

Multiscale Roughness and Stability of Superhydrophobic Biomimetic Interfaces

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The stability of a composite interface of roughness-induced superhydrophobic surfaces is studied. To have high contact angle and low contact angle hysteresis, superhydrophobic surfaces should be able to form a composite interface with air pockets in the valleys between asperities (pillars). However, the composite interface may be unstable and can be irreversibly transformed into a homogeneous interface. We formulate a stability criterion and analyze the stability of the composite interface for several typical roughness profiles. To resist destabilizing mechanisms, multiscale (hierarchical) roughness is required. Such multiscale roughness is found in natural and artificial superhydrophobic surfaces.

1. Introduction

The wetting of rough surfaces has been investigated since the 1930s;^{1–3} however, the topic has received special attention in the past few years because of the development of nanotechnology applications.^{4–8} The surface area-to-volume ratio grows with miniaturization and surface forces become dominant, so the ability to measure and control surface properties becomes critical. One of the crucial surface properties for materials in micro/nanoscale applications is nonwetting or hydrophobicity.^{9–10} It is also usually desirable to reduce wetting in fluid flow applications in order for liquid droplets to flow easily along a surface. Some natural surfaces, including leaves of water-repellent plants such as the lotus (*Nelumbo nucifera*), legs of insects such as the water strider (*Gerris remigis*), and butterfly wings, are known to be very hydrophobic as a result of the roughness of their surface.^{11–13} This phenomenon, along with the self-cleaning abilities of very hydrophobic surfaces, is called in the literature the “lotus effect”.¹¹ There are a significant number of reports in the literature about the lotus effect and numerous attempts to produce artificial biomimetic roughness-induced hydrophobic surfaces have been made,^{14–22} but many details of the mechanism of roughness-

induced nonwetting are still not well understood. In particular, it is not clear why the lotus leaf and other natural hydrophobic surfaces have a multiscale (or hierarchical) roughness structure; that is, nanoscale bumps superimposed over microscale asperities. Gao and McCarthy²³ recently suggested that multiscale roughness affects the kinetics of droplet motion and the Laplace pressure at which water intrudes between the bumps. In the present study, we investigate the effect of multiscale roughness upon the stability of the roughness-induced hydrophobic interface.

The wetting of a solid by a liquid is characterized by the contact angle, which is the angle between the solid–air and the liquid–air interfaces (Figure 1). The greater the contact angle, the more hydrophobic the material. The value of the contact angle is usually greater when the liquid is added (the so-called advancing contact angle) than when it is removed (the receding contact angle). The difference between the advancing and receding contact angles constitutes contact angle hysteresis. Contact angle hysteresis is related to energy barriers, which a liquid droplet should overcome during its flow along a solid surface, and thus characterizes the resistance to flow.³ The lower is the adhesion of a liquid droplet to the solid; the smaller are the energy barriers and the lower is the value of contact angle hysteresis and the easier it is for the droplet to flow along the surface. Surfaces with very high contact angles ($> 150^\circ$) and low contact angle hysteresis are called superhydrophobic.^{7,18}

Several mechanisms are responsible for the superhydrophobicity of natural surfaces, such as lotus leaves. First, these surfaces are coated with wax, which is hydrophobic itself (with a contact angle of about 103° ²⁴). Second, they have a complicated geometrical structure with bumps or asperities (in the case of plant leaves called papillae) on the microscale (for the lotus leaf, the typical size of papillae is on the order of $10\ \mu\text{m}$) covered with much smaller nanoscale bumps or nanometer-scale structures.^{7,20} In a similar manner, water strider legs are covered with a large number of oriented tiny hairs (microsetae) with fine nano-

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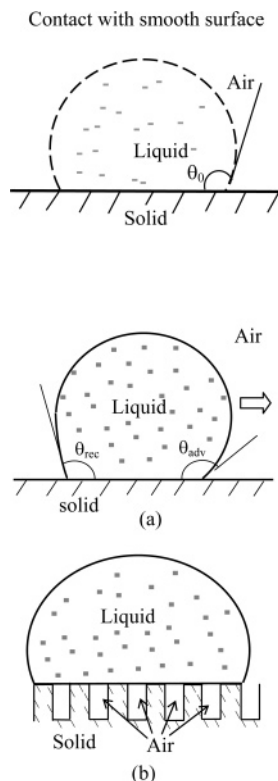


Figure 1. (a) Contact angle with a smooth surface (θ_0) and advancing (θ_{adv}) and receding (θ_{rec}) contact angles for a droplet moving along a solid surface. (b) Composite interface air pockets between the pillars (asperities) dramatically reduce the solid–liquid contact area and the adhesion of a droplet to the solid.

grooves.¹³ Neinhuis and Barthlott¹¹ suggested that hierarchical surfaces are less vulnerable to mechanical damage caused by nanostructures and therefore maintain their functionality even after being damaged. Wagner et al.¹² showed that hierarchically structured surfaces are more readily able to repel water even if the surface tension is drastically reduced as compared to surfaces with only one length scale of roughening. This might be important in wetlands or other aquatic habitats where water is often polluted by decaying plant material and other contamination that reduces surface tension.¹² Herminghaus pointed out that certain self-affine profiles with multiscale roughness may result in superhydrophobic surfaces even for hydrophilic materials.²⁵ However, a theoretical explanation of the predominance of hierarchically structured surfaces in nature remains an important task.

It is believed that in order to be superhydrophobic, a rough surface should be able to maintain a composite interface with air pockets or bubbles trapped in the valleys between the asperities,^{2–6} as opposed to a homogeneous solid–liquid interface. In many cases both the composite interface and the homogeneous interface may exist for the same surface; however, only the composite interface provides the required superhydrophobic properties. Furthermore, the composite interface is much less stable than the homogeneous interface, and it may be destroyed by liquid filling the valleys between asperities and form a homogeneous interface, whereas the opposite transition has never been observed.⁷ The mechanisms of this transition have been the subject of intensive investigation in recent years.^{4,6,20,26–27} Among the suggested factors that affect the transition are the effects of the droplet's weight and curvature. For small droplets, surface

effects dominate over gravity, and the latter is hardly responsible for the transition, whereas the droplet's curvature may be responsible. The above suggests that the stability of a composite interface is a key issue in the design of roughness-induced superhydrophobic surfaces. In this article, we formulate a geometrical stability criterion, and then investigate typical 2D and 3D surfaces with roughness at several scale levels. We show that multiscale (hierarchical) roughness may enhance the stability of a composite interface.

2. Stability of a Composite Interface

The spreading of liquid through porous media with periodic geometry was studied by several authors;^{28,29} however, stability of the composite interface has not been studied in detail in the literature. In this section, a geometrical stability condition for a composite interface will be formulated on the basis of the free-energy minimization using the Lagrange method of finding a minimum of a function of several variables with constraints. First, we will formulate the extremum criterion and show that it leads to the well-known Young equation, and then we will mathematically derive a stability criterion and discuss its physical meaning.

The liquid–air interface is at equilibrium if the free energy of the solid–liquid–air system reaches its minimum. To find local conditional minima of the free surface energy $W = A_{SL}\gamma_{SL} + A_{SA}\gamma_{SA} + A_{LA}\gamma_{LA}$ with the constant volume constraint $V = V_0$, the Lagrange function is constructed

$$L(A_{SL}, A_{SA}, A_{LA}, V, \lambda) = A_{SL}\gamma_{SL} + A_{SA}\gamma_{SA} + A_{LA}\gamma_{LA} + \lambda(V - V_0) \quad (1)$$

where A_{SL} , A_{SA} , and A_{LA} are the areas of the solid–liquid, solid–air, and liquid–air interfaces and γ_{SL} , γ_{SA} , and γ_{LA} are the corresponding free energies, V_0 is the volume, and λ is the Lagrange multiplier.³⁰ The corresponding change in L is given by

$$\delta L = \delta A_{SL}\gamma_{SL} + \delta A_{SA}\gamma_{SA} + \delta A_{LA}\gamma_{LA} + \lambda\delta V + \delta\lambda(V - V_0) \quad (2)$$

Note that the arguments of L are interdependent with $\delta A_{SL} = -\delta A_{SA}$ whereas δA_{LA} consists of two terms, $\delta A_{LA} = \delta A_{LAT} + \delta A_{LAV}$. The first term, δA_{LAT} , is due to a change in the position of the triple line (line of contact between solid, liquid, and air), and the second, δA_{LAV} , is due to a change in the shape of the liquid–air interface. Furthermore, $\delta A_{LAT} = \delta A_{SL} \cos \theta$ from geometrical considerations.

Suppose the shape of the liquid–air interface is given parametrically by vector $\vec{r}(u, v)$, where u and v are parameters that uniquely characterize any point on a surface and the shape changes slightly

$$\vec{r}(u, v) = \vec{r}(u, v) + \vec{\delta r}(u, v) \quad (3)$$

The change due to the shape of the liquid–air interface is given by the area of an element of the liquid–air interface $A(u, v) du dv$ times the normal displacement multiplied by the sum of principal radii of curvature $\vec{n} \cdot \vec{\delta r}(1/R_1 + 1/R_2)$, where $\vec{n}$ is the normal vector and R_1 and R_2 are the principal radii of curvature³¹

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$$\delta A_{\text{LAV}} = \int_{A_{\text{LA}}} \int \bar{n} \bar{\delta r} (1/R_1 + R_2) A \, du \, dv \quad (4)$$

where³⁰

$$A(u, v) = \left[\left(\frac{\partial \bar{r}}{\partial u} \right)^2 \left(\frac{\partial \bar{r}}{\partial v} \right)^2 - \left(\frac{\partial \bar{r}}{\partial u} \frac{\partial \bar{r}}{\partial v} \right)^2 \right]^{1/2} \quad (5)$$

The change in volume is given by

$$\delta V = \int_{A_{\text{LA}}} \int \bar{n} \bar{\delta r} A \, du \, dv \quad (6)$$

Combining eqs 4–6 and setting $\delta L(\delta A_{\text{SL}}, \delta \mathbf{r}, \delta V) = 0$ yields

$$\delta L = \delta A_{\text{SL}} \left[\cos \theta_0 - \frac{\gamma_{\text{SA}} - \gamma_{\text{SL}}}{\gamma_{\text{LA}}} \right] \gamma_{\text{LA}} + \int_{A_{\text{LA}}} \int \left[\gamma_{\text{LA}} \left(\frac{1}{R_1} + \frac{1}{R_2} \right) + \lambda \right] \bar{n} \bar{\delta r} A \, du \, dv + \lambda \delta V \quad (7)$$

which results in three equations that should be satisfied simultaneously. The first is the Young equation for the contact angle θ_0 , which should be satisfied at the points of the triple line

$$\cos \theta_0 = \frac{\gamma_{\text{SA}} - \gamma_{\text{SL}}}{\gamma_{\text{LA}}} \quad (8)$$

The second equation for the Lagrange multipliers $\lambda = -\gamma_{\text{LA}}(1/R_1 + 1/R_2)$ is satisfied only if the curvature $1/R_1 + 1/R_2$ is a constant independent of u and v throughout the entire liquid–air interface.³¹ The third equation is just the condition of constant volume $V = V_0$.

For the extremum to be a local minimum (rather than the maximum) of W , the equilibrium should also satisfy the stability condition $d^2W > 0$. Differentiating $W = A_{\text{SL}}\gamma_{\text{SL}} + A_{\text{SA}}\gamma_{\text{SA}} + A_{\text{LA}}\gamma_{\text{LA}}$ twice and using $\delta A_{\text{LA}} = \delta A_{\text{SL}} \cos \theta$ yields

$$d^2W = d^2A_{\text{SL}} \left[\cos \theta_0 - \frac{\gamma_{\text{SA}} - \gamma_{\text{SL}}}{\gamma_{\text{LA}}} \right] \gamma_{\text{SL}} + dA_{\text{LA}} d(\cos \theta) > 0 \quad (9)$$

We ignored the effect of the changing shape of the liquid–air interface (the term corresponding to δA_{LAV}) because it is known that $1/R_1 + 1/R_2 = \text{const}$ provides the minimum (rather than the maximum) liquid–air interface area condition³¹ and only the effect of moving the triple line is of interest to us. Using eq 8, which is satisfied at the equilibrium, and the fact that $\cos \theta$ decreases monotonically with θ in the domain of interest, $0 < \theta < 180^\circ$, yields

$$dA_{\text{SL}} d\theta < 0 \quad (10)$$

In other words, for the interface to be stable, for an advancing liquid (increasing A_{SL}) the value of the contact angle should decrease, whereas for a receding liquid the contact angle should increase. Note also that for a liquid–air interface coming to the solid surface under the angle θ an advance of the interface results in the change in energy

$$\begin{aligned} dW &= dA_{\text{SL}}(\gamma_{\text{SL}} - \gamma_{\text{SA}}) + dA_{\text{LA}}\gamma_{\text{LA}} = \\ &\quad dA_{\text{SL}}(\gamma_{\text{SL}} - \gamma_{\text{SA}}) + dA_{\text{SL}}\gamma_{\text{LA}} \cos \theta \\ &= dA_{\text{SL}}\gamma_{\text{LA}} \left(-\frac{\gamma_{\text{SA}} - \gamma_{\text{SL}}}{\gamma_{\text{LA}}} + \cos \theta \right) = \\ &\quad dA_{\text{SL}}\gamma_{\text{LA}} (\cos \theta - \cos \theta_0) \quad (11) \end{aligned}$$

Thus, if $\theta > \theta_0$, the energy decreases and it is energetically profitable for the liquid to advance, whereas if $\theta < \theta_0$, the liquid would retreat. Therefore, the physical meaning of eq 10 is that for a small advance/retreat of the liquid it should be more energetically profitable to return to the original position rather than to continue advancing/retreating.

For a 2D surface, because a change in angle $d\theta$ is equal to the change in slope of the surface, whether the configuration is stable depends on the sign of curvature of the surface. The convex (bumpy) surface leads to a stable interface, whereas a concave (groovy) surface leads to an unstable interface. The liquid keeps spreading until both eqs 8 and 10 are satisfied at the triple line and $1/R_1 + 1/R_2 = \text{const}$ at the liquid–air interface, provided the volume of the liquid is conserved.

In the next section, we will apply the stability criterion (eq 10) to typical 2D and 3D surfaces with multiscale roughness.

3. Hierarchical Roughness

In this section, we will consider several surfaces with nanoscale roughness superimposed over larger microscale pillars, and we will investigate the effect of concave and convex nanoroughness upon the stability of a composite interface. We will study the case of an infinitely large reservoir of liquid on top of the pillars. In most applications, liquid droplets of finite size are in contact with a rough surface; however, the size of roughness details is small compared to the size of the droplets, and for practical purposes, droplet size can be considered to be infinite.

3.1. Two-Dimensional Roughness. Consider a 2D structure with rectangular pillars of height h and width a separated by distance b , covered with small semicircular ridges and grooves of radius r (Figure 2a). Because the distance between the pillars is small in comparison with the capillary length and therefore the effect of gravity is negligible, we can assume that the liquid–air interface is a horizontal plane and its position is characterized by the vertical coordinate z . The free energy is given by

$$W = A_{\text{SL}}\gamma_{\text{SL}} + A_{\text{SA}}\gamma_{\text{SA}} + A_{\text{LA}}\gamma_{\text{LA}} = rL\gamma_{\text{LA}}(\sin \alpha - \alpha \cos \theta_0) \quad 0 < z < h \quad (12)$$

where $\alpha = a \cos((r - z)/r) + 2\pi N$ is the angle corresponding to the vertical position of the interface z , N is the number of a ridge or groove, and L is the length of the grooves in the y direction, which is required on the basis of the dimensional considerations. The dependence is presented in Figure 2b for the cases of hydrophobic ($\theta_0 = 150^\circ$) and hydrophilic ($\theta_0 = 30^\circ$) materials for both the bumpy and the groovy surface. It is seen that for the bumpy surface there are many stable equilibrium states (shown in Figure 2a with dotted lines) separated by energy barriers, which correspond to every ridge, whereas for the grooved surface the equilibrium states are unstable. Therefore, the ridges can pin the triple line and thus lead to a composite interface. In the case of a hydrophilic surface, each lower position of the equilibrium state corresponds to a lower value of W ; therefore, when the liquid advances from one equilibrium state to the next, the total energy decreases and thus the liquid's advance is energetically profitable. When the liquid reaches the bottom of the valley and completely fills the space between the pillars forming a homogeneous interface, the total energy decreases dramatically by the value of

$$\Delta W = bL(\gamma_{\text{SA}} + \gamma_{\text{LA}} - \gamma_{\text{SL}}) = bL\gamma_{\text{LA}}(1 + \cos \theta_0) \quad (13)$$

The opposite transition from a homogeneous to a composite interface requires high activation energy ΔW and is thus unlikely,

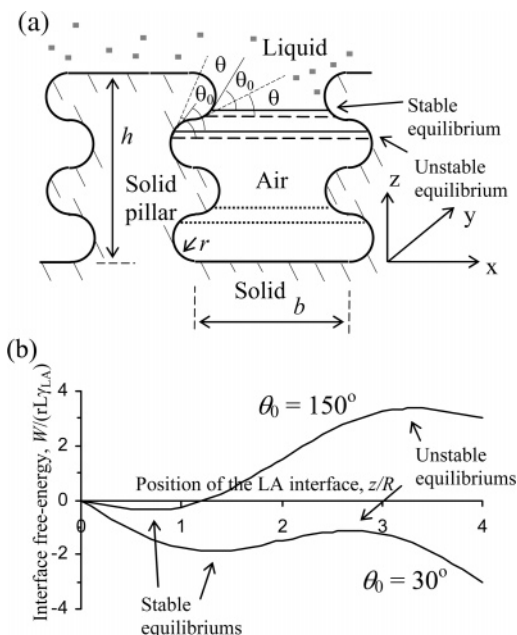


Figure 2. Two-dimensional pillars with semicircular bumps/grooves. (a) Schematic of the structure. The bumps may pin the triple line because an advancing LA interface results in a decrease in the contact angle ($\theta < \theta_0$), making the equilibrium stable. Grooves provide equilibrium positions that satisfy the Young equation; however, the equilibrium is unstable because an advancing LA interface results in an increase in the contact angle ($\theta > \theta_0$). (b) Energy profiles for configurations in part a with bumps and grooves for hydrophilic ($\theta_0 = 30^\circ$) and hydrophobic ($\theta_0 = 150^\circ$) materials. Energy (normalized by $Lr\gamma_{LA}$) is shown as a function of the vertical position of the interface z (normalized by the radius of bumps/grooves r). Bumps result in stable equilibria (energy minima), whereas grooves result in unstable equilibria (energy maxima).

making the transition from composite to homogeneous interface irreversible. Because the distance between the pillars b is much greater than r , the energy barriers that separate the equilibrium states, $2\pi r L \gamma_{LA} \cos \theta_0$, are relatively small compared to ΔW , and low activation energy is required for the liquid to spread and propagate from one equilibrium state to the other.

Because the change in angle $d\theta$ for a 2D surface is equal to the change in surface slope, based on eq 10, whether the configuration is stable depends upon the sign of curvature of the surface. The convex (bumpy) surface leads to a stable interface, whereas the concave (groovy) surface leads to an unstable interface. The liquid keeps spreading until both eqs 8 and 10 are satisfied at the triple line and $1/R_1 + 1/R_2 = \text{const}$ at the liquid–air interface, provided the volume of the liquid is conserved.

3.2. Three-Dimensional Pillars with Ridges and Grooves.

Consider now a 3D structure with circular pillars of height h and radius R separated by distance b and distributed hexagonally with a density of $\eta = 2/[\sqrt{3}(2R + b)^2]$ pillars per unit area, covered with small ridges and grooves of radius r (Figure 3a). As in the preceding section, the free energy per area S is given by the circumference of a pillar $2\pi R$ times the number of pillars ηS times $r\gamma_{LA}(\sin \alpha - \alpha \cos \theta_0)$:

$$W = 2\pi R \eta S r \gamma_{LA} (\sin \alpha - \alpha \cos \theta_0) \quad 0 < z < h \quad (14)$$

The similarity between eqs 12 and 14 is noted. Both energy profiles are different only in their normalization constant, so the dependence of the free energy upon the position of the interface presented in Figure 2b for the case of 2D pillars has the same

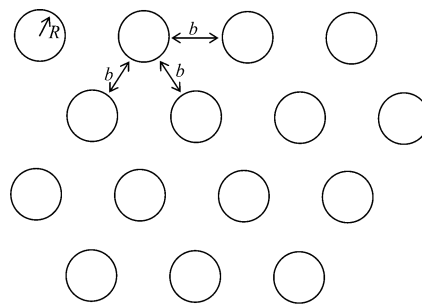


Figure 3. Schematic of the spatial distribution of 3D pillars with semicircular bumps/grooves upon a surface.

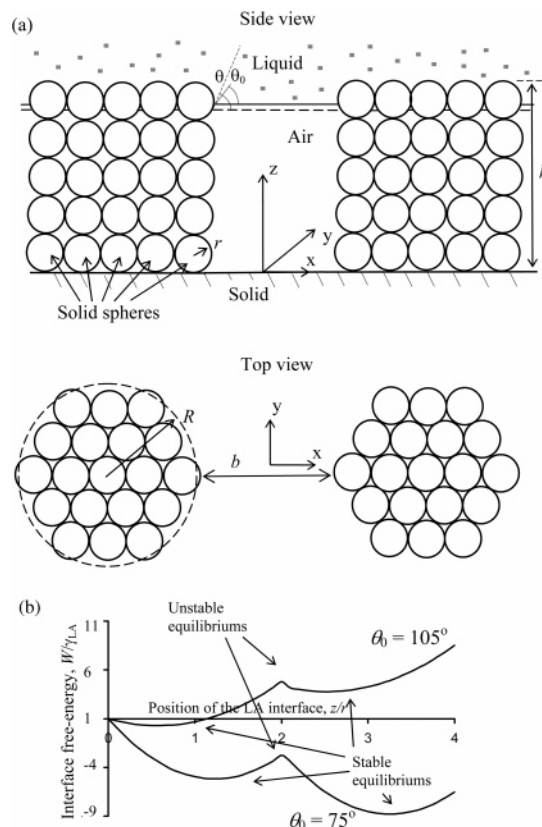


Figure 4. Three-dimensional pillars consisting of small solid spheres. (a) Schematics of the structure. (b) Energy (normalized by $A_0\gamma_{LA}$) as a function of the vertical position of the interface z (normalized by the radius of bumps/grooves r) for $\pi^2 R^2 / (2\sqrt{3}r^2) = 1$.

profile in a qualitative sense as for the case of 3D pillars. In a similar manner to the case of 2D pillars, the ridges can pin the triple line.

3.3. Three-Dimensional Surface. In the previous sections, we considered 2D nanoscale ridges and grooves superimposed over 2D and 3D pillars. Real superhydrophobic surfaces, such as plant leaves, are 3D with 3D nanobumps. For 3D surfaces, the shape of the liquid–air interface may be quite complex, and thus the stability of the composite interface is difficult to analyze. To consider a 3D configuration that allows for a planar horizontal liquid–air interface, we will investigate the surface, composed of circular pillars of height h and radius R separated by distance b with a density of $\eta = 2/[\sqrt{3}(2R + b)^2]$ pillars per unit area (following the hexagonal distribution pattern shown in Figure 3), which are formed from layers of small spheres of radius r , packed according to the hexagonal pattern (Figure 4a). The packing density of the spheres is equal to $1/(2\sqrt{3}r^2)$ spheres per unit area in every horizontal layer. The liquid–air interface area

is now given by the total flat area of the surface, A_0 , minus the cross-sectional area of spheres under water. The latter is given by

$$A_{LA} = A_0 \left(1 - \frac{\eta \pi^2 R^2 \sin^2 \alpha}{2\sqrt{3}} \right) \quad (15)$$

where η is the pillar density, πR^2 is the pillar area, $1/(2\sqrt{3}r^2)$ is the packing density of the spheres, and $\pi(r \sin \alpha)^2$ is the cross-sectional area of an individual sphere under water. The solid–liquid interface area is equal to the total surface area of the spheres under water

$$A_{SL} = \frac{\eta A_0 \pi^2 R^2}{2\sqrt{3}r^2} [4r^2 N + (z^2 + 2z(2r - z))] \quad (16)$$

where $\eta A_0 \pi^2 R^2 / (2\sqrt{3}r^2)$ is the number of spheres, $4\pi r^2 N$ is the spheres' surface area multiplied by the number of layers, and $\pi(z^2 + 2z(2r - z))$ is the area of the spheres in the layer, which is only partially under water. Using $\sin^2 \alpha = 1 - \cos^2 \alpha = 1 - ((r-z)/r)^2 = 2z/r - (z/r)^2$, the free energy is now given by

$$\begin{aligned} W &= A_{LA} \gamma_{LA} + A_{SL} (\gamma_{LA} - \gamma_{SA}) = \gamma_{LA} (A_{LA} + A_{SL} \cos \theta_0) \\ &= A_0 \gamma_{LA} \left(1 - \frac{\eta \pi^2 R^2}{2\sqrt{3}} \left\{ \frac{2z}{r} - \left(\frac{z}{r} \right)^2 - \left[4\pi N + \left(\frac{z}{r} \right)^2 + \right. \right. \right. \\ &\quad \left. \left. \left. 2 \left(\frac{z}{r} \right) \left(2 - \frac{z}{r} \right) \right] \cos \theta_0 \right\} \right) \end{aligned} \quad (17)$$

The dependence of the free energy, normalized by $A_0 \gamma_{LA}$, upon the vertical position z is presented in Figure 4b for the cases of hydrophobic ($\theta_0 = 105^\circ$) and hydrophilic ($\theta_0 = 75^\circ$) materials.

4. Results and Discussion

We studied three different surface profiles with large-scale pillars and small-scale roughness superimposed over the pillars. It is observed from Figures 2b and 4b that for both the hydrophobic and hydrophilic materials a convex surface leads to stable equilibria whereas a concave surface leads to unstable equilibria. Therefore, convex small-scale roughness can pin the liquid–air interface even in the case of a hydrophilic material. This may be important for producing reliable superhydrophobic surfaces because the factors destabilizing the liquid–air interface, such as nanodroplet condensation,^{20,32} chemical surface heterogeneity,³³ and capillary waves,²⁶ are scale-dependent and therefore multiscale roughness is required to control the stability.

An experiment suggesting that the sign of curvature is indeed important for hydrophobicity was conducted by Sun et al.²¹ They produced both a positive and a negative replica of a lotus leaf

surface by nanocasting using poly(dimethylsiloxane), which has a contact angle with water of about 105° . This value is close to the contact angle of wax, which covers lotus leaves (about 103° ²⁴). The positive and negative replicas have the same roughness factor and thus should produce the same contact angle in the case of a homogeneous interface; however, the values of the surface curvature are opposite. The value of the contact angle for the positive replica was found to be 160° (which is the same as for lotus leaf), whereas for the negative replica it was only 110° . This result suggests that the high contact angle of the lotus leaf is due to the composite rather than the homogeneous interface and that the sign of surface curvature indeed plays a critical role in the formation of the composite interface.

Natural and successful artificial superhydrophobic surfaces exhibit hierarchical multiscale roughness. Thus, the lotus leaf has microscale bumps (papillae) with a typical height and radius of $10\text{--}20\text{ }\mu\text{m}$; these bumps are covered with hydrophobic paraffin wax. Upon these bumps much smaller nanobumps are found, with typical submicrometer sizes. Artificial biomimetic superhydrophobic surfaces should also have multiscale roughness.

To summarize, biomimetic superhydrophobic surfaces should satisfy the following requirements: they should have a hydrophobic coating, high roughness factors, providing a high contact angle, and the ability to form a composite interface. To achieve a stable composite interface, a hierarchical roughness structure with nanoscale bumps upon microscale asperities and valleys is required.

5. Conclusions

The mechanism of roughness-induced hydrophobicity is complicated and involves effects over various scale ranges. For most superhydrophobic surfaces, it is important that a composite solid–liquid–air interface is formed. A composite interface dramatically decreases the area of contact between the liquid and solid and therefore decreases the adhesion of a liquid droplet to the solid surface and contact angle hysteresis. The formation of a composite interface is also a multiscale phenomenon that depends upon the relative sizes of the liquid droplet and roughness details. The composite interface is fragile, since transition to a homogeneous interface is irreversible. Therefore, the stability of a composite interface is crucial for superhydrophobicity and should be addressed for the successful development of superhydrophobic surfaces. We have demonstrated that multiscale roughness can help to resist the destabilization, with convex surfaces pinning the interface and thus leading to a stable equilibrium and preventing the filling of gaps between the pillars even in the case of a hydrophilic material. The effect of roughness on wetting is scale-dependent, as are mechanisms that lead to the destabilization of a composite interface. To resist these scale-dependent mechanisms, multiscale roughness is required. Such multiscale roughness was found in natural and successful artificial superhydrophobic surfaces.

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