle on one side of the droplet differs from that on the other side; in other words, two contact angles, namely, an advancing angle θ_A and a receding angle θ_R , are formed. The relationship between the sliding angle α and the contact angles is given as follows:

$$\sin \alpha = \frac{\gamma_{LV}}{\rho g V} (\cos \theta_R - \cos \theta_A) \quad (2)$$

where ρ , g , and V are the density of liquid, gravitational acceleration, and volume of the droplet, respectively. The difference between θ_A and θ_R becomes constant the droplet slides down the inclined surface. This difference should be minimized in order to obtain a surface on which droplets can slide down easily.

When the radius of the droplet is larger than the capillary length as shown Fig. 1 (c), the top of the droplet becomes flat due to the effect of gravity. The length of the flat area is determined from the capillary length κ^{-1} , which is given as follows:

$$\kappa^{-1} = \sqrt{\frac{\gamma_{LV}}{\rho g}} \quad (3)$$

If the radius of the droplet is larger than κ^{-1} , gravity force flattens the droplet.

Fig. 1 Basic theory of wetting

From the standpoint of quick-dry performance, the profile of a droplet is important. To decrease the evaporation time of a droplet, it is necessary to increase the surface area exposed to air ⁽⁹⁾. However, the surface area decreases during evaporation. It is possible to increase the surface area by applying the following method.

Figure 2 shows movement and distortion of the contact line when a substrate with a pillar is moved upward from water ⁽¹⁰⁾. It is found that contact line is strongly distorted at the pillar. The lower edge of the pillar serves as a pin. After the pillar is lifted to a certain

height, it is observed that the contact line drops to the original level. Since the lower edge of the pillar serves as a pin, this phenomenon is called pinning and is often observed on a hydrophilic surface. The force F required to remove the contact line from the pillar per unit length can be given as

$$F \equiv \gamma_{LV}(\cos\theta_p - \cos\theta) \quad (4)$$

where θ_p is the contact angle in the case of pinning. The contact line does not move until the contact angle is below a certain value. Since it is possible to increase the surface area with the elongation of the droplet, the surface area in the case of pinning is larger than that in the case of no pinning.

Fig. 2 Pinning at the contact line by pillar ⁽¹⁰⁾

Figure 3 shows droplets with and without pinning. Since an additional force is necessary to move the droplets in the case of pinning, θ_R is less than that in the case of no pinning and the sliding angle increases ($\alpha < \alpha_p$). Thus, pinning should be avoided in order to remove droplets under sliding motion that is necessary to make quick-dry surface. An appropriate design for quick-dry surface should compromise these inconsistent conditions of pinning. Thus, systematic experiments are necessary.

Fig. 3 Sliding angle of droplet with and without pinning

3. Experimental procedure

3.1 Preparation of substrates

Structures were prepared by photolithography using a negative photoresist SU-8 (MicroChem Corp.). SU-8 is used extensively because it allows us to produce microstructures with a high aspect ratio (>7) and excellent mechanical properties ⁽¹¹⁾. The structures were arrays of pillars of different sizes and pitches. SU-8 has a hydrophilic characteristic: the contact angle for pure water is approximately 70° on a flat surface. This hydrophilic characteristic enhances pinning ⁽¹⁰⁾.

Figure 4 shows the fabrication process of the pillars. SU-8 was spin-coated on a silicon wafer and its whole area was exposed. Then, SU-8 was recoated on the first layer and exposed through a mask with a pattern. Finally, the substrate was developed. Using this process, the entire structure was made of SU-8. Figure 5 shows an SEM image of the

fabricated pillars together with specific parameters, namely, the diameter D , pitch P , and height H .

Fig. 4 Fabrication process of pillars

Fig. 5 SEM image of pillars

3.2 Definition of sliding angles and their measurement

Figure 6 shows the sliding behavior of a droplet. When the substrate is inclined, the advancing line starts to move, and further inclination triggers the motion of the receding line. The angles of inclination thus formed are defined as advancing sliding angle α_A and receding sliding angle α_R , respectively. The smaller the value of α_A , the easier it is for the droplet to spread. On the other hand, α_R is related to the sliding of the droplet. Thus, the smaller the value of α_R , the easier it is for the droplet to slide. A large difference between these angles distorts the droplet profile and increases the surface area; therefore, it will shorten the evaporation time.

Fig. 6 Definition of sliding angles

The values of α_A and α_R were measured by using the setup shown in Fig. 7. A droplet with a definite volume was dropped on a sample with a microstructure using the motorized

syringe. The contact angle was measured by a combination of a CCD camera and processing software. The sample stage was inclined by tilting the entire system. Thus, the sliding angles were measured by determining the contact angle and inclining the system. The thermal effect of light on the droplet could be neglected.

Fig. 7 Setup for sliding angle measurement

3.3 Setup for measurement of evaporation time

The evaporation time is the time required for the weight of the droplet to become zero through evaporation. Figure 8 shows the setup for the measurement of the evaporation time. The apparatus was installed in a chamber to eliminate any disturbance (contamination or wind). The mass of the droplet was measured using an electric balance. A CCD camera was set above the droplet to observe its profile during evaporation.

Fig. 8 Setup for measurement of evaporation time

3.4 Experimental conditions

Table 1 shows the experimental conditions. All experiments were conducted in a clean room by controlling the temperature and humidity. The temperature was maintained at 20 °C. The radius of the droplets was larger than the capillary length of pure water ($\kappa^{-1} = 2.7$ mm); therefore, the effect of gravity on the droplet profile cannot be neglected.

Table 1 Experimental conditions

Evaluation figure	Sliding angle	Evaporation
Liquid	Pure Water	
Droplet volume	90 μ l	40 μ l
Inclining speed	1.0 deg./s	
Environment	Temperature: 20 deg. C, Relative humidity: 50 %	

4. Result and discussions

4.1 Sliding angle on pillar array

Figure 9 (a) shows the relationship between D and α_A and α_R . The ratio of the diameter to the pitch, D/P , was kept constant. Both α_A and α_R were almost independent of the change in D in the range of these dimensions. Figure 9 (b) shows the relationship between P and α_A

and α_R . D was kept constant at 200 μm . α_R decreased with an increase in P . Thus, a flat surface has the smallest value of α_R . On the other hand, α_A was independent of the change in P . Thus, a narrow pitch is preferable for evaporation on an inclined surface since the difference between α_A and α_R increases; thus, pinning distorts the droplet profile.

These results can be explained by pinning. Figure 10 (a) shows the mechanism for the movement of the receding line when the ratio D/P is constant, as shown in Fig. 9 (a). A high density of pillars increases the pinning strength since the length of the contact line surrounding the pillars increases ⁽⁷⁾⁽¹⁰⁾. Since the equivalent ratio of the diameter to the pitch implies the equivalent sum of L , the forces required to move the receding line F in Eq. (4) are equal, independent of the diameter ($F = F'$). On the other hand, Fig. 10 (b) shows the movement when the ratio D/P is different as shown in Fig. 9 (b). In this case, the force decreases with an increase in P since the sum of L decreases ($F > F''$). Thus, it is considered that α_R decreased because a low force was required for sliding at a high value of P .

Fig. 9 Sliding angle on pillars ($H = 50 \mu\text{m}$)

Fig. 10 Pinning at the receding line

4.2 Evaporation time of droplet on pillar array

We also investigated the relationship between P and the evaporation time of a droplet, as shown in Fig. 11. The evaporation time decreased with P . Thus, it is inferred that the

evaporation time of a droplet is the longest on a flat surface. Figure 12 shows the top view of a droplet during evaporation. When $P = 1000 \mu\text{m}$, the projected area of the droplet began to decrease after 50 min on the flat surface. However, when $P = 340 \mu\text{m}$, the projected area was maintained until the final stage of evaporation. Pinning also causes this behavior. Therefore, the result of Fig. 11 can also be explained by the pinning of the droplet, as in the case of the sliding angle in Fig. 9. As shown in Fig. 10, the force required to move the droplet when P is small is greater than that required when P is large; thus, the projected area should be increased. The evaporation time decreased since the droplet was exposed to air over the large surface area.

Fig. 11 Relationship between P and evaporation time ($D = 200 \mu\text{m}$, $H = 50 \mu\text{m}$)

t min.	0	50	80	110	130	150
Flat						
$P: 1000\mu\text{m}$						
$P: 320\mu\text{m}$						

Fig. 12 Change in droplet profile with time

4.3 Design of reticular pattern

As mentioned above, the sliding angle decreases at a large value of P . This indicates that the flat surface has the smallest sliding angle; however, the evaporation time of a droplet on the flat surface is longer than that on a pillared surface. We prepared some reticular patterns, consisting of pillared and flat parts, to achieve a fast evaporation time and a small sliding angle.

Figure 13 shows the specifications of the reticular patterns. W_i and W_f are the widths of the pillared and flat parts, respectively. The sum of W_i and W_f was kept constant ($W_i + W_f = 1700 \mu\text{m}$). The widths $W_i = 0 \mu\text{m}$ and $W_i = 1700 \mu\text{m}$ corresponded to those of the flat surface (no pillars) and fully arrayed surface, respectively. The diameter, pitch, and height of the pillars were also kept constant ($D = 100 \mu\text{m}$, $P = 170 \mu\text{m}$, $H = 50 \mu\text{m}$) in order to focus only on the design of the reticular patterns. The patterns were tested using different sliding angles and evaporation times. Figure 14 shows photographs of $40 \mu\text{l}$ droplets on two types of reticular patterns ($W_i = 340 \mu\text{m}$ and $1360 \mu\text{m}$). In these experiments, droplets spread over some pitches of structure, three or four pitches of reticular patterns, thus actual reticular design will be discussed neither on flat surface nor on pillared surface.

Fig. 13 Schematic illustration and specifications of reticular patterns

Fig. 14 Droplet on reticular patterns (droplet volume: 40 μl)

4.4 Sliding angle on reticular pattern

Figure 15 shows the relationship between W_t and α_A and α_R . These angles were almost the same as those on the fully arrayed surface ($W_t = 1700 \mu\text{m}$). The flat surface had the smallest sliding angles. Thus, the sliding angles could not be improved by using reticular patterns. This result can be explained on the basis of the fact that the force required to move the receding line is constant when the distance between a pillar and the receding line is constant as shown in Fig. 10.

Fig. 15 Sliding angles on reticular patterns

Remarkable difference was observed after sliding down of droplet. Figure 16 shows the residual droplet after it slid down the residual patterns ($W_t = 340 \mu\text{m}$ and $1360 \mu\text{m}$). The sliding direction is downward in the figure. The residual water was found only on the pillar part; therefore, the amount of residual water increased with W_t . This could be explained as follows: the receding line was intermittently pinned when the droplet passed through the pillars as described in Fig. 10, so that the droplet partially remained among them. Thus, a small value of W_t is required to remove the droplet efficiently.

Fig. 16 Relationship between W_t and residual droplet after sliding on reticular patterns

4.5 Evaporation time on reticular pattern

Figure 17 shows the relationship between W_t and the evaporation time. It was found that the evaporation time decreased with W_t . However, in the case of the flat surface ($W_t = 0 \mu\text{m}$), the evaporation time was the longest. Therefore, in this study, an appropriate design of the reticular pattern for reducing the evaporation time is $W_t = 340 \mu\text{m}$. Figure 18 shows the profile of the droplet during evaporation on the reticular patterns ($W_t = 340 \mu\text{m}$ and $1360 \mu\text{m}$). The droplet was trapped along the pattern by pinning at $t = 120 \text{ min}$ on the surface with $W_t = 340 \mu\text{m}$. It is thought that the surface area of the droplet at $W_t = 340 \mu\text{m}$ was larger than that at other values of W_t , although the projected area was small. It may not be appropriate to use the projected area in the estimation of the surface area, as discussed in section 4.2, since the droplet profile is not hemisphere but complicated spreading over some pitches of reticular patterns.

Fig. 17 Relationship between W_t and evaporation time

<i>t</i> min.	0	30	60	90	120
W_t : 340µm W_f : 1360µm					
W_t : 1360µm W_f : 340µm					

Fig. 18 Change in droplet profile with time on reticular patterns ($W_t = 340 \mu\text{m}$ and $1360 \mu\text{m}$)

5. Conclusion

We conducted experiments to design pillared surfaces for quick drying. The results are

summarized as follows:

- (1) The sliding angle decreased with an increase in the pillar pitch, although the evaporation time increased due to the pinning of the droplets.
- (2) The evaporation time decreased when the width of the pillar part in the reticular pattern was small, although the sliding angle was large. The small width was effective in the removal of the droplets.

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