Advances in the development of superhydrophobic and icephobic surfaces

Assem Elzaabalawy · Shaker A. Meguid

Received: 14 February 2022 / Accepted: 26 March 2022 / Published online: 25 May 2022
© The Author(s), under exclusive licence to Springer Nature B.V. 2022

Abstract Superhydrophobicity and icephobicity are governed by surface chemistry and surface structure. These two features signify a potential advance in surface engineering and have recently garnered significant attention from the research community. This review aims to simulate further research in the development of superhydrophobic and icephobic surfaces in order to achieve their wide-spread adoption in practical applications. The review begins by establishing the fundamentals of the wetting phenomenon and wettability parameters. This is followed by the recent advances in modeling and simulations of the response of superhydrophobic surfaces to static and dynamic droplets contact and impingement, respectively. In view of their versatility and multifunctionality, a special attention is given to the development of these surfaces using nanocomposites. Furthermore, the review considers advances in icephobicity, its comprehensive characterization and its relation to superhydrophobicity. The review also includes the importance of the use of superhydrophobic surface to combat viral and bacterial contamination that exist in fomites.

Keywords Superhydrophobicity · Icephobicity · Wettability · Nanocomposites · Anti-icing · Antiviral

1 Introduction

The wettability of a surface is defined as the tendency of a fluid to spread or adhere to that surface. In order to assess surfaces’ wettability, the angle formed between the liquid–gas interface and the surface due to surface tension forces is evaluated. This angle is known as the contact angle (θ_{CA}). Based on the contact angle, surfaces can be classified as being hydrophilic (θ_{CA} < 90°) and hydrophobic (θ_{CA} > 90°), as schematically shown in Fig. 1. A surface is classified as being superhydrophobic if the contact angle is greater than 150°. Furthermore, the inclination angle at which droplets roll off the surface, known as the sliding angle (θ_{SA}), should be less than 10° for a surface to be classified as superhydrophobic. This classification is due to the observations that a surface that acquires a high contact angle and low sliding angle exhibits extreme water repellency (Shirtcliffe et al. 2010; Yan et al. 2011).

Superhydrophobic surfaces are characterized by extreme water repellency; i.e., they are extremely difficult to wet (Shirtcliffe et al. 2010; Yan et al. 2011). These surfaces, which exist widely in nature, have been a source of inspiration for the research community. For example, one of the most recognized superhydrophobic surfaces in nature is the Lotus plant. It acquires its self-cleaning ability from the low surface energy of the hydrophobic wax covering the surface and the surface’s hierarchical structure (Shirtcliffe et al. 2010; Yan et al. 2011; Liu et al. 2017; Teisala
and Butt 2018), as depicted in Fig. 2a. Due to its superhydrophobicity characteristics, water droplets falling on the lotus plant leaves maintain their spherical form and roll off the surface gathering and removing the surface contaminants, as shown in Fig. 2b.

In view of their highly desirable characteristics and potential in numerous applications, superhydrophobic surfaces have received considerable attention from the research community. For instance, superhydrophobic surfaces can effectively reduce the drag associated with fluid flow, which leads to improved energy efficiency (Zhang et al. 2015; Schäffel et al. 2016; Türk et al. 2014; Dubov et al. 2018; Fu et al. 2017), suppress icing and frosting, which reduces economic losses and safety hazards associated with ice accretion (Oberli et al. 2014; Kim et al. 2017; Filion et al. 2014; Jamil et al. 2018; Shen et al. 2019a; Kreder et al. 2016; Song et al. 2019), enhance the rate of heat transfer associated with boiling and condensations processes (Khatir et al. 2016; Chavan et al. 2016; Lu et al. 2017; Kousalya et al. 2015), and separate oil/water mixtures, which resolves the problem of oil-polluted water (Hu et al. 2017a; Zhang et al. 2018a; Latthe et al. 2019; Liu and Kang 2018). Additionally, these surfaces have successfully been implemented in several biomedical applications due to their blood repellency and ability to reduce viral and bacterial transmissions (Katoh et al. 2019; Tomšič et al. 2008; Yeerken et al. 2019; Shin et al. 2016; Falde et al. 2016; Jaggessar et al. 2017).

Despite the extensive past and current research in superhydrophobic surfaces, many challenges remain. These include the need for more analytical and numerical studies to provide a better understanding and define the role of the governing parameters that dictate surface wettability and ultimately the design and development of superhydrophobic surfaces. Additionally, the hierarchical structure and hydrophobic functional groups that are mostly used to modify the surface are susceptible to damage by the surface environment or mechanical forces. Thus, the stability and durability of superhydrophobic surfaces remain to be major challenges (Ellinas et al. 2017; Mortazavi and Khonsari 2017). Moreover, most of the fabrication techniques reported for the development of superhydrophobic surfaces are not scalable and have not yet succeeded in facilitating their practical implementation in real world applications.

Considering repellency at subfreezing temperature, different forms of precipitation that cause water to freeze are experienced in nature. Typically, this takes place over a range of temperatures and humidity. This
includes freezing rain, icing, snow, and frost formation (Kreder et al. 2016; Sojoudi et al. 2016). As a result, ice or frost may accumulate on surfaces leading to serious performance degradation, economic losses, and safety hazards in various applications, such as wind turbines (Lamraoui et al. 2014; Dalili et al. 2009), photovoltaic devices (Fillion et al. 2014), power lines (Laforte et al. 1998), aircrafts (Cao et al. 2015; Cebeci and Kafyeke 2003), and heat exchangers (Kim et al. 2017). Multiple deicing strategies are adopted in industry, including, chemical deicing, mechanical vibration, electro-thermal heating, and infrared heating. Nevertheless, these strategies are usually energy inefficient, costly, and harmful to the environment (Jamil et al. 2018; Shen et al. 2019a; Kreder et al. 2016). Alternatively, passive and more economical and reliable strategies have recently garnered attention due to their ability to eliminate the drawbacks experienced in active deicing strategies. Specifically, surfaces that can be designed to suppress ice accumulation and reduce its adhesion. These surfaces are known as icephobic surfaces.

Many aspects of icephobicity have recently been reported in the literature (Jamil et al. 2018; Sojoudi et al. 2016; Zhang et al. 2017a). However, icephobic surfaces can be comprehensively defined as surfaces that can passively demonstrate four different aspects of ice repellency (Jamil et al. 2018; Shen et al. 2019a; Li and Guo 2018), as schematically shown in Fig. 3: (i) shedding of supercooled water droplets via rebound or roll-off prior to freezing on the cold surface, (ii) reducing the ice nucleation temperature, (iii) delaying the freezing or frosting time, and (iv) reducing the ice adhesion strength, when its accretion is inevitable. Due to the diversity of environmental conditions that can cause ice or frost accretion, all of these icephobicity aspects are necessary to develop an effective icephobic surface (Shen et al. 2019a; Kreder et al. 2016).

Superhydrophobic surfaces have been sought as potential candidates to achieve icephobicity because of their extreme water repellency. However, superhydrophobic surfaces do not necessarily exhibit icephobicity (Shen et al. 2019a; Nosonovsky and Hejazi 2012; Vercillo et al. 2020). Accordingly, the development of icephobic surfaces should be carefully investigated in order to understand the parameters that govern the anti-icing performance of the treated surfaces. The development of icephobic surfaces remains a challenge. For instance, existing research in the literature has focused on the development of surfaces that acquire one or two aspects of icephobicity rather than the parameters that are needed to completely characterize icephobicity (Jamil et al. 2018; Shen et al. 2019a). Additionally, similar to superhydrophobic surfaces, the durability of the developed icephobic surfaces and the scalability of the fabrication technique remain to be major challenges.
2 Wetting states and wettability parameters

2.1 Young’s equation

Surface tension originates from the cohesive interactions between the molecules at the surface of a liquid (Shirtcliffe et al. 2010; Yan et al. 2011). These cohesive forces tend to minimize the surface energy of the liquid by reducing its surface area and pulling it into a spherical shape. However, when a liquid is in contact with a solid surface, adhesive interactions between the liquid and solid molecules tend to distort the shape of the interface (Shirtcliffe et al. 2010; Yan et al. 2011). The balance between the cohesive and adhesive forces controls the tendency of the liquid to spread or adhere on the solid surface, which is defined as the wettability.

The concept of surface tension and contact angles as a measure for the wetting capability of a surface is ascribed to Thomas Young (1804) (Young 1805). According to Young, a liquid droplet that rests on a solid surface will create three interfaces with their corresponding interfacial tension forces: liquid–vapor ($\gamma_{LV}$), solid–liquid ($\gamma_{SL}$), and solid–vapor ($\gamma_{SV}$), as depicted in Fig. 4. At equilibrium, all interfacial tension forces balance at the three-phase contact line, which can be expressed as:

$$\gamma_{SL} + \gamma_{LV}\cos\theta_Y = \gamma_{SV}$$

By rearranging Eq. (1), Young’s equation can be expressed as:

$$\cos\theta_Y = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}}$$

where $\theta_Y$ is the apparent contact angle. Young’s equation implies that a hydrophobic state ($\theta > 90^\circ$) will exist if the surface tension at the solid–liquid interface is higher than at the solid–vapor interface. This condition will be satisfied at lower solid surface energy and will result in a lower liquid adhesion to the solid surface.

The contact angle obtained from Young’s equation is also known as the intrinsic contact angle and is considered a material property for a given solid–liquid-vapor combination. For example, if we consider a smooth flat surface placed in air, the highest possible contact angle for a water droplet is ~120°, which is obtained by fluoropolymers, such as PTFE (Teflon) (Shirtcliffe et al. 2010). Higher contact angles obtained by superhydrophobic surfaces can only be achieved by modifying the surface roughness (Shirtcliffe et al. 2010; Yan et al. 2011; Liang et al. 2014; Ji et al. 2013). Although Young’s equation is grossly oversimplified, it advanced the science of wettability somewhat. It does not take into account the substrate surface roughness and contact angle hysteresis.

2.2 Wenzel wetting state

Surface roughness is one of the parameters that contributes to superhydrophobicity. Accordingly, it is essential to include the effect of surface roughness when modeling the wettability of surfaces. To overcome one of the limitations of Young’s equation, Robert Wenzel (1936) proposed a theoretical model relating the contact angle and the surface roughness (Wenzel 1936, 1949). Wenzel hypothesized that for a droplet to reach a Wenzel wetting state (also known as “the homogeneous wetting state”), the liquid should penetrate the surface’s protrusions and be in contact with the entire rough surface, as depicted in Fig. 5.

Accordingly, the interfacial tension force balance equation can be expressed as (Wenzel 1936, 1949):

![Fig. 4 Interfacial tension forces and contact angle for a liquid droplet resting on a solid surface](image)

![Fig. 5 A schematic of Wenzel wetting state](image)
\[ \gamma_{SL} \cdot r + \gamma_{LV} \cos \theta_W = \gamma_{SV} \cdot r \]  
(3)

where \( \theta_W \) is the apparent Wenzel contact angle and \( r \) is the roughness factor. The roughness factor represents the effect of surface roughness on the wettability of a solid surface. It can be defined as the ratio between the actual surface area of a rough surface and the projected geometrical area of that surface. Rearranging Eq. (3) yields:

\[ \cos \theta_W = \frac{(\gamma_{SV} - \gamma_{SL}) \cdot r}{\gamma_{LV}} = r \cos \theta_Y \]  
(4)

As can be observed from Eq. (4), surface roughness tends to amplify the effect of surface chemistry, as represented in the form of Young’s (intrinsic) contact angle. This implies that the roughness of a surface will enhance the hydrophobicity of an originally hydrophobic material (\( \theta_Y > 90^\circ \)) by further increasing its contact angle. In contrast, the roughness will enhance the hydrophilicity of a hydrophilic material by further reducing its contact angle (\( \theta_Y < 90^\circ \)). For a droplet that exhibits a Wenzel wetting state, the complete wetting and adhesion of the surface roughness will result in a mechanical interlock with the surface. Accordingly, such a wetting state is not favorable for achieving superhydrophobicity.

2.3 Cassie–Baxter wetting state

Superhydrophobic surfaces in nature were found to exhibit another interesting wetting state in which liquid droplets will be suspended on top of the surface’s protrusions and air will fill the space in between the roughness features, as demonstrated in Fig. 6. This wetting state was first introduced in 1944 by A. Cassie and S. Baxter; refer to Ref. (Cassie and Baxter 1944).

For a droplet to experience the Cassie-Baxter state (also known as the heterogeneous wetting state), the interfacial tension force balance can be expressed as (Cassie and Baxter 1944):

\[ \gamma_{SL} \cdot \phi_S + (1 - \phi_S) \gamma_{LV} + \gamma_{LV} \cos \theta_{CB} = \gamma_{SV} \cdot \phi_S \]  
(5)

where \( \theta_{CB} \) is the apparent Cassie-Baxter contact angle and \( \phi_S \) is the solid area fraction that is wetted by the liquid with respect to the total area of the solid–liquid and liquid–vapor interfaces. Thus, \((1-\phi_S)\)

\[ \cos \theta_{CB} = -1 + \phi_S \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \]  
(6)

A modified version of the Cassie-Baxter equation has also been reported, which considers the hierarchical multiscale structure of a superhydrophobic surface (Patankar 2004). Considering a surface that has microscopic protrusions with a solid fraction \( \phi_S \) and a superimposed nanoscopic roughness with a roughness factor \( r \), the modified Cassie-Baxter contact angle \( \theta^*_CB \) can be expressed as (Patankar 2004):

\[ \cos \theta^*_CB = -1 + \phi_S (r \cdot \cos \theta_Y + 1) \]  
(7)

Equation (7) indicates that micro and nano-asperities play a critical role in determining the level of surface wettability.

2.4 Critical contact angle

The wetting state that a droplet will exhibit on a solid surface is the state that provides the minimum potential energy. In order to predict the resulting wetting state, Bico et al. (2002) proposed a critical contact angle by equating Eqs. (4) and (6). Utilizing the modified Cassie-Baxter equation, the critical contact angle \( \theta_c \) can be expressed as (Gao and Yan 2009):

\[ \cos \theta_c = -1 + \frac{\phi_S}{r} \frac{1}{1 - \phi_S} \]  
(8)
According to Eq. (8), a Cassie-Baxter state will only exist if it results in an apparent contact angle that is higher than the critical contact angle; otherwise, a liquid droplet will exist in a Wenzel state. It is worth noting that apart from theoretical formulations, experimental studies have shown that an unstable Cassie-Baxter wetting state can exist below $\theta_c$, which means that both wetting states can sometimes coexist on the same surface (Patankar 2004; Ishino and Okumura 2008; Koishi et al. 2009; Jung and Bhushan 2007; Park et al. 2009).

2.5 Sliding angle and contact angle hysteresis

In addition to the contact angle, the sliding angle ($\theta_{SA}$) is another important angle that characterizes superhydrophobic surfaces. The sliding angle is related to the contact angle hysteresis phenomenon, which was originally explained by Johnson and Dettre (Johnson and Dettre 1964). When a liquid droplet is resting on an inclined surface, it experiences two different contact angles at the front and rear edges, as depicted in Fig. 7. The maximum and minimum values of these angles, before the droplet slides or rolls off the surface, are known as the advancing and receding contact angles, respectively. The difference between these two angles is defined as the contact angle hysteresis (CAH) and is equal to the sliding angle, which is defined as the minimum surface inclination angle that causes the droplet to slide or roll off the surface.

3 Numerical wettability models

Although Wenzel and Cassie-Baxter models provide an important theoretical foundation for understanding the wetting phenomenon on superhydrophobic surfaces, they fail to predict the apparent contact angles in some situations that include transition wetting states and droplets with smaller size (Yan et al. 2011; Yildirim Erbil and Elif Cansoy 2009; Cansoy et al. 2011). Additionally, these models are not capable of representing complex and important events such as droplet impact, evaporation, condensation, and contact angle hysteresis. Accordingly, numerous attempts have been recently reported in the literature to numerically model the wettability of superhydrophobic surfaces. The modeling techniques used vary in terms of complexity and capabilities.

3.1 Lattice–Boltzmann modeling

The Lattice–Boltzmann method (LBM) has recently witnessed development and popularity in various fields (He and Luo 1997). LBM is originally derived from the continuous Boltzmann equation, which is discretized to solve the continuum equations and density distribution functions using a particle-based algorithm (Zhang et al. 2014a). This method has been adopted in modeling the wettability of superhydrophobic surfaces due to its capability to handle fluid flow problems at small length scales. The first attempt to implement the LBM in modeling droplets on superhydrophobic surfaces was performed by Dupuis and Yeomans (Dupuis and Yeomans 2005). They used the LBM to solve the equations of motion that govern the spreading of droplets on a superhydrophobic surface with micrometer-scale square pillars. Their approach allowed simulating the equilibrium condition of droplets, which can be used to estimate the apparent contact angle, and the dynamic transition between Cassie-Baxter and Wenzel wetting states. Similar approaches were consequently adopted by Kusumaatmaja et al. (2008) and Vrancken et al. (2010) to study the transition of wetting states on micro-textured (square pillars) and corrugated (square grooves) superhydrophobic surfaces, respectively. The results were experimentally verified by contact angle measurements and direct observation of wetting state transition using an optical microscope.

Fig. 7 A schematic of the advancing and receding contact angles
With the aim of providing a better understanding of dynamic wetting and fluid flow in superhydrophobic channels, LBM was adopted by Zhang et al. (2006) and Huang et al. (2009) to simulate droplet motion inside micro-grooved superhydrophobic channels. The models were utilized to study the flow patterns, track the three-phase contact line, and estimate the induced drag. Zu and Yan (2010; 2016) proposed an analytical model to predict the wetting state transition using the concept of free energy and energy barrier, and they developed a numerical model using LBM to address the limitations of the theoretical analysis. The numerical analysis was performed for a superhydrophobic surface with micro-scale square pillars and can predict the wetting state and droplet shape evolution with time. Results from the analytical and numerical models were compared and found in good agreement.

LBM was also used to model more complex wettablity events such as droplet impact. Zhang et al. (2014a) developed a numerical model using LBM to simulate the low velocity impact (Weber number values 20 and 300) of liquid droplets on superhydrophobic surfaces, which leads to bouncing or spreading of droplets rather than splashing. Micro-textured surfaces with square pillars of different sizes and spacing were considered, and the model was used to study the droplet deformation and spreading pattern. Their study also included comparisons with other numerical methods developed at different length scales. With the aim of providing a better-controlled droplet manipulation, Zhang et al. (2016a) used LBM simulations to study the droplet rebound pattern and trajectory on superhydrophobic surfaces with a wettability gradient, which arises from the unbalanced interfacial forces created by surface heterogeneities. Their results indicated that a droplet would rebound following the direction of wettablitity gradient when the time scale for the droplet penetration and capillary emptying is smaller than the lateral spreading, as shown in Fig. 8a. However, significant capillary penetration and emptying will cause a droplet rebound against the wettability gradient direction, as depicted in Fig. 8b.

3.2 Molecular dynamics

Molecular dynamics (MD) simulations involve numerically solving the equations of motion for a system of interacting particles (atoms or molecules) (Binder et al. 2004). Accordingly, this method is capable of studying the molecular interactions with the nanoscale roughness structures, which makes it suitable for studying the wettability of superhydrophobic surfaces. For instance, several researchers have used MD simulations to understand the wetting transition between Cassie-Baxter and Wenzel states that occurs on rough surfaces (Bormashenko 2015). Giacomello et al. (Giacomello et al. 2012) studied the wetting of a surface with one nanogroove at various temperatures and densities. They concluded that the transition from

![Fig. 8 Droplet impact on a superhydrophobic surface with a wettability gradient at a dimensionless velocity of a 0.15 and b 0.24 (Zhang et al. 2016a)](image-url)
Cassie-Baxter to Wenzel follows an asymmetric path, in which a liquid column is formed on one side of the groove and a vapor bubble is formed on the other. Koishi et al. (2009) performed MD simulations of the wetting state transition on a periodic nano-pillared surface and investigated the effect of different parameters such as pillar height, spacing, and intrinsic contact angle. Khan et al. (2014) investigated the effect of system size on the wetting behavior of nanodroplets on textured surfaces. They reported that when the pillar and droplet sizes are comparable, the contact line pinning causes the contact angle to fluctuate with increasing droplet size. Shahraz et al. (2013) studied the wetting on surfaces patterned with nanogrooves and demonstrated that the same droplets can exhibit various metastable states on the same surfaces, which is an experimentally observed condition. MD simulations have also been used to study the wetting kinetics of oily fluids on rough surfaces (Savoy and Escobedo 2012).

Although being computationally demanding, MD simulations have been also conducted to investigate the droplet impact and sliding on superhydrophobic surfaces. Hirvi et al. (2008) conducted a comprehensive analysis for impacting and sliding droplets on rough surfaces. The parameters investigated include the impact velocity, angle, surface material, pillar height, and geometry. Their simulations can predict the rebound pattern, as shown in Fig. 9, friction against lateral motion, and final wetting states of droplets. Zhang et al. (2014a) performed MD simulations for the bouncing and splashing of droplets upon impact on microtextured superhydrophobic surfaces with the aim of predicting the rebound pattern and droplet deformation.

3.3 Surface evolver

Surface evolver (SE) is a finite-element based tool developed by Brakke (1992) that is specifically designed to model wettability problems and can be used for modeling liquid surfaces formed by different forces and varied boundary conditions. Brakke articulated his approach by assuming that a liquid surface with an arbitrary shape can initially be defined using a set of nodes, edges, and faces. Subsequently, the gradient descent method can be applied to allow the nodes to displace and achieve a global minimum energy position, in which the energy constituents are the surface tension at the three-phase contact line and

**Fig. 9** Snapshots at times (a) 25 ps, (b) 53.5 ps, (c) 150 ps, and (d) 200 ps of a nanodroplet with an impact velocity of 200 m/s (Hirvi and Pakkanen 2008)
gravity. Although SE lacks the capability of modeling complex wettability events such as droplet impact, it has gained popularity in the field of superhydrophobicity in view of its high computational efficiency, compared to other numerical techniques, and ability to efficiently handle complex geometries.

Some researchers have conducted SE simulations in order to predict the wetting state and apparent contact angle of droplets resting on superhydrophobic surfaces. Dorrer et al. (2007) investigated the shape of the three-phase contact line for a drop lying on a textured surface with square shaped pillars. Their results showed that the contact line is strongly distorted rather than being a straight line, which indicates a strong tendency of the droplet to be suspended in a Cassie-Baxter state in those regions. SE simulations were also performed for patterned surfaces with cylindrical holes or pillars by Chatain et al. (2006). They indicated that in Cassie-Baxter state, the droplet will experience a drop below the pillars’ top surface, in which the gap between the surface’s microstructures will be composite, i.e., partly solid/liquid and partly liquid/vapor. Other studies used SE to predict the apparent contact angle on textured superhydrophobic surfaces and investigate its dependence on the droplet size, intrinsic contact angle, pillar spacing, and geometry (Hao and Wang 2016; Goswami and Rahman 2017). Chen et al. (Chen et al. 2005) investigated the anisotropy of the apparent contact angle on rough surfaces textured with parallel grooves. They indicated that the apparent contact is no longer uniform in that case and proposed a methodology to quantify the apparent contact angle and the drop shape. Their results were also experimentally validated and found in good agreement. Elzaabalawy and Meguid (2019) used SE simulations to investigate the effect of different micropillars’ geometries and surface energy on the wettability of textured superhydrophobic surfaces, as depicted in Fig. 10. Their results indicated that for hydrophobic materials with a $\theta_Y$ higher than 105°, the apparent contact angle is affected by the pillars’ top surface area rather than the pillar geometry. The simulations were also extended study re-entrant structures (e.g., inverted conical pillars) that are used to achieve repellency against liquids with low surface tension.

Additionally, SE has been implemented in studying the wetting of superhydrophobic fibers. Aziz et al. (2017) studied the ability of orthogonally layered fibrous coatings to provide sufficient capillary forces for the droplet to remain in a Cassie-Baxter wetting state. They indicated that the apparent contact angle can be different in longitudinal and transverse directions, and they both increase by decreasing the diameter of the fibers or by increasing their spacing. Moghadam et al. (2018) used SE to track the air–water interface intrusion into hydrophobic fibrous membranes and study the effect of the membrane’s microstructure on its water intrusion resistance. Their results showed that increasing the volume fraction of the fine fibers, or fibers with a higher intrinsic contact angle, leads to an increase in the intrusion pressure. SE was also used to model the contact angle hysteresis on superhydrophobic surfaces with cosine wave-like square-array pattern (Promraksa and Chen 2012) and smooth hydrophobic surfaces (Prabhala et al. 2013). Zhao et al. (2012, 2011) used SE to simulate hexadecane droplets on pillared surfaces, as shown in Fig. 11. They used the numerical simulations to investigate the effect of induced pressure on the penetration of the droplet between the surface’s microstructures. Their results showed that the penetration

---

**Fig. 10** A droplet on a micro-grooved surface: (a) initial arbitrary droplet shape and (b) final droplet at equilibrium (Elzaabalawy and Meguid 2019)
of the hexadecane droplet causes contact line pinning and the effect on the receding contact angle and hysteresis is larger relative to that of water.

3.4 CFD modeling techniques

While most of the numerical models reported in the literature utilize the aforementioned techniques, it is worth mentioning that other numerical models have also been reported. For instance, OpenFOAM computational fluid dynamics (CFD) software has been used to model the coalescence of micro-droplets superhydrophobic surfaces (Attarzadeh and Dolatabadi 2017), as shown in Fig. 12, and the impact and freezing of droplets on cooled superhydrophobic surfaces (Yao et al. 2017). Both studies utilized

![Velocity vectors temporal variation during the coalescence of two micro-droplets (Attarzadeh and Dolatabadi 2017)](attachment:image.png)
the volume of fluid (VOF) numerical technique to tackle the multiphase problem. The numerical models were used to predict the droplet dynamics, and the results were found in good agreement with experimental data. Based on the VOF formulation (Hirt and Nichols 1981), the mass conservation equation of a droplet impinging a solid surface can be expressed as:

$$\frac{\partial}{\partial t} (\rho \alpha_i) + \nabla \cdot (\rho \alpha_i \vec{u}_i) = 0$$

(9)

and the combined momentum conservation equation that accounts for the gas and liquid phases can be written as:

$$\frac{\partial}{\partial t} (\rho \hat{\vec{u}}) + \nabla \cdot (\rho \hat{\vec{u}} \hat{\vec{u}}) = -\nabla p + \nabla \cdot (\mu \nabla \hat{\vec{u}}) + \rho g + \hat{F}$$

(10)

where $\rho$ is the density, $\hat{\vec{u}}$ is the velocity vector, $p$ is the pressure, $\mu$ is the dynamic viscosity, $g$ is the gravity vector, and $\hat{F}$ is the volumetric surface tension force. The surface tension force term dictates the radius of curvature $\kappa$ of the liquid–gas interface, and is expressed according to the continuum surface force (CSF) model (Brackbill et al. 1992) as:

$$\hat{F} = \sigma \frac{\rho \kappa \nabla \alpha_1}{(\rho_1 + \rho_2) / 2}$$

(11)

where $\sigma$ is the surface tension and subscripts 1 and 2 refer to the primary and secondary phases, respectively.

Additionally, Quan et al. (2014) utilized the commercial CFD software, ANSYS Fluent, combined with the VOF technique to study the impinging and bouncing of droplets on micro-textured superhydrophobic surfaces. Different geometries and operating conditions were considered, and they concluded that a surface with crisscross pillars exhibits the best rebound ability due to its large capillary pressure and ability to capture air in its gaps. Karapetsas et al. (2016) also conducted numerical investigations of droplets impacting and sliding on textured surfaces using COMSOL multiphysics commercial software with the aim of predicting the dynamic contact angle and the effect of CAH, as depicted in Fig. 13. Their results show that the presence of air inclusions trapped in the micro-structures (Cassie–Baxter state) result in the decrease of CAH and in the increase of the droplet migration velocity.

Despite the numerous modeling attempts reported in the literature, most of the studies deal only with simplified geometries of microscopic pillars. There is also lack of numerical studies that are concerned with re-entrant structures, which are used to repel low surface tension liquids. Accordingly, further efforts are needed to systematically investigate the effect of the role of the governing parameters on the wettability of textured surfaces.

4 Advances in development of superhydrophobic surfaces

In order to develop superhydrophobic surfaces, a combination of multiscale hierarchical structure and low surface energy should be obtained. Numerous fabrication techniques have been adopted by researchers and in industry in order to achieve those crucial parameters. The fabrication techniques are usually classified into two main categories (Jiang et al. 2015; Jeevahan et al. 2018): top-down approaches, such as lithography, etching, and templating, and bottom-up approaches, such as chemical vapor deposition, sol–gel method, and layer-by-layer deposition. A summary of the widespread methods used to fabricate superhydrophobic surfaces is also shown in Fig. 14 (Bhushan 2018). In the following sections, the advances in the development of superhydrophobic surfaces using some of the most common nanofabrication techniques will be discussed in detail.

4.1 Lithography

Lithography is a well-established technique that is commonly used to fabricate superhydrophobic surfaces with precise control over the surface structure. Surfaces patterned with microstructures or nanostructures of different shapes, such as square or circular pillars, sizes, and spacing can be prepared using lithography (Jiang et al. 2015; Jeevahan et al. 2018). Lithography is normally performed using a flat master mask layer that is placed over a substrate. The whole substrate is then subjected to a reaction that removes some of the uncovered substrate material allowing a structured surface opposite to the mask layer pattern to be formed. The reaction can be controlled using various techniques including a photoactive polymer.
and ultraviolet rays (photolithography), X-rays, electron beam, or laser.

Martines et al. (2005) fabricated superhydrophobic surfaces using electron beam lithography to create arrays of nanopits or nanopillars in a silicon wafer. The patterned surfaces were then chemically treated using octadecyltricholorosilane (OTS) to achieve superhydrophobicity. They studied the behavior of the water droplets on the fabricated surfaces and reported a $\theta_{CA}$ of 164° and $\theta_{SA}$ of ~ 1°. In order to eliminate the post-chemical treatment, Park et al. (Park et al. 2010) used photolithography to create cylindrical nanoshell arrays on a silicon substrate. Their surfaces showed a $\theta_{CA}$ of 166° and $\theta_{SA}$ of 5°. They attributed this superior water-repellency to the air pillar that exists in the nanoshells and is being maintained under the effect of negative capillary pressure. Combining photolithography (ultraviolet) with nanoprocesing, Li et al. (2013a) fabricated superhydrophobic surfaces using nanoimprint lithography. This technique can create precise patterns at the nanoscale. In order to develop the hierarchical surface structure, they then used a spontaneous wrinkling process to create microscopic wrinkles, as shown in Fig. 15. Their results show that the hierarchically wrinkled surface exhibits a $\theta_{CA}$ of 160° and $\theta_{SA}$ of 5°. They also demonstrated the ability to tune the wettability between hydrophobicity and superhydrophobicity by varying the initial film thickness.

The lithography technique was also adopted to create superoleophobic surfaces (repellent to oils with low surface tension). Im et al. (2010) fabricated inverse-trapezoidal microstructures on polydimethylsiloxane (PDMS) substrates using lithography.
Further reduction in the surface energy was achieved by adding a layer of a fluoropolymer. They reported repellency features for the fabricated surfaces against water and methanol. Additionally, Zhao et al. (2011) used photolithography to create a surface of extreme repellency against low surface tension inks used in printers. The superoleophobicity was achieved via the deposition of an additional fluorosilane layer. They investigated the performance of different micropillar geometries and reported a $\theta_{CA}$ of 156° and 158° against water and hexadecane, respectively.

Numerous successful attempts have been reported in the literature to create superhydrophobic surfaces using different lithography techniques (Yan et al.
Although these methods can precisely control the shape and dimensions of the surface structure, they are still slow and expensive, which hinders the adoption of such techniques in large-scale production of superhydrophobic surfaces.

4.2 Etching

Etching is simply a technique in which a substrate is engraved to create a rough surface structure using either chemical, plasma, laser, or electrochemical techniques. Ebert and Bhushan (2016) used deep reactive ion etching to create a transparent superhydrophobic surfaces. In this technique, a PDMS substrate was etched using an oxygen-carbon tetrafluoride (O₂/CF₄) plasma. Subsequently, surfaces were fluorinated to achieve superhydrophobicity. The effect of using different fluorination techniques was studied, and the results showed θCA up to 169° and θSA as low as 2°. Yang et al. (2017) developed an electrochemical etching technique (by applying a voltage difference in a sodium chloride solution) to create microscopic patterns on aluminum substrates. The etched substrates were then immersed in fluoroalkylsilane to lower the surface energy. Their wettability results indicate that a θCA of 160° can be achieved by this technique. Moreover, Gao et al. (2018) chemically etched steel substrates using piranha solution (mixture of sulphuric acid and hydrogen peroxide). The etched steel substrates were then soaked in a fluorosilane solution to chemically treat the external surface. Figure 16 shows SEM images for the evolution of the surface structure during the different fabrication steps. They reported a θCA of 164°, θSA of ~1°, and good durability against mechanical abrasion.

Although etching is sought as a simple fabrication technique, precisely controlling the surface structure usually requires equipment that is complex and more expensive (Jiang et al. 2015). Additionally, it is usually followed by a chemical modification step, which increases the complexity of the fabrication technique. The chemical modification also usually involves the use of fluorinated compounds, which are costly and have recently raised concerns due to their environmental impact (Zhang et al. 2017b; Wu et al. 2016a; Bae et al. 2009).

4.3 Templating

In the templating fabrication technique, also referred to as soft lithography, a master template is initially prepared. An elastomeric material, such as PDMS, is then used to mold a replica. Finally, the template

---

![Fig. 16 SEM images of a, b plain steel; c, d etched steel; and e, f modified etched steel surfaces (2018)](image)
is removed leaving an imprinted surface structure on the replica. Since superhydrophobic surfaces are originally bioinspired by nature, the master templates can be naturally existing surfaces. For example, Yuan et al. (2007) used plant leaves (taro) as templates and polystyrene polymer to create a superhydrophobic surface of $\theta_{CA}$ and $\theta_{SA}$ of 158° and 3°, respectively. Gecko’s feet were also used by Cho and Choi (2008) to replicate the hairy-like structure of the reptile on a PDMS film. Moreover, Sato et al. (2009) utilized butterfly wings to achieve a bumpy surface microstructure in polystyrene.

Other methods can also be used to prepare synthetic master templates. Wang et al. (2014) reported the fabrication of teraethoxysilane-assisted silica nanostructures against a 3D nanostructured hydrogel template. A schematic illustration of the fabrication steps is shown in Fig. 17. The technique was used on different substrate materials, and the reported $\theta_{CA}$ was higher than 160° on all substrates. Martin and Bhushan (2017) prepared micropatterned PDMS surfaces using a four-step procedure: (i) apply an impression material to a micropatterned silicon master, (ii) pour epoxy to create a positive mold, (iii) pour urethane to create a negative mold, and (iv) pour PDMS to obtain the final surface. Their results indicate a $\theta_{CA}$ and $\theta_{SA}$ of 151° and 7°, respectively. They also reported that an additional fluorination step would only change the $\theta_{CA}$ and $\theta_{SA}$ to 152° and 5°. A master template was also developed using carbon soot by Gao et al. (2019). In their technique, a silicon wafer was maintained above a paraffin candle’s flame to deposit the carbon soot particles; then, magnetic sputtering was used to deposit a titanium oxide ($\text{TiO}_2$) film on top of the rough surface created by the carbon soot. Their results showed that a $\text{TiO}_2$ film solely deposited on the silicon wafer results in a $\theta_{CA}$ of 61°, while the $\theta_{CA}$ becomes 155° when the $\text{TiO}_2$ film is deposited on the carbon soot.

Although templating is considered a more economic and facile fabrication technique, the master templates are usually limited to microfeatures. Accordingly, the nanoscale roughness, which constitutes the other portion of the hierarchical structure, is not controlled (Yan et al. 2011; Bhushan 2018). Additionally, applying the method might be challenging to applications that involve large surface areas or irregular surfaces with extremely complex structures, due to the peeling-off procedure (Yan et al. 2011).

### 4.4 Chemical vapor deposition

Chemical vapor deposition (CVD) is another common method for fabricating superhydrophobic surfaces. In a typical CVD process, a substrate is exposed to a gaseous precursor. This exposure results in depositing a thin film on the substrate via a chemical reaction. Carbon nanotubes (CNTs) are considered one of the most common deposited nanoparticles that are used in CVD due to their excellent mechanical strength as well as low surface energy (Zhu et al. 2005; Huang et al. 2005; Zhao et al. 2006). Superhydrophobic CNT forests were created by Lau et al. (Lau et al. 2003) using a plasma-enhanced CVD technique. This method ensures that grown CNTs are vertically aligned and untangled, as demonstrated in Fig. 17. Schematic of the hydrogel templating technique (Wang et al. 2014)
After the functionalization of CNTs using polytetrafluoroethylene (PTFE), an advancing and receding contact angle of 170° and 160°, respectively, were achieved.

CVD attempts using other materials have also been reported. For example, Zhang et al. (2017b) chemically deposited PDMS on a substrate that is coated with silica nanotubes (SNT) in order to create SNT@PDMS oligomer coatings. The coating exhibited high transparency as well as excellent superhydrophobicity with a $\theta_{CA}$ and $\theta_{SA}$ of 165° and 3°, respectively. Ishizaki et al. (2010) also used microwave plasma-enhanced CVD to deposit a superhydrophobic film on magnesium alloy substrates. The precursor consisted of gaseous trimethylmethoxydisilane and resulted in the deposition of Si–CH₃ groups on the substrate. Due to the low surface energy of the –CH₃ group, superhydrophobicity was achieved with $\theta_{CA}$ higher than 150°. Moreover, a conformal copolymer of 1H,1H,2H,2H-perfluorodecyl acrylate and ethylene glycol diacrylate [p(PFDA-co-EGDA)] was deposited on a copper substrate using initiated CVD (Vilaró et al. 2016). The substrate was first etched in order to generate the microroughness, while the nanoworm-like structures were grown on top during the CVD, as depicted in Fig. 19. The developed surface exhibited a $\theta_{CA}$ and $\theta_{SA}$ of 163° and 1°, respectively.

### 4.5 Sol–gel method

The sol–gel technique is one of the well-established methods to create superhydrophobic surfaces. It is classified as a wet chemical technique in which a chemical solution (referred to as sol) is deposited on a substrate. The process starts by a hydrolysis and polycondensation to change the precursor into a gel-like structure. Subsequently, the gel-like structure undergoes aging, drying, densification, and crystallization (Neacșu et al. 2016). Sheen et al. (2009) fabricated superamphiphobic (surfaces with repellency against polar and nonpolar liquids) using...
a sol–gel approach. They utilized mixtures with different compositions of tetraethoxysilane (TEOS) and methyltriethoxysilane (MTES), and the gelation process was achieved using ammonium hydroxide. Upon drying, the coated surfaces demonstrated a $\theta_{CA}$ of $\sim 150^\circ$ and $133^\circ$ against water and methylene iodide, respectively. In order to maintain the fabrication technique as environmentally friendly, no additional fluorination steps were used. However, this resulted in the relatively low $\theta_{CA}$ that was reported.

Due to its compatibility with glass, sol–gel methods have been preferred to create transparent superhydrophobic surfaces (Yan et al. 2011). Xiu et al. (2009) utilized a eutectic liquid (choline chloride and urea) to prepare thin transparent superhydrophobic films on glass substrates. Hydrolysis and condensation were achieved by adding hydrochloric acid, and the gelation process was promoted by adding an ammonia solution. After a prolonged drying period (two weeks), a fluorination process was applied to obtain a superhydrophobic performance with a $\theta_{CA}$ of $\sim 170^\circ$ and $\theta_{SA}$ slightly less than $10^\circ$. Moreover, Liu et al. (2015) reported transparent superhydrophobic surfaces fabricated via a sol–gel process of long-chain fluoroalkylsilane (17FTMS). Network-like structures of non-hydrolyzable fluorocarbon groups were formed via the hydrolysis and polycondensation reactions of the functional methoxy groups in the 17FTMS. They studied the effect of deposition time on the wettability of the coatings and reported a $\theta_{CA}$ and $\theta_{SA}$ of $169^\circ$ and $5^\circ$, respectively.

Mechanically robust superhydrophobic and superoleophobic surfaces were also developed by Wu et al. (2016b) via a sol–gel technique. A fluorine-based polymer (PFOTES) solution was utilized, and a mixture of low and high surface energy silica nanoparticles was added to the solution. Their results show that controlling the ratio of low and high surface energy nanoparticles can tune the surface topology and optimize the wettability and mechanical properties of the coating. At a molar ratio of 2:4, the coating demonstrated a $\theta_{CA}$ and $\theta_{SA}$ of $166^\circ$ and $6^\circ$, respectively, while showing the best mechanical properties. Although sol–gel techniques are typically facile, they are usually very slow (Jiang et al. 2015) and can be costly and have an environmental impact if fluorinated compounds are involved.

### 4.6 Nanocomposites

The fabrication of superhydrophobic surfaces using nanocomposites has gained popularity as being a scalable, facile, and economic alternative. Typically, a nanocomposite is developed via the dispersion of nanoscale fillers into a binding polymeric matrix (Mai and Yu 2006). Superhydrophobic nanocomposites can be applied to substrates using facile deposition techniques, such as spray and dip coating, to create superhydrophobic surfaces. Within a superhydrophobic nanocomposite, the role of the binding polymer is to attach the nanoparticles jointly and adhere the entire coating to the substrate, while the nanoparticles are responsible for reducing the surface energy and creating the nanoscale roughness. To complement the surface hierarchical structure, the microscopic roughness is created by the agglomerations of nanoparticles and their interaction with the polymeric material.

#### 4.6.1 Selection of binding polymer

The characteristics of the developed nanocomposite are greatly influenced by the selection of the polymeric binding material. This includes the wettability, mechanical durability, and chemical stability. For instance, hydrophobic polymers with inherent low surface energy, such as polysiloxanes (Momen et al. 2015; Mokarian et al. 2016; Elzaabalawy et al. 2019; Muthiah et al. 2013), polydimethylsiloxane (PDMS) (Li et al. 2013b; Yang et al. 2018; Qing et al. 2019), and fluoroacrylic copolymers (Asthana et al. 2014; Das et al. 2012; Bayer et al. 2013a), are sought when excellent water repellency features are desired. Additionally, utilizing elastomeric polymers such as polysiloxanes (Ju et al. 2017; Davis et al. 2018), styrene-ethylene-butylene-styrene (Li et al. 2017a), polyolefin (Mates et al. 2015), and polybutadiene (Hu et al. 2017b) would create stretchable nanocomposites, as depicted in Fig. 20. In order to achieve higher mechanical durability and design superhydrophobic nanocomposites that can operate in mechanically harsh environments involving friction and wear, polymers with high mechanical strength, such as epoxy (Zhang et al. 2018b, 2018c; Wu et al. 2017), can be utilized.

Epoxy resins is one of the most common polymeric materials used to create superhydrophobic nanocomposites. Previous attempts shows its compatibility
with a wide range of nanoparticles such as CNTs (Bhushan and Jung 2009; Hsu et al. 2013), silica (Zhang et al. 2018a, 2018b; Wu et al. 2017; Peng et al. 2018; Jia et al. 2018; Cui et al. 2009), calcium carbonate (Atta et al. 2016), carbon soot (Esmeryan et al. 2013), zinc oxide (Zhang et al. 2017c), and magnesium hydroxide (Peng et al. 2019). Although epoxy resins are characterized by excellent properties such as high tensile strength, chemical corrosion resistance, and excellent adhesion (Chruściel and Leśniak 2015), they suffer high surface energy due to the high content of polar groups in their polymeric chains. One of the proposed solutions to overcome this inherent property of epoxy is to chemically modify the resin in order to reduce its surface energy. Polysiloxanes have been previously utilized to enhance the mechanical properties of epoxy resins (Chruściel and Leśniak 2015, 2012). Due to the hydrophobic nature of siloxanes, a siloxane-modified epoxy resin would have a great potential to create nanocomposites with excellent mechanical properties as well as exceptional superhydrophobicity. Elzaabalawy and Meguid (Elzaabalawy and Meguid 2020a) developed a siloxane-modified epoxy–silica nanocomposite coating, in which the chemical modification was performed using an amino-functionalized polysiloxane. The developed coating demonstrated excellent water repellency features, with a $\theta_{CA}$ of 165° and a $\theta_{SA}$ of 3°, was suitable for a variety of substrates, as shown in Fig. 21, and demonstrated durability against peeling, abrasion, corrosion, and elevated temperature environments exposure tests.

### 4.6.2 Selection of Nanoparticles

With the aim of achieving multifunctionality, the characteristics of the developed nanocomposites is governed by the appropriate selection of nanoparticles. For instance, silica nanoparticles are usually employed, in addition to an appropriate binding polymer, when transparent nanocomposite coatings are sought (Zhang et al. 2017b; Zhong et al. 2018; Ebert and Bhushan 2012). Other parameters should also be included to reduce the light scattering such as controlling the agglomerations of silica nanoparticles (Bravo et al. 2007). Due to their compatibility, silica nanoparticles are also usually employed in biomedical applications that require superhydrophobicity or blood repellency (Falde et al. 2016). In order to fabricate electrically conductive nanocomposites, conductive...
nanofillers such as CNTs (Asthana et al. 2014; Bayer et al. 2013a; Han et al. 2017; Su et al. 2019; Balram et al. 2016), carbon black (CB) (Asthana et al. 2014; Shen et al. 2012), carbon nanofibers (CNFs) (Das et al. 2012), graphene nanoplatelets (Asthana et al. 2014), or silver nanoparticles (Su et al. 2018) can be utilized. CNFs have been also employed to achieve thermally conductive superhydrophobic coatings (Baldelli et al. 2021; Hu et al. 2020).

4.6.3 Nanocomposite monoliths

Mechanical durability has always been a major challenge when fabricating superhydrophobic surfaces (Ellinas et al. 2017; Jeevahan et al. 2018). This concern is attributed to the fragility of the hierarchical structures, which can be easily damaged under the effect of wear, friction, or applied load during service (Mortazavi and Khonsari 2017; Jeevahan et al. 2018). This damage can lead to serious performance degradation and loss in superhydrophobicity. Consequently, the fabrication of self-healing superhydrophobic surfaces has been recently receiving a lot of attention (Ellinas et al. 2017; Xu et al. 2016; Milionis et al. 2016). Recently, self-healing superhydrophobic films were developed using spray-coating (Golovin et al. 2017) and layer-by-layer deposition (Wu et al. 2016a). However, these methods can only provide a very thin (usually micrometers in thickness) film or coating that can be totally destroyed due to mechanical damage.

An alternative method to face the aforementioned challenge is fabricating superhydrophobic monoliths with regenerative capabilities (Liu and Kang 2018; Hayase et al. 2013). Accordingly, if these monoliths are subjected to a damaging force, external stimuli can be used to restore their superhydrophobic performance. Chen et al. (2014) fabricated a superhydrophobic nanocomposite monolith that utilizes polystyrene and graphene oxide. The fabricated monolith demonstrated a \( \theta_{CA} \) of 156° and an ability to separate oil from water due to its porous structure and affinity for oils. Superhydrophobic/Superoleophilic performance was also reported by Li et al. (2018a). They fabricated a porous nanocomposite monolith using polycarbonate and CNTs. The monolith showed a \( \theta_{CA} \) of 159° and ~1° against water and oil, respectively, which grants it the ability to selectively adsorb various oils/organic liquids from oil–water mixtures.

Additionally, PDMS-silica nanocomposites have been successfully used to fabricate superhydrophobic nanocomposites. Zhang et al. (2016b) reported a monolith with a \( \theta_{CA} \) and \( \theta_{SA} \) of 154° and 7°, respectively, that utilizes a mix of silica microparticles and nanoparticles to enhance the surface structure. In order to further improve the surface structure and superhydrophobicity, Davis et al. (2018) developed a water-in-PDMS emulsion technique to fabricate superhydrophobic monoliths. The water droplets that were added to the emulsion were kept until the nanocomposite was cured then evaporated to create a special surface structure. Their monolith demonstrated a \( \theta_{CA} \) and \( \theta_{SA} \) of 159° and 5°, respectively, and a repellency performance after being subjected to different severe environmental conditions. Elzaabalawy et al. (Elzaabalawy et al. 2019) reported a scalable technique to develop superhydrophobic silicone-silica nanocomposite monoliths with regenerative capabilities, as depicted in Fig. 22. The superhydrophobic monolith exhibited a \( \theta_{CA} \) and \( \theta_{SA} \) of 167° and 6°, respectively, and can be regenerated after being subjected to a compressive load of 10 MPa by abrasive removal of the damaged layer.

The concept of regenerative monoliths is considered an emerging field and is still facing multiple challenges. Specifically, most existing attempts typically require an external stimulus, such as heat, ultraviolet, and chemical treatment, and are limited to restoring the surface chemistry rather than the surface hierarchical structure. Moreover, many of these attempts utilize fabrication techniques that are not scalable or environmentally unfriendly.

4.7 Miscellaneous Techniques

There are various techniques that have been used in the literature to develop superhydrophobic surfaces. Bayer et al. (2015, 2013b) adhered polytetrafluoroethylene (PTFE) particles onto microtextured surfaces using triboelectric charging. They reported a \( \theta_{CA} \) of up to 164° and a \( \theta_{SA} \) as low as 2°, and the developed surfaces exhibited resistance against high-pressure impinging water jets under normal or oblique conditions. Moreover, superhydrophobic surfaces were developed by depositing carbon soot (amorphous carbon nanoparticles) on substrates using a flame (Deng et al. 2012; Bayer et al. 2014). Other researchers also utilized 3D microprinting to achieve
4.8 Slippery liquid-infused porous surfaces

Superhydrophobicity can also be achieved by techniques that do not rely on the conventional hierarchical multiscale structure. Slippery liquid infused porous surfaces or SLIPS were first proposed by Wong et al. (2011). Inspired by the Nepenthes pitcher plants, SLIPS is based on introducing an immiscible liquid into a porous solid structure, as schematically shown in Fig. 23. SLIPS surfaces have demonstrated low CAH as well as impalement resistance of water into the surface structure (Xue and Ma 2013; Zhang and Lv 2015).

Numerous attempts have been reported for fabricating superhydrophobic surfaces utilizing the SLIPS concept. Kim et al. (2012) deposited polypyrrole on aluminum substrates and infused perfluoroalkyl ether (perfluorinated lubricant) into its solid structure. Their results reveal that the fabricated surface is capable of delaying the frost formation and reducing the ice adhesion strength. Subramanyam et al. (2013) also reported a reduced ice adhesion for a SLIPS fabricated impregnating lubricating oil into microtextured silicon substrates. Moreover, Fu et al. (2017) utilized direct numerical simulations to demonstrate the passive ability of SLIPS to reduce the turbulent drag. Wang et al. (2016) created SLIPS by first etching metallic surfaces to create the necessary surface roughness. Subsequently, the surface was coated with a perfluorinated silane through liquid-phase silanization to induce complete wetting of the liquid lubricant. Finally, a perfluorinated lubricant was applied by spray or spin coating.

Fig. 22 Fabrication of monolith: a a schematic of the fabrication technique, b images of the developed monolith showing repellency against water droplets, and c SEM images of the monolith’s surface structure (Elzaabalawy et al. 2019)
Despite the excellent characteristics and the extensive research, the utilization of SLIPS in practical applications is still facing major challenges (Li et al. 2019). For instance, the leakage of the infused lubricating oil can deteriorate the performance (Rykaczewski et al. 2013) or contaminate biological samples (Ellinas et al. 2017). Moreover, the lubricating oils used are usually fluorinated and costly.

4.9 Eco-friendly fabrication

As seen in the previous sections, fluorination or perfluorinated compounds is often used to achieve further reduction in surface energy and achieve superhydrophobicity. Additionally, some of the chemical compounds or solvents used during the fabrication are deemed not eco-friendly. These challenges hinder the large-scale production and utilization of superhydrophobic surfaces. In order to tackle this issue, researchers have recently explored the development of superhydrophobic surfaces using eco-friendly materials and approaches. For instance, superhydrophobic surfaces can be developed using natural wax (Niemietz et al. 2009) or fatty acids (Bi et al. 2019). Additionally, the fabrication technique can utilize waterborne systems (Chen et al. 2017) or be solvent-free (Zhang et al. 2014b). For more comprehensive details on eco-friendly and sustainable approaches to develop superhydrophobic surfaces, readers may refer to review articles focusing on this subject (Bayer 2020; Zahid et al. 2019; Ghasemlou et al. 2019).

5 Advances in developments of icephobic surfaces

As mentioned earlier, the complete characterization of icephobicity should account for the ability of surfaces to repel impinging supercooled water droplets, reduction of ice nucleation temperature, delay in the freezing process, and reduction in the adhesion strength of ice. In the following sections, these issues are considered and advances in developing icephobic surfaces to achieve them are considered.

5.1 Supercooled droplet repellency

Due to their high $\theta_{CA}$ and low $\theta_{SA}$, superhydrophobic surfaces are expected to be able to repel supercooled water droplets. When room temperature water droplets impact a cold surface, they will experience spreading, receding, and oscillations under the effect of gravitational, surface tension, and inertia forces (Šikalo et al. 2002; Yarin 2006). However, if the droplet is initially supercooled, it will experience additional processes that include nucleation, reccalescence, freezing, and cooling (Alizadeh et al. 2012; Zhang et al. 2017d). A schematic of the impact dynamics events that a supercooled water droplet undergoes when impacting a cold surface is demonstrated in Fig. 24 (Zhang et al. 2020b). First, upon impact, vibrations are induced throughout the droplet. Since these vibrations are capable of initiating the nucleation process within the droplet (Sun et al. 2019), the supercooled droplet experiences a sudden increase in temperature and change in the crystal structure, known as the reccalescence phase. During that phase, the droplet changes into a water–ice mixture with different physical properties and a temperature equal to the freezing point ($0 ^\circ C$) (Zhang et al. 2017e; Jung et al. 2012). The droplet then starts the spreading, receding, and oscillating phases under the effect of gravitational, surface tension, and inertia forces. During these stages, the contact line between the droplet...
and the cold surface may experience freezing while the rest of the droplet is still moving and oscillating. Subsequently, the freezing front will advance from the cold surface towards the rest of the droplet until complete solidification is achieved, which is characterized by the conical tip that forms at the end of the freezing process (Marín et al. 2014).

Recent attempts have been reported to study the impingement of supercooled droplets on subfreezing surfaces. Some studies experimentally examined the combined effect of nucleation and impact dynamics on the freezing of impinging supercooled droplets on surfaces with different thermal conductivities (Sun et al. 2019; Wang et al. 2019a). Other studies investigated the effect of different surface hierarchical structures on the adhesion and rebound of impacting supercooled droplets (Mishchenko et al. 2010; Zhang et al. 2018d). Moreover, few researchers developed Volume of fluid (VOF) numerical models to simulate the impingement and freezing of supercooled droplets on superhydrophobic surfaces (Zhang et al. 2020b; Tembely et al. 2018; Shinan et al. 2019; Blake et al. 2015).

For a cold superhydrophobic surface to attain ice-phobicity, it should be able to fully rebound the supercooled droplets before they experience any freezing (Liu et al. 2017). This includes having sufficiently low surface energy and the necessary hierarchical surface structure to repel water droplets at low temperatures. Mishchenko et al. (2010) presented a comprehensive study of supercooled droplet impact dynamics on a superhydrophobic surface with $\theta_{CA}$ ranging between $150^\circ$ and $174^\circ$. The superhydrophobic surfaces had different macrotextures and were fluorinated to achieve higher water repellency. They investigated the impact of supercooled water droplets at $-5^\circ$C on cold surfaces of temperatures ranging between $20^\circ$C and $-30^\circ$C. Their results revealed that cold superhydrophobic surfaces can fully rebound supercooled droplets down to a temperature of $-25^\circ$. Beyond that, a nonwetting freezing transition caused the droplets to freeze before they can fully rebound, as depicted in Fig. 25.

Moreover, Zheng et al. (2011) demonstrated the ability of superhydrophobic surfaces fabricated by depositing CNTs on glass substrates to repel

---

Fig. 24  Impact dynamics of a supercooled water droplet on a cold surface a prior to impact, b upon impact, c spreading, d receding, e oscillating, and f cooling after completely frozen (Zhang et al. 2020b)
supercooled water droplets. Their surface was able to repel supercooled water droplets, when both are maintained at a subfreezing temperature of \(-8 \, ^\circ\text{C}\), at a tilt angle of 30°. However, no binding polymeric material was used, and the CNTs were only attached to the substrate via Van der Waals forces.

### 5.2 Ice nucleation temperature

Since ice nucleation is the first event that occurs during the freezing of water, an icephobic surface should be capable of reducing the temperature at which nucleation starts when subjected to a continuous cooling. Based on the classical nucleation theory, ice nucleation can be classified into two main types: (i) homogeneous nucleation, and (ii) heterogeneous nucleation. During homogeneous nucleation, a spontaneous phase change is experienced in the droplet when a sufficient temperature reduction is present to overcome the Gibbs free energy barrier. This thermodynamic driving force is responsible for supplying a sufficient amount of energy to develop and sustain the hydrogen bonds that cause the crystallization of the entire system (Whale et al. 2015; Moore and Molinero 2011). The free energy barrier can be expressed as (Kalikmanov 2013):

\[
\Delta G_{\text{heterogenous}} = \frac{2 - 3 \cos \theta_{CA} + \cos^3 \theta_{CA}}{4}
\]  

It can be observed from Eq. (13) that as the \(\theta_{CA}\) increases, the heterogeneous free energy barrier approaches the homogeneous energy barrier, which further retards the nucleation.

The nucleation of ice on subfreezing surfaces has also been studied using molecular dynamics (MD) simulations. For instance, Li et al. (2017b) investigated the kinetics of ice nucleation using MD. They studied the dynamics of the hydrogen bond network and its effect on the crystallization of water at the liquid–solid interface. Their results reveal that comparable surface energy and thermal effects leads to long lasting bonds, which ultimately causes nucleation. Metya et al. (2016) studied the nucleation of supercooled droplets on nanoscale textured surfaces using MD. Their results reveal the significant effect of the wetting state (Cassie-Baxter or Wenzel) on the nucleation rate and the effect of the surface roughness fraction. As depicted in Fig. 26, a surface with high roughness fraction leads to heterogeneous nucleation, while homogeneous nucleation is experienced at low roughness fraction. The effect of nanopillar height was also investigated, and it was found that the nucleation rate is enhanced with increasing heights.

The ability of superhydrophobic surfaces to reduce the ice nucleation temperature under continuous cooling has been verified by multiple researchers. Ruan et al. (2013) fabricated superhydrophobic surfaces with \(\theta_{CA}\) of \(\approx 159^\circ\) using electrochemical anodic oxidation and chemical etching of metallic surfaces and investigated its ability to reduce the nucleation temperature. Their results indicate a nucleation temperature reduction from \(-2.2 \, ^\circ\text{C}\) to \(-6.1 \, ^\circ\text{C}\). Fu et al. (2015) investigated the effect of varying the surface energy and roughness on the nucleation temperature of water droplets. They utilized a test rig consisting of cascaded Peltier coolers and a laser detecting system. The test rig was also automated to conduct 500 cycles of freezing events to precisely monitor the nucleation temperature. The surfaces they used were fabricated...
using a sol–gel technique and reported a nucleation
temperature reduction of up to 6.9 °C.

Zhan et al. (2014) also reported a nucleation tem-
perature reduction of 6.8 °C experienced by freez-
ing water droplets on fluorinated polymer–silica
nanocomposites of θ_{CA} ~ 170°. It is worth noting that
the nucleation temperature usually depends on the
cooling rate as verified by Zhang et al. (Zhang et al.
2016c). They showed that in order to obtain a consist-
ent nucleation temperature, a cooling rate above 5 °C/
min is recommended.

5.3 Freezing delay

The freezing delay is defined as the time required
for a water droplet to freeze when placed on a sur-
face that is maintained at a constant subfreezing
temperature. The magnitude of this delay is gov-
erned by the rate of heat transfer that the old sur-
face is capable of withdrawing from the water dro-
plet (Zheng et al. 2016). The freezing process of the
water droplet consists mainly of the precooling and
ice growth stages (Shen et al. 2015a). The time Δt
required to complete the precooling stage can be
calculated from the cooling rate per unit mass q as
follows (Guo et al. 2012):

$$\Delta t_{\text{precooling}} = \frac{\rho_w C_w \Delta T}{q}$$  \hspace{1cm} (14)

where ΔT is the droplet’s change in temperature, and
ρ and C are the density and specific heat of water,
respectively. Since the droplet experiences phase
change during the ice growth stage, the time Δt
required to complete that stage can be expressed as:

$$\Delta t_{\text{icegrowth}} = \frac{\rho_w \Delta H}{q}$$  \hspace{1cm} (15)

where ΔH is the enthalpy change of the droplet during
the ice growth stage, which accounts for both the sen-
sible and latent heat components. It can be observed
from Eqs. (14) and (15) that the freezing process can
be mainly delayed by reducing the rate of heat transfer from the droplet to the cold surface.

For a superhydrophobic surface to achieve freezing delay, it should be able to maintain a Cassie-Baxter wetting state throughout the entire droplet freezing process. At that state, the droplet is resting on top of the surface microstructures, and the spaces in-between these structures are filled with air, which is characterized by a low thermal conductivity. Moreover, the high $\theta_{CA}$ will result in a reduced contact area between the cold surface and water. Both of these effects will cause a reduction in the heat transfer rate from the water droplet leading to a freezing delay.

Multiple attempts have been reported to verify the ability of superhydrophobic surfaces to cause a freezing delay. Shen et al. (2015b) fabricated superhydrophobic surfaces by growing and fluorinating titanium oxide nanowires on top of microtextured titanium alloy surfaces and studied their anti-icing properties. They reported a freezing delay of up to $\sim$750 s mainly during the precooling stage. Li et al. (2018b) sprayed a nanocomposite coating prepared from polyurethane and silica nanoparticles on glass substrates. They compared the freezing time between plain and coated glass, as depicted in Fig. 27, and reported a freezing delay time of $\sim$40 min.

Moreover, Shen et al. (2019b) studied the icephobic performance of surfaces created by spraying nanocomposite coatings on aluminum substrates. The nanocomposite was prepared using PDMS and fluorinated silica nanoparticles, and it showed a freezing delay time of $\sim$276 s. It should be noted that the freezing delay times reported in the literature vary significantly for different substrate materials. This is attributed to the different thermal conductivity of those materials, which greatly impacts the heat transfer rate from the water droplet to the cold surface.

5.4 Adhesion strength of ice

The ability of hierarchically structured superhydrophobic surfaces to reduce the ice adhesion strength has been a debatable topic (Shen et al. 2019a; Kreder et al. 2016). Some researchers have reported that when water freezes while in a Wenzel wetting state, the ice adhesion strength is going to increase due to the mechanical interlocking that takes place between the surface roughness structures and ice (Nosonovsky and Hejazi 2012; Chen et al. 2012; Davis et al. 2014; Farhadi et al. 2011). However, if a Cassie-Baxter state is maintained throughout the entire freezing process, the ice adhesion strength will be significantly reduced. This reduction can be explained by the entrapped air voids that act as points of stress concentrations and reduce the contact area when a force is applied (Nosonovsky and Hejazi 2012; Hejazi et al. 2013). This stress concentration will be experienced in case of either tension or shear is applied, as depicted in Fig. 28.

Although ice adhesion strength is an important parameter for icephobic surfaces, there is no standard method to evaluate it. In fact, numerous measurement methods have been reported in the literature (Work and Lian 2018). These methods can be mainly classified into tensile and shear adhesion strength tests. However, each group of methods has been reported with multiple variations and test apparatus. Accordingly, more efforts are needed in order to achieve a standardization of ice adhesion strength testing methods.

Regardless of the measurement method, superhydrophobic surfaces have demonstrated a reduction in ice adhesion strength in numerous studies. Wang et al. (2013) prepared superhydrophobic surfaces by etching and fluorinating aluminum substrates and tested their tensile ice adhesion strength using

---

**Fig. 27** Freezing of water droplets on plain and coated glass substrates (Li et al. 2018b)
a tensile testing machine. Their results showed an ice adhesion strength of ~200 kPa after the water was frozen at −10 °C for 24 h. An in-house testing apparatus was used by Fu et al. (2014) to evaluate the shear ice adhesion strength for superhydrophobic surfaces created by sol–gel technique. Surfaces with different surface roughness were considered, and the results showed a reduction of ice adhesion strength down to ~75 kPa. Similar test methods with minor variations were used by other researchers (Shen et al. 2015b, 2019b; Emelyanenko et al. 2017; Wang et al. 2018; Wu et al. 2018; Wu and Chen 2018), and all the results confirmed the fact that textured superhydrophobic surfaces are capable of reducing the ice adhesion strength. A schematic of an ice adhesion shear strength testing apparatus is shown in Fig. 29.

In addition, other researchers studied the effect of the detailed surface topology and geometry of the hierarchical structures on the ice adhesion strength. It was found that the surface roughness only is inadequate to describe or predict the icephobic performance and different surface structure design might lead to significant variations in the ice adhesion strength (Wu et al. 2019). A well-textured surface structure with nanopillars of very small top diameter, regardless of their height, was also found to reduce the adhesion strength and maintain a Cassie-Baxter wetting state (Nguyen et al. 2018).

5.5 Drawbacks of hierarchical structures

The reliance of superhydrophobic surfaces on hierarchical structures to achieve icephobicity can sometimes lead to performance degradation. For instance, operating conditions that lead to penetration of water in-between the surface’s hierarchical structures, e.g., condensation of micro-droplets or supercooled airflow, will impose a Wenzel wetting state. When water freezes in that state, the surface will experience higher ice adhesion strength as a result of the mechanical interlocking that takes place between the surface’s hierarchical structures and the ice layer (Nosonovsky and Hejazi 2012; Chen et al. 2012; Davis et al. 2014; Farhadi et al. 2011). Moreover, under this condition, the removal of the ice layer will mechanically damage the surface’s hierarchical structures leading to performance deterioration after a series of icing/deicing cycles (Shen et al. 2019a). To overcome these challenges, alternative strategies were sought by researchers, as will be discussed in the following section.
5.6 Alternative passive strategies

Alternative passive strategies that do not rely on hierarchically structured superhydrophobic surfaces have also been reported in the literature. For example, anti-icing is considered as one of the main applications for SLIPS, and many attempts have verified their ability to provide an icephobic performance (Kim et al. 2012; Yang et al. 2015; Archer et al. 2020; Yin et al. 2015). However, the adoption of SLIPS in real-world applications remains to be challenged by multiple drawbacks, as mentioned previously. Anti-freezing proteins, which are capable of suppressing ice accretion by lowering the ice growth temperature, have also been utilized (Gwak et al. 2015; Liu et al. 2016). Nevertheless, multiple disadvantages of using these proteins still exist, including toxicity, high cost, and purification problems (Jamil et al. 2018; Gibson 2010).

Other strategies that can achieve ultra-low shear ice adhesion strength \( (\tau_{\text{ice}} < 1 \text{ kPa}) \) have also been receiving recent attention; e.g., low-interfacial toughness materials (Golovin et al. 2019) and organogels (Wang et al. 2015; Golovin et al. 2016). Although such strategies significantly facilitate ice removal after accreting on surfaces, they do not offer a comprehensive icephobic performance and target only one aspect of icephobicity. In fact, the entire problem of ice accretion can be eliminated in some situations (e.g., freezing rain) by simply repelling supercooled water droplets.

6 Biomedical applications of superhydrophobicity

As mentioned earlier, superhydrophobic surfaces can be utilized in numerous applications. However, their utilization in biomedical applications and combating viral transmission and bacterial infection has recently gained attention due to the recent pandemic. At the end of 2019, a devastating novel coronavirus, known as SARS-CoV-2, was discovered, and it rapidly developed into an outbreak of an infectious disease (COVID-19) (Yang and Wang 2020; Munster et al. 2020). Shortly after, the World Health Organization declared it as a global pandemic due to its contagious nature (WHO) (Yang and Wang 2020; Munster et al. 2020). Due to its disastrous effects on the wellbeing, life, and economy, researchers worldwide commenced enormous effort and time in order to discover a cure, develop a vaccine, or combat the virus transmission via novel engineering solutions.

The novel coronavirus can be transmitted either directly through airborne droplets, which are ejected due to coughing or sneezing, or indirectly through contact with contaminated surfaces (Yang and Wang 2020; Gralinski and Menachery 2020). The contamination might occur when the surfaces are exposed to respiratory droplets, saliva, nasal discharge, or blood from an infected person (Ong et al. 2020). The National Institute of Allergy and Infectious Diseases (USA) have demonstrated that the virus can contaminate surfaces with different materials for extended durations (from hours to days) (Doremalen et al. 2020), which may increase the virus transmission considerably among the public. In addition, previous studies have reported that infections among the health care workers (HCW) are common during donning or undressing due to the adhesion of contaminated body fluids to their personal protective equipment (PPE) (Katoh et al. 2019; Galante et al. 2020; Tanabe et al. 2020). This risk has been evidently demonstrated by the numerous COVID-19 cases reported among HCW despite the utilization of PPE (Bowdle and Munoz-Price 2020; Wang et al. 2019b).

Although superhydrophobicity is defined as water repellency, superhydrophobic surfaces have gained significant popularity in the biomedical field due to their ability to repel blood as well as reduce the bacterial or viral adhesion to surfaces (Shin et al. 2016; Falde et al. 2016; Jaggessar et al. 2017; Liu and Guo 2018). For instance, Tomšič et al. (Tomšič et al. 2008) coated cotton fibers with repellent coatings that are fabricated using a sol–gel technique and demonstrated its antibacterial properties. Yeerken et al. (Yeerken et al. 2019) also developed a superhydrophobic coating using polytetrafluoroethylene and silica nanoparticles that can be used for fabricating PPE with enhanced protection. In addition, Zhong et al. (Zhong et al. 2020) reported a laser-induced fabrication technique to deposit graphene layers onto surgical masks to help improve their protection against COVID-19. The coated masks demonstrated superhydrophobicity, as depicted in Fig. 30, and were reported to be reusable and recyclable.

Further combating of COVID-19 can involve the implementation of copper due to its antiviral and antibacterial properties. Copper surfaces were found
to provide antiviral characteristics against influenza A virus particles (Noyce et al. 2007), and the fastest to eradicate the activity of the novel coronavirus when compared to other surfaces, as shown in Fig. 31 (Doremalen et al. 2020). Moreover, copper-based nanoparticles were found to inactivate H1N1 influenza virus particles (Fujimori et al. 2009), eliminate other virus’ strands (Ravishankar Rai and a. Jamuna Bai, 2011; Shionoiri et al. 2012), and possess antibacterial properties (Suryaprabha and Sethuraman 2017; Anita et al. 2011; Agrawal et al. 2019). Meguid and Elzaabalawy (Meguid and Elzaabalawy 2020; Elzaabalawy and Meguid 2020b) proposed a three-step combating strategy that involves encapsulation, contamination suppression, and virus elimination, as schematically shown in Fig. 32. The encapsulation
and contamination suppression steps rely on the extreme repellency of superhydrophobic surfaces, while the elimination step rely on the antiviral characteristics of copper nanoparticles.

Although copper nanoparticles have already been incorporated into superhydrophobic coatings to obtain antibacterial properties (Suryaprabha and Sethuraman 2017; Berendjchi et al. 2011), further research is necessary to design and develop surfaces and coatings specifically for combatting COVID-19.

7 Conclusions and outlook

In view of their importance and potential use in numerous engineering applications, superhydrophobicity and icephobicity have recently garnered considerable interest from the community. This interest has led to considerable progress and advance in the development of surfaces that acquire these remarkable features. Despite this extensive effort, superhydrophobic and icephobic surfaces are not yet widely implemented in real world applications due to a number of challenges. These challenges include durability and scalability. In this review, we provided the fundamentals of surface wettability, including the different wetting states and wettability parameters. Although these theoretical formulations represent a necessary foundation for understanding wettability, they fail to explain more complex wetting phenomena. Numerical modeling attempts to simulate more complicated wettability events, such as droplet impact, evaporation, condensation, and contact angle hysteresis, should be explored to provide a better understanding of the governing parameters that effect surface wettability.

State-of-the-art nanofabrication techniques have led to numerous advances in the development of superhydrophobic surfaces. Recent attempts that make use of the most common techniques exist in the literature. Additionally, special attention should be given to nanocomposite superhydrophobic surfaces because of their potential to achieve scalability and ability to create superhydrophobic surfaces with regenerative capabilities. Future research in this field should also be directed to the development of multifunctional superhydrophobic surfaces that acquire additional features such electrical conductivity, thermal conductivity, or piezoelectric characteristics.

Moreover, different aspects of icephobicity were identified and their complete description was outlined. These included the ability of surfaces to repel supercooled water droplets, reduce nucleation temperature, delay freezing, and reduce the adhesion strength of ice. Focusing on the potential of superhydrophobic surfaces to exhibit anti-icing characteristics, the fundamentals and underlying mechanisms of the different icephobicity aspects were discussed. More studies are essential in order to better understand the impingement of supercooled droplets on subfreezing icephobic and superhydrophobic surfaces. This multiphysics-multiphase impingement that involve a number of highly coupled processes, including fluid dynamics, heat transfer, freezing of water,
substrate adhesion, and dynamic contact angle, plays a crucial role in achieving supercooled droplet repellency. Although different strategies can be adopted to prevent or suppress ice accretion, icephobic surfaces with hierarchical surface structure are believed to be the best alternative. Further efforts are needed to provide a better understanding of the characterization of wettability at subfreezing temperatures.

Finally, the review highlighted the use of superhydrophobic surfaces to combat pandemics and the strategies of developing repellent surfaces with antiviral and antibacterial properties. This is a very rich field with many challenges that require the joint collaboration of surface scientists, and epidemiologists.

Acknowledgements This work was supported by the Natural Sciences and Engineering Research Council (NSERC) of Canada (Grant number RGPIN-2018-03804).

Declarations

Conflict of interest The authors declare no competing financial interest.

References

Agrawal, N., Low, P.S., Tan, J.S.J., Fong, E.W.M., Lai, Y., Chen, Z.: Durable easy-cleaning and antibacterial cotton fabrics using fluorine-free silane coupling agents and CuO nanoparticles. Nano Mater. Sci. (2019). https://doi.org/10.1016/j.nanoms.2019.09.004

Alizadeh, A., Yamada, M., Li, R., Shang, W., Otta, S., Zhong, S., Ge, L., Dhinojwala, A., Conway, K.R., Bahadur, V., Vinciquerra, A.J., Stephens, B., Blohm, M.L.: Dynamics of ice nucleation on water repellent surfaces. Langmuir 28, 3180–3186 (2012). https://doi.org/10.1021/la2045256

Anita, S., Ramachandran, T., Rajendran, R., Koushik, C.V., Mahalakshmi, M.: A study of the antimicrobial property of encapsulated copper oxide nanoparticles on cotton fabric. Text. Res. J. 81, 1081–1088 (2011). https://doi.org/10.1177/0040517510397577

Archer, R.J., Becher-Nienhaus, B., Dunderdale, G.J., Hozumi, A.: Recent progress and future directions of multifunctional (super) wetting smooth/structured surfaces and coatings. Adv. Funct. Mater. 30, 1907772 (2020)

Asthana, A., Maitra, T., Büchel, R., Tiwari, M.K., Poulikakos, D.: Multifunctional superhydrophobic polymer/carbon nanocomposites: graphene, carbon nanotubes, or carbon black? ACS Appl. Mater. Interfaces. 6, 8859–8867 (2014). https://doi.org/10.1021/am501649w

Atta, A.M., Al-Lohedan, H.A., Ezzat, A.O., Al-Hussain, S.A.: Characterization of superhydrophobic epoxy coatings embedded by modified calcium carbonate nanoparticles. Prog. Org. Coat. 101, 577–586 (2016). https://doi.org/10.1016/j.porgcoat.2016.10.008

Attarzadeh, R., Dolatabadi, A.: Coalescence-induced jumping of micro-droplets on heterogeneous superhydrophobic surfaces. Phys. Fluids. 29, 012104 (2017). https://doi.org/10.1063/1.4973823

Aziz, H., Amrei, M.M., Dotivala, A., Tang, C., Tafreshi, H.V.: Modeling Cassie droplets on superhydrophobic coatings with orthogonal fibrous structures. Colloids Surfaces A Physicochem. Eng. Asp. 512, 61–70 (2017). https://doi.org/10.1016/j.colsurfa.2016.10.031

Bae, G.Y., Min, B.G., Jeong, Y.G., Lee, S.C., Jang, J.H., Koo, G.H.: Superhydrophobicity of cotton fabrics treated with silica nanoparticles and water-repellent agent. J. Colloid Interface Sci. 337, 170–175 (2009). https://doi.org/10.1016/j.jcis.2009.04.066

Balderli, A., Ou, J., Barona, D., Li, W., Amirfazli, A.: Sprayable, superhydrophobic, electrically, and thermally conductive coating. Adv. Mater. Interfaces. 8, 1–9 (2021). https://doi.org/10.1002/admi.201902110

Balram, A., Santhanagopalan, S., Hao, B., Yap, Y.K., Meng, D.D.: Electrophoretically-deposited metal-decorated CNT nanostructures with high thermal/electric conductivity and wettability tunable from hydrophilic to superhydrophobic. Adv. Funct. Mater. 26, 2571–2579 (2016)

Bayer, I.S.: Superhydrophobic coatings from ecofriendly materials and processes: a review. Adv. Mater. Interfaces 7, 1–25 (2020). https://doi.org/10.1002.admi.202000095

Bayer, I.S., Steele, A., Loth, E.: Superhydrophobic and electrically conductive carbon nanotube–fluorinated acrylic copolymer nanocomposites from emulsions. Chem. Eng. J. 221, 522–530 (2013a). https://doi.org/10.1016/j.cej.2013.01.023

Bayer, I.S., Brandi, F., Cingolani, R., Athanasiiou, A.: Modification of wetting properties of laser-textured surfaces by depositing triboelectrically charged Teflon particles. Colloid Polym. Sci. 291, 367–373 (2013b). https://doi.org/10.1007/s00396-012-2757-0

Bayer, I.S., Davis, A.J., Biswas, A.: Robust superhydrophobic surfaces from small diffusion flame treatment of hydrophobic polymers. RSC Adv. 4, 264–268 (2014). https://doi.org/10.1039/c3ra44169e

Bayer, I.S., Davis, A.J., Loth, E., Steele, A.: Water jet resistant superhydrophobic carbonaceous films by flame synthesis and tribocharging. Mater. Today Commun. 3, 57–68 (2015). https://doi.org/10.1016/j.mtcomm.2015.04.004

Berendjchi, A., Khajavi, R., Yazdanshenas, M.E.: Fabrication of superhydrophobic and antibacterial surface on cotton fabric by doped silica-based sols with nanoparticles of copper. Nanoscale Res. Lett. 6, 1–8 (2011). https://doi.org/10.1186/1556-276X-6-594

Bhushan, B.: Nanofabrication techniques used for superhydrophobic surfaces. In: Biomimetics, 3rd edn., pp. 109–119. Springer, Cham (2018)

Bhushan, B., Jung, Y.C.: Mechanically durable carbon nanotube–composite hierarchical structures with superhydrophobicity, self-cleaning, and low-drag. ACS Nano 3, 4155–4163 (2009). https://doi.org/10.1021/nn901509r

Bi, P., Li, H., Zhao, G., Ran, M., Cao, L., Guo, H., Xue, Y.: Robust super-hydrophobic coating prepared by
electrochemical surface engineering for corrosion protection. Coatings 9, 452 (2019)
Bico, J., Thiele, U., Quéré, D.: Wetting of textured surfaces. Colloids Surfaces A Physicochem. Eng. Asp. 206, 41–46 (2002). https://doi.org/10.1016/S0927-7757(02)00061-4
Binder, K., Horbach, J., Kob, W., Wolfgang, F., Fatollah, Y.: Molecular dynamics simulations. J. Phys. Condens. Matter. 16, S429–S53 (2004). https://doi.org/10.1088/0953-8984/16/5/006
Blake, J., Thompson, D., Raps, D., Strobl, T.: Simulating the freezing of supercooled water droplets impacting a cooled substrate. AIAA J. 53, 1725–1739 (2015). https://doi.org/10.2514/1.J053391
Bormashenko, E.: Progress in understanding wetting transitions on rough surfaces. Adv. Colloid Interface Sci. 222, 92–103 (2015). https://doi.org/10.1016/j.cis.2014.02.009
Bowdle, A., Munoz-Price, L.S.: Preventing infection of patients and healthcare workers should be the new normal in the era of novel coronavirus epidemics. Anesthesiology 132, 1292–1295 (2020). https://doi.org/10.1097/ALN.0000000000003295
Brackbill, J.U., Kothe, D.B., Zemach, C.: A continuum method for modeling surface tension. J. Comput. Phys. 100, 335–354 (1992). https://doi.org/10.1016/0021-9991(92)90240-Y
Brakke, K.A.: The surface evolver. Exp. Math. 1, 141–165 (1992). https://doi.org/10.1080/10586458.1992.10504253
Bravo, J., Zhai, L., Wu, Z., Cohen, R.E., Rubner, M.F.: Transparent superhydrophobic films based on silica nanoparticles. Langmuir 23, 7293–7298 (2007). https://doi.org/10.1021/la070519q
Cansoy, C.E., Erbil, H.Y., Akar, O., Akin, T.: Colloids and Surfaces a: Physicochemical and Engineering Aspects Effect of pattern size and geometry on the use of Cassie–Baxter equation for superhydrophobic surfaces. Colloids Surfaces A Physicochem. Eng. Asp. 386, 116–124 (2011). https://doi.org/10.1016/j.colsurfa.2011.07.005
Cao, Y., Wu, Z., Su, Y., Xu, Z.: Aircraft flight characteristics in icing conditions. Prog. Aerosp. Sci. 74, 62–80 (2015). https://doi.org/10.1016/j.paerosci.2014.12.001
Cassie, A.B.D., Baxter, S.: Wettability of porous surfaces. Trans. Faraday Soc. 40, 546–551 (1944)
Cebeci, T., Kafyeke, F.: Aircraft icing. Annu. Rev. Fluid Mech. 35, 11–21 (2003). https://doi.org/10.1146/annurev.fluid.35.101101.161217
Chatain, D., Lewis, D., Baland, J.P., Carter, W.C.: Numerical analysis of the shapes and energies of droplets on micropatterned substrates. Langmuir 22, 4237–4243 (2006). https://doi.org/10.1021/la605134q
Chavan, S., Cha, H., Orejon, D., Nawaz, K., Singla, N., Yeung, Y.F., Park, D., Kang, D.H., Chang, Y., Takata, Y., Miljkovic, N.: Heat Transfer through a Condensate Droplet on Hydrophobic and Nanostructured Superhydrophobic Surfaces. Langmuir 32, 7774–7787 (2016). https://doi.org/10.1021/acs.langmuir.6b01903
Chen, Y., He, B., Lee, J., Patankar, N.A.: Anisotropy in the wetting of rough surfaces. J. Colloid Interfaces Sci. 281, 458–464 (2005). https://doi.org/10.1016/j.jcis.2004.07.038
Chen, J., Liu, J., He, M., Li, K., Cui, D., Zhang, Q., Zeng, X., Zhang, Y., Wang, J., Song, Y.: Superhydrophobic surfaces cannot reduce ice adhesion. Appl. Phys. Lett. 101, 95–98 (2012). https://doi.org/10.1063/1.4752436
Chen, C., Li, R., Xu, L., Yan, D.: Three-dimensional superhydrophobic porous hybrid monoliths for effective removal of oil droplets from the surface of water. RSC Adv. 4, 17393–17400 (2014). https://doi.org/10.1039/c4ra0047a
Chen, C., Yang, S., Liu, L., Xie, H., Liu, H., Zhu, L., Xu, X.: A green one-step fabrication of superhydrophobic metallic surfaces of aluminum and zinc. J. Alloys Compd. 711, 506–513 (2017)
Chen, Q., Zhao, J., Ren, J., Rong, L., Cao, P., Avincula, R.C.: 3D printed multifunctional, hyperelastic silicone rubber foam. Adv. Funct. Mater. 29, 1900469 (2019)
Cho, W.K., Choi, I.S.: Fabrication of hairy polymeric films inspired by Geckos: wetting and high adhesion properties. Adv. Funct. Mater. 18, 1089–1096 (2008). https://doi.org/10.1002/adfm.200701454
Chruściel, J.J., Leśniak, E.: Modification of thermoplastics with reactive silanes and siloxanes. In: Thermoplast, pp. 155–192. InTech, London (2012)
Chruściel, J.J., Leśniak, E.: Modification of epoxy resins with functional silanes, polysiloxanes, silsesquioxanes, silica and silicates. Prog. Polym. Sci. 14, 67–121 (2015). https://doi.org/10.1016/j.progpolymsci.2014.08.001
Cui, Z., Yin, L., Wang, Q., Ding, J., Chen, Q.: A facile dip-coating process for preparing highly durable superhydrophobic surface with multi-scale structures on paint films. J. Colloid Interface Sci. 337, 531–537 (2009). https://doi.org/10.1016/j.jcis.2009.05.061
Dalili, N., Edrisy, A., CARRIVEAU, R.: A review of surface engineering issues critical to wind turbine performance. Renew. Sustain. Energy Rev. 13, 428–438 (2009). https://doi.org/10.1016/j.rser.2007.11.009
Das, A., Schutzius, T.M., Bayer, I.S., Megaridis, C.M.: Superoleophobic and conductive carbon nanofiber/fluoropolym composite films. Carbon 50, 1346–1354 (2012). https://doi.org/10.1016/j.carbon.2011.11.006
Davis, A., Yeong, Y.H., Steele, A., Bayer, I.S., Loth, E.: Superhydrophobic nanocomposite surface topography and ice adhesion. ACS Appl. Mater. Interfaces 6, 9272–9279 (2014). https://doi.org/10.1021/acsami.7b15088
Davis, A., Surdo, S., Caputo, G., Bayer, I.S., Athanassiou, A.: Environmentally benign production of stretchable and robust superhydrophobic silicone monoliths. ACS Appl. Mater. Interfaces 10, 2907–2917 (2018). https://doi.org/10.1021/acsami.7b15088
Deng, X., Mammen, L., Butt, H.J., Vollmer, D.: Candle soot as a template for a transparent robust superamphiphobic coating. Science 335, 67–70 (2012). https://doi.org/10.1126/science.1207115
Dorner, C., Rühe, J.: Contact line shape on ultrahydrophobic post surfaces. Langmuir 23, 3179–3183 (2007). https://doi.org/10.1021/la062596v
Dubov, A.L., Nizkaya, T.V., Asmolov, E.S., Vinogradova, O.I.: Boundary conditions at the gas sectors of superhydrophobic surfaces. Phys. Rev. Fluids. 3, 1–12 (2018). https://doi.org/10.1103/PhysRevFluids.3.014002
Advances in the development of superhydrophobic and icephobic surfaces

Goswami, A., Rahman, M.A.: Numerical study of energetics and wetting stability of liquid droplets on microtextured surfaces. Colloid Polym. Sci. 295, 1787–1796 (2017). https://doi.org/10.1007/s00396-017-4158-x

Gralinski, L.E., Menachery, V.D.: Return of the coronavirus: 2019-nCoV. Viruses 12, 1–8 (2020). https://doi.org/10.3390/v12020135

Guo, P., Zheng, Y., Wen, M., Song, C., Lin, Y., Jiang, L.: Icephobic/anti-icing properties of micro/nanostructured surfaces. Adv. Mater. 24, 2642–2648 (2012). https://doi.org/10.1002/adma.201104412

Gwak, Y., Park, J.I., Kim, M., Kim, H.S., Kwon, M.J., Oh, S.J., Kim, Y.P., Jin, E.: Creating anti-icing surfaces via the direct immobilization of antifreeze proteins on aluminum. Sci. Rep. 5, 1–9 (2015). https://doi.org/10.1038/srep12019

Han, J.T., Kim, B.K., Woo, J.S., Jang, J.I., Cho, J.Y., Jeong, H.J., Jeong, S.Y., Seo, S.H., Lee, G.W.: Bioinspired multifunctional superhydrophobic surfaces with carbon-nanotube-based conducting pastes by facile and scalable printing. ACS Appl. Mater. Interfaces. 9, 7780–7786 (2017). https://doi.org/10.1021/acsami.6b15292

Hao, J.H., Wang, Z.J.: Modeling Cassie-Baxter State on Superhydrophobic Surfaces. J. Dispers. Sci. Technol. 37, 1208–1213 (2016). https://doi.org/10.1080/01932691.2015.1089407

Hayase, G., Hasegawa, K., Hasegawa, G., Maeno, A., Kaji, H., Nakanishi, K.: A superamphiphobic macroporous silicon cone monolith with marshmallow-like flexibility. Angew. Chemie. 125, 10988–10991 (2013). https://doi.org/10.1002/ange.201304169

He, X., Luo, L.: Theory of the lattice Boltzmann method: from the Boltzmann equation to the lattice Boltzmann equation. Phys. Rev. E 56, 6811–6817 (1997). https://doi.org/10.1103/PhysRevE.56.6811

Hejazi, V., Sobolev, K., Nosonovsky, M.: From superhydrophobicity to icephobicity: Forces and interaction analysis. Sci. Rep. (2013). https://doi.org/10.1038/srep02194

Hirt, C.W., Nichols, B.D.: Volume of fluid (VOF) method for the dynamics of free boundaries. J. Comput. Phys. 39, 201–225 (1981). https://doi.org/10.1016/0021-9991(81)90145-5

Hirvi, J.T., Pakkanen, T.A.: Nanodroplet impact and sliding on structured polymer surfaces. Surf. Sci. 602, 1810–1818 (2008). https://doi.org/10.1016/j.susc.2008.03.020

Hsu, C.P., Chang, L.Y., Chiu, C.W., Lee, P.T.C., Lin, J.J.: Facile fabrication of robust superhydrophobic epoxy film with polyanime dispersed carbon nanotubes. ACS Appl. Mater. Interfaces. 5, 538–545 (2013). https://doi.org/10.1021/am400132p

Hu, Y., Zhu, Y., Wang, H., Wang, C., Li, H., Zhang, X., Yuan, R., Zhao, Y.: Facile preparation of superhydrophobic metal foam for durable and high efficient continuous oil-water separation. Chem. Eng. J. 322, 157–166 (2017a). https://doi.org/10.1016/j.cej.2017.04.034

Hu, X., Tang, C., He, Z., Shao, H., Xu, K., Mei, J., Lau, W.M.: Highly stretchable superhydrophobic composite coating based on self-adaptive deformation of hierarchical structures. Small 13, 1–10 (2017b). https://doi.org/10.1002/smll.201602353

Hu, D., Ma, W., Zhang, Z., Ding, Y., Wu, L.: Dual bio-inspired design of highly thermally conductive and superhydrophobic nanocellulose composite films. ACS Appl. Mater. Interfaces. (2020). https://doi.org/10.1021/acsami.0c01425

Huang, L., Lau, S.P., Yang, H.Y., Leong, E.S.P., Yu, S.F., Prawer, S.: Stable superhydrophobic surface via carbon nanotubes coated with a ZnO thin film. J. Phys. Chem. B. 109, 7746–7748 (2005). https://doi.org/10.1021/jp046549s

Huang, J.J., Shu, C., Chew, T.Y.: Lattice Boltzmann study of droplet motion inside a grooved channel. Phys. Fluids. 21, 022103 (2019). https://doi.org/10.1063/1.3077800

Im, M., Im, H., Lee, J.H., Yoon, J.B., Choi, Y.K.: A robust superhydrophobic and superoleophobic surface with inverse-trapezoidal microstructures on a large transparent flexible substrate. Soft Matter 6, 1401–1404 (2010). https://doi.org/10.1039/b925970h

Ishino, C., Okumura, K.: Wetting transitions on textured hydrophilic surfaces. Eur. Phys. J. E 25, 415–424 (2008). https://doi.org/10.1140/epje/i2007-10308-y

Ishizaki, T., Hieda, J., Saito, N., Saito, N., Takai, O.: Corrosion resistance and chemical stability of super-hydrophobic film deposited on magnesium alloy AZ31 by microwave plasma-enhanced chemical vapor deposition. Electrochim. Acta. 55, 7094–7101 (2010). https://doi.org/10.1016/j.electacta.2010.06.064

Jaggersass, A., Shahahi, H., Mathew, A., Yarlagadda, P.K.D.V.: Bio-mimicking nano and micro-structured surface fabrication for antibacterial properties in medical implants. J. Nanobiotechnology. 15, 1–20 (2017). https://doi.org/10.1186/s12951-017-0306-1

Jamil, M.I., Ali, A., Haq, F., Zhang, Q., Zhan, X., Chen, F.: Icephobic strategies and materials with superwettability: design principles and mechanism. Langmuir 34, 15425–15444 (2018). https://doi.org/10.1021/acs.langmuir.8b03276

Jeevahan, J., Chandrasekaran, M., Britto Joseph, G., Durairaj, R.B., Mageshwaran, G.: Superhydrophobic surfaces: a review on fundamentals, applications, and challenges. J. Coatings Technol. Res. 15, 231–250 (2018). https://doi.org/10.1007/s11998-017-0011-x

Ji, H., Chen, G., Hu, J., Wang, M., Min, C., Zhao, Y.: Biomimetic superhydrophobic surfaces. J. Dispers. Sci. Technol. 34, 1–21 (2013). https://doi.org/10.1080/01932691.2011.646625

Jia, S., Lu, X., Luo, S., Qing, Y., Yan, N., Wu, Y.: Efficiently textures hierarchical epoxy layer for smart superhydrophobic surfaces with excellent durability and exceptional stability exposed to fire. Chem. Eng. J. 348, 212–223 (2018). https://doi.org/10.1016/j.cej.2018.04.195

Jiang, T., Guo, Z., Liu, W.: Biomimetic superoleophobic surfaces: focusing on their fabrication and applications. J. Mater. Chem. A 3, 1811–1827 (2015). https://doi.org/10.1039/C4TA05582A

Johnson, R.E., Dettre, R.H.: Contact angle hysteresis. III. Study of an idealized heterogeneous surface. J. Phys. Chem. 68, 1744–1750 (1964). https://doi.org/10.1021/j100789a012

Ju, J., Yao, X., Hou, X., Liu, Q., Zhang, Y.S., Khademhosseini, A.: A highly stretchable and robust non-fluorinated
superhydrophobic surface. J. Mater. Chem. a. 5, 16273–16280 (2017). https://doi.org/10.1039/c6ta11133e

Jung, Y.C., Bhushan, B.: Wetting transition of water droplets on superhydrophobic patterned surfaces. Scr. Mater. 57, 1057–1060 (2007). https://doi.org/10.1016/j.scriptamat.2007.09.004

Jung, S., Tiwari, M.K., Doan, N.V., Poulikakos, D.: Mechanism of supercooled droplet freezing on surfaces. Nat. Commun (2012). https://doi.org/10.1038/ncomms1630

Kalikmanov, V.I.: Classical nucleation theory. In: Nucleation Theory, pp. 17–41. Springer, Dordrecht (2013)

Karapetsas, G., Chamakos, N.T., Papatheasis, A.G.: Efficient modelling of droplet dynamics on complex surfaces. J. Phys. Condens. Matter. 28, 085101 (2016). https://doi.org/10.1088/0953-8984/28/8/085101

Katoh, I., Tanabe, F., Kasai, H., Morishii, K., Shimasaki, N., Shinohara, K., Uchida, Y., Koshiba, T., Arakawa, S., Morimoto, M.: Potential risk of virus carryover by fabrics of personal protective gowns. Front. Public Health. 7, 3–8 (2019). https://doi.org/10.3389/fpubh.2019.00121

Khan, S., Singh, J.K.: Wetting transition of nanodroplets of water on textured surfaces: a molecular dynamics study. Mol. Simul. 40, 458–468 (2014). https://doi.org/10.1080/08927022.2013.819578

Khatir, Z., Kubiat, K.J., Jmack, P.K., Mathia, T.G.: Dropwise condensation heat transfer process optimisation on superhydrophobic surfaces using a multi-disciplinary approach. Appl. Therm. Eng. 106, 1337–1344 (2016). https://doi.org/10.1016/j.applthermaleng.2016.06.128

Kim, P., Wong, T.S., Alvarenga, J., Kreder, M.J., Adorno-Martinez, W.E., Aizenberg, J.: Liquid-infused nanostructured surfaces with extreme anti-ice and anti-frost performance. ACS Nano 6, 6569–6577 (2012). https://doi.org/10.1021/nm302310q

Kim, M.H., Kim, H., Lee, K.S., Kim, D.R.: Frosting characteristics on hydrophobic and superhydrophobic surfaces: A review. Energy Convers. Manag. 138, 1–11 (2017). https://doi.org/10.1016/j.enconman.2017.01.067

Koishi, T., Yasuoka, K., Fujikawa, S., Ebisuzaki, T., Xiao, C.Z.: Coexistence and transition between Cassie and Wenzel state on pillared hydrophobic surface. Proc. Natl. Acad. Sci. USA 106, 8435–8440 (2009). https://doi.org/10.1073/pnas.0902027106

Kousalya, A.S., Singh, K.P., Fisher, T.S.: Heterogeneous wetting surfaces with graphic petal-decorated carbon nanotubes for enhanced flow boiling. Int. J. Heat Mass Transf. 87, 380–389 (2015). https://doi.org/10.1016/j.ijheatmasstransfer.2015.04.029

Kreder, M.J., Alvarenga, J., Kim, P., Aizenberg, J.: Design of anti-icing surfaces: smooth, textured or slippery? Nat. Rev. Mater. (2016). https://doi.org/10.1038/natrevmats.2015.3

Kusumaatmaja, H., Blow, M.L., Dupuis, A., Yeamans, J.M.: The collapse transition on superhydrophobic surfaces. Euro Phys. Lett. 81, 36003 (2008). https://doi.org/10.1209/0295-5075/81/36003

Lafort, J.L., Allaire, M.A., Laflamme, J.: State-of-the-art on power line de-icing. Atmos. Res. 46, 143–158 (1998). https://doi.org/10.1016/S0169-8095(97)00057-4

Lamraoui, F., Fortin, G., Benoit, R., Perron, J., Masson, C.: Atmospheric icing impact on wind turbine production. Cold Reg. Sci. Technol. 100, 36–49 (2014). https://doi.org/10.1016/j.coldregions.2013.12.008

Lattke, S.S., Sutar, R., Shinde, T., Pawar, S., Khot, T., Bho-sale, A., Sadasivuni, K.K., Xing, R., Mao, L., Liu, S.: Superhydrophobic leaf mesh decorated with SiO2 nanoparticle-polystyrene nanocomposite for oil-water separation. ACS Appl. Nano Mater. 2, 799–805 (2019). https://doi.org/10.1021/acsnano.8b02021

Lau, K.K.S., Bico, J., Teo, K.B.K., Chhowalla, M., Amaratunga, G.A.J., Milne, W.I., McKinley, G.H., Gleason, K.K.: Superhydrophobic carbon nanotube forests. Nano Lett. 3, 1701–1705 (2003). https://doi.org/10.1021/nl034704t

Li, Q., Guo, Z.: Fundamentals of icing and common strategies for designing biomimetic anti-icing surfaces. J. Mater. Chem. a. 6, 13549–13581 (2018). https://doi.org/10.1039/c8ta03259a

Li, Y., Dai, S., John, J., Carter, K.R.: Superhydrophobic surfaces from hierarchically structured wrinkled polymers. ACS Appl. Mater. Interfaces. 5, 11066–11073 (2013a). https://doi.org/10.1021/am403209r

Li, K., Zeng, X., Li, H., Lai, X., Ye, C., Xie, H.: Study on the wetting behavior and theoretical models of polydimethylsiloxane/silica coating. Appl. Surf. Sci. 279, 458–463 (2013b). https://doi.org/10.1016/j.apsusc.2013.04.137

Li, L., Bai, Y., Li, L., Wang, S., Zhang, T.: A superhydrophobic smart coating for flexible and wearable sensing electronics. Adv. Mater. 29, 1–8 (2017a). https://doi.org/10.1002/adma.201702517

Li, C., Gao, X., Li, Z.: Roles of surface energy and temperature in heterogeneous ice nucleation. J. Phys. Chem. c. 121, 11552–11559 (2017b). https://doi.org/10.1021/acs.jpccl.7b02848

Li, Z., Wang, B., Qin, X., Wang, Y., Liu, C., Shao, Q., Wang, N., Zhang, J., Wang, Z., Shen, C., Guo, Z.: Superhydrophobic/superoleophilic polycarbonate/carbon nanotubes porous monolith for selective oil adsorption from water. ACS Sustain. Chem. Eng. 6, 13747–13755 (2018a). https://doi.org/10.1021/acs.suschemeng.8b01637

Li, Y., Li, B., Zhao, X., Tian, N., Zhang, J.: Totally waterborne, nonfluorinated, mechanically robust, and self-healing superhydrophobic coatings for actual anti-icing. ACS Appl. Mater. Interfaces. 10, 39391–39399 (2018b). https://doi.org/10.1021/acsami.8b15061

Li, J., Ueda, E., Paulissen, D., Levkin, P.A.: Slippery lubricant-infused surfaces: properties and emerging applications. Adv. Funct. Mater. 29, 1802317 (2019)

Liang, C., Li, B., Wang, H., Li, B., Yang, J., Zhou, L., Li, H., Wang, X., Li, C.: Preparation of hydrophobic and oleophilic surface of 316 L Stainless steel by femtosecond laser irradiation in water. J. Dispers. Sci. Technol. 35, 1345–1350 (2014). https://doi.org/10.1080/01932691.2013.838900

Liu, S., Guo, W.: Anti-biofouling and healable materials: preparation, mechanisms, and biomedical applications. Adv. Funct. Mater. 28, 1800596 (2018)

Liu, H., Kang, Y.: Superhydrophobic and superoleophilic modified EPDM foam rubber fabricated by a facile approach for oil/water separation. Adv. Surf. Sci. 451, 223–231 (2018). https://doi.org/10.1016/j.jpsusc.2018.04.179
Advances in the development of superhydrophobic and icephobic surfaces

Liu, S., Liu, X., Latthe, S.S., Gao, L., An, S., Yoon, S.S., Liu, B., Xing, R.: Self-cleaning transparent superhydrophobic coatings through simple sol-gel processing of fluoroalkylsilane. Appl. Surf. Sci. 351, 897–903 (2015). https://doi.org/10.1016/j.apsusc.2015.06.016

Liu, K., Wang, C., Ma, J., Shi, G., Yao, X., Fang, H., Song, Y., Wang, J.: Janus effect of antifreeze proteins on ice nucleation. Proc. Natl. Acad. Sci. USA 113, 14739–14744 (2016). https://doi.org/10.1073/pnas.1614379114

Liu, M., Wang, S., Jiang, L.: Nature-inspired superwettability systems. Nat. Rev. Mater. (2017). https://doi.org/10.1038/s41578-017-0036

Lu, M.C., Lin, C.C., Lo, C.W., Huang, C.W., Wang, C.C.: Superhydrophobic Si nanowires for enhanced condensation heat transfer. Int. J. Heat Mass Transf. 111, 614–623 (2017). https://doi.org/10.1016/j.ijheatmasstransfer.2017.04.021

Mai, Y.-W., Yu, Z.-Z.: Polymer Nanocomposites. WOOD-HEAD PUBLISHING, Cambridge (2006)

Marín, A.G., Enríquez, O.R., Brunet, P., Colinet, P., Snoeijer, J.H.: Universality of tip singularity formation in freezing water drops. Phys. Rev. Lett. 113, 1–5 (2014). https://doi.org/10.1103/PhysRevLett.113.054301

Martin, S., Bhushan, B.: Transparent, wear-resistant, superhydrophobic and superoleophobic poly(dimethylsiloxane) (PDMS) surfaces. J. Colloid Interface Sci. 488, 118–126 (2017). https://doi.org/10.1016/j.jcis.2016.10.094

Martines, E., Seunarine, K., Morgan, H., Gadegaard, N., Wilkinson, C.D.W., Richle, M.O.: Superhydrophobicity and superhydrophilicity of regular nanopatterns. Nano Lett. 5, 2097–2103 (2005). https://doi.org/10.1021/nl051435t

Mates, J.E., Bayer, I.S., Palumbo, J.M., Carroll, P.J., Megaridis, C.M.: Extremely stretchable and conductive water-repellent coatings for low-cost ultra-flexible electronics. Nat. Commun. 6, 1–8 (2015). https://doi.org/10.1038/ncomms9874

Meguid, S.A., Elzaabalawy, A.: Potential of combating transmission of COVID-19 using novel self-cleaning superhydrophobic surfaces: part I—protection strategies against fomites. Int. J. Mech. Mater. Des. (2020). https://doi.org/10.1007/s10999-020-09513-x

Metya, A.K., Singh, J.K., Müller-Plathe, F.: Ice nucleation on nanotextured surfaces: the influence of surface fractal dimension, pillar height and wetting states. Phys. Chem. Chem. Phys. 18, 26796–26806 (2016). https://doi.org/10.1039/c6cp04382h

Milionis, A., Loth, E., Bayer, I.S.: Recent advances in the mechanical durability of superhydrophobic materials. Adv. Colloid Interface Sci. 229, 57–79 (2016). https://doi.org/10.1016/j.cis.2015.12.007

Mishchenko, L., Hatton, B., Bahadur, V., Taylor, J.A., Krupenkin, T., Aizenberg, J.: Design of ice-free nanostructured surfaces based on repulsion of impacting water droplets. ACS Nano 4, 7699–7707 (2010). https://doi.org/10.1021/nn102557p

Moghadam, A., Jamali, M., Venkateshan, D.G., Vahedi Tafreshi, H., Pourdeyhimi, B.: A new approach to modeling liquid intrusion in hydrophobic fibrous membranes with heterogeneous wettabilities. Colloids Surfaces A Physicochem. Eng. Asp. 558, 154–163 (2018). https://doi.org/10.1016/j.colsurfa.2018.08.051

Mokarian, Z., Rasuli, R., Abedini, Y.: Facile synthesis of stable superhydrophobic nanocomposite based on multi-walled carbon nanotubes. Appl. Surf. Sci. 369, 567–575 (2016). https://doi.org/10.1016/j.apsusc.2016.02.031

Momen, G., Jafari, R., Farzaneh, M.: Ice repellency behaviour of superhydrophobic surfaces: Effects of atmospheric icing conditions and surface roughness. Appl. Surf. Sci. 349, 211–218 (2015). https://doi.org/10.1016/j.apsusc.2015.04.180

Moore, E.B., Molinero, V.: Structural transformation in supercooled water controls the crystallization rate of ice. Nature 479, 506–508 (2011). https://doi.org/10.1038/nature10586

Mortazavi, A., Khonsari, M.M.: On the degradation of superhydrophobic surfaces: a review. Wear 372–373, 145–157 (2017). https://doi.org/10.1016/j.wear.2016.11.009

Munster, V.J., Koopmans, M., van Doremalen, N., van Riel, D., de Wit, E.: A novel coronavirus emerging in China—key questions for impact assessment. N. Engl. J. Med. 382, 692–694 (2020). https://doi.org/10.1056/NEJMp2000929

Muthiah, P., Bhushan, B., Yun, K., Kondo, H.: Dual-layered-coated mechanically-durable superomniphobic surfaces with anti-smudge properties. J. Colloid Interface Sci. 409, 227–236 (2018). https://doi.org/10.1016/j.jcis.2013.07.032

Naeçsu, I.A., Nicoară, A.I., Vasile, O.R., Vasile, B Ş.: Inorganic micro- and nanostructured implants for tissue engineering. In: Nanobiomaterials Hard Tissue Engineering, pp. 271–295. Elsevier, New York (2016)

Nguyen, T.B., Park, S., Lim, H.: Effects of morphology parameters on anti-icing performance in superhydrophobic surfaces. Appl. Surf. Sci. 435, 585–591 (2018). https://doi.org/10.1016/j.apsusc.2017.11.137

Niemietz, A., Wandelt, K., Barthlott, W., Koch, K.: Thermal evaporation of multi-component waxes and thermally activated formation of nanotubules for superhydrophobic surfaces. Prog. Org. Coatings. 66, 221–227 (2009)

Nosonovsky, M., Hejazi, V.: Why superhydrophobic surfaces are not always icedephic. ACS Nano 6, 8488–8491 (2012). https://doi.org/10.1021/nn302138r

Noyce, J.O., Michels, H., Kevil, C.W.: Inactivation of influenza A virus on copper versus stainless steel surfaces. Appl. Environ. Microbiol. 73, 2748–2750 (2007). https://doi.org/10.1128/AEM.01139-06

Oberli, L., Caruso, D., Hall, C., Fabretto, M., Murphy, P.J., Evans, D.: Condensation and freezing of droplets on superhydrophobic surfaces. Adv. Colloid Interface Sci. 210, 47–57 (2014). https://doi.org/10.1016/j.cis.2013.10.018

Ong, S.W.X., Tan, Y.K., Chia, P.Y., Lee, T.H., Ng, O.T., Wong, M.S.Y., Marimuthu, K.: Air, surface environmental, and personal protective equipment contamination by severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from a SYMPTOMATIC Patient. JAMA J. Am. Med. Assoc. 323, 1610–1612 (2020). https://doi.org/10.1001/jama.2020.3227

Park, C.I., Jeong, H.E., Lee, S.H., Cho, H.S., Suh, K.Y.: Wetting transition and optimal design for microstructured surfaces with hydrophobic and hydrophilic materials. J.
Colloid Interface Sci. 336, 298–303 (2009). https://doi.org/10.1016/j.cis.2009.04.022

Park, Y.B., Im, M., Im, H., Choi, Y.K.: Superhydrophobic cylindrical nanoshell array. Langmuir 26, 7661–7664 (2010). https://doi.org/10.1021/la100911s

Patankar, N.A.: Transition between superhydrophobic states on rough surfaces. Langmuir 20, 7097–7102 (2004). https://doi.org/10.1021/la049329e

Peng, C., Chen, Z., Tiwari, M.K.: All-organic superhydrophobic coatings with mechemochemical robustness and liquid impalement resistance. Nat. Mater. 17, 355–360 (2018). https://doi.org/10.1038/s41563-018-0044-2

Peng, W., Gou, X., Qin, H., Zhao, M., Zhao, X., Guo, Z.: Robust Mg(OH)2/epoxy resin superhydrophobic coating applied to composite insulators. Appl. Surf. Sci. 466, 126–132 (2019). https://doi.org/10.1016/j.apsusc.2018.10.039

Prabhala, B.R., Panchagnula, M.V., Vedantam, S.: Three-dimensional equilibrium shapes of drops on hysteretic surfaces. Colloid Polym. Sci. 291, 279–289 (2013). https://doi.org/10.1007/s00396-012-2774-z

Promraksa, A., Chen, L.J.: Modeling contact angle hysteresis of a liquid droplet sitting on a cosine wave-like pattern surface. J. Colloid Interface Sci. 384, 172–181 (2012). https://doi.org/10.1016/j.jcis.2012.06.064

Qing, Y., Long, C., An, K., Hu, C., Liu, C.: Sandpaper as template for a robust superhydrophobic surface with self-cleaning and anti-snow/icing performances. J. Colloid Interface Sci. 548, 224–232 (2019). https://doi.org/10.1016/j.jcis.2019.04.040

Quan, Y., Zhang, L.Z.: Numerical and analytical study of the impinging and bouncing phenomena of droplets on superhydrophobic surfaces with microtextured structures. Langmuir 30, 11640–11649 (2014). https://doi.org/10.1021/la502836p

Ravishankar Rai, V., Jamuna Bai, A.: Nanoparticles and their potential application as antimicrobials. Formatex 2011, 197–209 (2011)

Ruan, M., Li, W., Wang, B., Deng, B., Ma, F., Yu, Z.: Preparation and anti-icing behavior of superhydrophobic surfaces on aluminum alloy substrates. Langmuir 29, 8482–8491 (2013). https://doi.org/10.1021/la400979d

Rykczeewski, K., Anand, S., Subramanyam, S.B., Varanasi, K.K.: Mechanism of frost formation on lubricant-impregnated surfaces. Langmuir 29, 5230–5238 (2013). https://doi.org/10.1021/la040801s

Sato, O., Kubo, S., Zhong-Ze, G.U.: Structural color films with lotus effects, superhydrophilicity, and tunable stopbands. Acc. Chem. Res. 42, 1–10 (2009). https://doi.org/10.1021/ar700197v

Savoy, E.S., Escobedo, F.A.: Molecular simulations of wetting of a rough surface by an oily fluid: effect of topology, chemistry, and droplet size on wetting transition rates. Langmuir 28, 3412–3419 (2012). https://doi.org/10.1021/la203921h

Schäffel, D., Koynov, K., Vollmer, D., Butt, H.J., Schönecker, C.: Local flow field and slip length of superhydrophobic surfaces. Phys. Rev. Lett. 116, 1–5 (2016). https://doi.org/10.1103/PhysRevLett.116.134501

Shahraz, A., Borhan, A., Fichthorn, K.A.: Wetting on physically patterned solid surfaces: the relevance of molecular dynamics simulations to macroscopic systems. Langmuir 29, 11632–11639 (2013). https://doi.org/10.1021/la4023618

Sheen, Y.C., Chang, W.H., Chen, W.C., Chang, Y.H., Huang, Y.C., Chang, F.C.: Non-fluorinated superamphiphobic surfaces through sol-gel processing of methyltriethoxysilane and tetraethoxysilane. Mater. Chem. Phys. 114, 63–68 (2009). https://doi.org/10.1016/j.matchemphys.2008.07.132

Shen, L., Ding, H., Cao, Q., Jia, W., Wang, W., Guo, Q.: Fabrication of Ketjen black-high density polyethylene superhydrophobic conductive surfaces. Carbons 50, 4284–4290 (2012). https://doi.org/10.1016/j.carbon.2012.05.018

Shen, Y., Tao, J., Tao, H., Chen, S., Pan, L., Wang, T.: Superhydrophobic Ti6Al4V surfaces with regular array patterns for anti-icing applications. RSC Adv. 5, 32813–32818 (2015a). https://doi.org/10.1039/c5ra03165h

Shen, Y., Tao, H., Chen, S., Zhu, L., Wang, T., Tao, J.: Icephobic/anti-icing potential of superhydrophobic Ti6Al4V surfaces with hierarchical textures. RSC Adv. 5, 1666–1672 (2015b). https://doi.org/10.1039/c4ra2150c

Shen, Y., Wu, X., Tao, J., Zhu, C., Lai, Y., Chen, Z.: Icephobic materials: fundamentals, performance evaluation, and applications. Prog. Mater. Sci. 103, 509–557 (2019a). https://doi.org/10.1016/j.pmatsci.2019.03.004

Shen, Y., Wu, Y., Tao, J., Zhu, C., Chen, H., Wu, Z., Xie, Y.: Spraying fabrication of durable and transparent coatings for anti-icing application: dynamic water repellency, icing delay, and ice adhesion. ACS Appl. Mater. Interfaces. 11, 3590–3598 (2019b). https://doi.org/10.1021/acsami.8b19225

Shin, S., Seo, J., Han, H., Kang, S., Kim, H., Lee, T.: Bio-inspired extreme wetting surfaces for biomedical applications. Materials 9, 116 (2016). https://doi.org/10.3390/ma9021116

Shinani, C., Liang, D., Mengjie, S., Mengyao, L.: Numerical investigation on impingement dynamics and freezing performance of micrometer-sized water droplet on dry flat surface in supercooled environment. Int. J. Multiph. Flow. 118, 150–164 (2019). https://doi.org/10.1016/j.ijmultiphaseflow.2019.06.011

Shionoiri, N., Sato, T., Fujimori, Y., Nakayama, T., Nemoto, M., Matsunaga, T., Tanaka, T.: Investigation of the antiviral properties of copper iodide nanoparticles against feline calicivirus. J. Biosci. Bioeng. 113, 580–586 (2012). https://doi.org/10.1016/j.jbiosci.2011.12.006

Shirtcliffe, N.J., McHale, G., Atherton, S., Newton, M.I.: An introduction to superhydrophobicity. Adv. Colloid Interface Sci. 161, 124–138 (2010). https://doi.org/10.1016/j.cis.2009.11.001

Šikalo, Š, Marengo, M., Tropea, C., Ganić, E.N.: Analysis of droplet impaction and anti-icing behavior of superhydrophobic surfaces with microtextured structures. Langmuir 29, 11632–11639 (2013). https://doi.org/10.1021/la4023618

Sojoudi, H., Wang, M., Boscher, N.D., McKinley, G.H., Gleason, K.K.: Durable and scalable icephobic surfaces: similarities and distinctions from superhydrophobic surfaces. Soft Matter 12, 1938–1963 (2016). https://doi.org/10.1039/c5sm02295a
Song, J., Li, Y., Xu, W., Liu, H., Lu, Y.: Inexpensive and Non-Fluorinated Superhydrophobic Concrete Coating for Anti-Icing and Anti-Corrosion. J. Colloid Interface Sci. 541, 86–92 (2019). https://doi.org/10.1016/j.jcis.2019.01.014

Su, X., Li, H., Lai, X., Chen, Z., Zeng, X.: Highly stretchable and conductive superhydrophobic coating for flexible electronics. ACS Appl. Mater. Interfaces. 10, 10587–10597 (2018). https://doi.org/10.1021/acsami.8b01382

Su, X., Li, H., Lai, X., Chen, Z., Zeng, X.: 3D porous superhydrophobic CNT/EVA composites for recoverable shape reconfiguration and underwater vibration detection. Adv. Funct. Mater. 29, 1900554 (2019)

Subramanyam, S.B., Rykaczewski, K., Varanasi, K.K.: Ice adhesion on lubricant-impregnated textured surfaces. Langmuir 29, 13414–13418 (2013). https://doi.org/10.1021/la402456c

Sun, M., Kong, W., Wang, F., Liu, H.: Impact freezing modes of supercooled droplets determined by both nucleation and icing evolution. Int. J. Heat Mass Transf. 142, 118431 (2019). https://doi.org/10.1016/j.ijheatmasstransfer.2019.07.081

Suryaprabha, T., Sethuraman, M.G.: Fabrication of copper-based superhydrophobic self-cleaning antibacterial coating over cotton fabric. Cellulose 24, 395–407 (2017). https://doi.org/10.1007/s10570-016-1110-z

Tanabe, F., Uchida, Y., Arakawa, S., Morimoto, M.: Increased adhesion of methicillin-resistant Staphylococcus aureus to the surface of personal protective clothing damaged by friction during nursing action. Am. J. Infect. Control. 48, 416–419 (2020). https://doi.org/10.1016/j.ajic.2019.08.028

Teisala, H., Butt, H.J.: Hierarchical structures for superhydrophobic and superoleophobic surfaces. Langmuir (2018). https://doi.org/10.1021/acs.langmuir.8b03086

Tembely, M., Attarzadeh, R., Dolatabadi, A.: On the numerical modeling of supercooled micro-droplet impact and freezing on superhydrophobic surfaces. Int. J. Heat Mass Transf. 127, 193–202 (2018). https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.104

Tomšič, B., Simončič, B., Orel, B., Černe, L., Tavčer, P.F., Tembely, M., Atta, S., Doughty, J.: Ice and icephobic properties of a superhydrophobic surface with anticorrosion properties fabricated by solventless CVD methods. ACS Appl. Mater. Interfaces 9, 1057–1065 (2016). https://doi.org/10.1021/acsami.6b01219

Vrancken, R.J., Kusumastmaja, H., Hermans, K., Prenen, A.M., Pierre-Louis, O., Bastiaansen, C.W.M., Broer, D.J.: Fully reversible transition from wenzel to cassie-baxter states on corrugated superhydrophobic surfaces. Langmuir 26, 3335–3341 (2010). https://doi.org/10.1021/la903091s

Wang, Y., Xue, J., Wang, Q., Chen, Q., Ding, J.: Verification of icephobic/anti-icing properties of a superhydrophobic surface. ACS Appl. Mater. Interfaces 5, 3370–3381 (2013). https://doi.org/10.1021/am400429q

Wang, Y., Shi, Y., Pan, L., Yang, M., Peng, L., Zong, S., Shi, Y., Yu, G.: Multifunctional superhydrophobic surfaces templated from innately microstructured hydrogel matrix. Nano Lett. 14, 4803–4809 (2014). https://doi.org/10.1021/nl5019782

Wang, Y., Yao, X., Chen, J., He, Z., Liu, J., Li, Q., Wang, J., Jiang, L.: Organogel as durable anti-icing coatings. Sci. China Mater. 58, 559–565 (2015). https://doi.org/10.1007/s40843-015-0069-7

Wang, J., Kato, K., Blois, A.P., Wong, T.S.: Bioinspired omniphobic coatings with a thermal self-repair function on industrial materials. ACS Appl. Mater. Interfaces 8, 8265–8271 (2016). https://doi.org/10.1021/acsami.6b00194

Wang, N., Tang, L., Tong, W., Xiong, D.: Fabrication of robust and scalable superhydrophobic surfaces and investigation of their anti-icing properties. Mater. Des. 156, 320–328 (2018). https://doi.org/10.1016/j.matdes.2018.06.053

Wang, L., Kong, W., Wang, F., Liu, H.: Effect of nucleation time on freezing morphology and type of a water droplet impacting onto cold substrate. Int. J. Heat Mass Transf. 130, 831–842 (2019a). https://doi.org/10.1016/j.ijheatmasstransfer.2018.10.142

Wang, J., Zhou, M., Liu, F.: Reasons for healthcare workers becoming infected with novel coronavirus disease 2019 (COVID-19) in China. J. Hosp. Infect. 105, 100–101 (2020). https://doi.org/10.1016/j.jhin.2020.03.002

Wenzel, R.N.: Resistance of solid surfaces to wetting by water. Ind. Eng. Chem. 28, 988–994 (1936). https://doi.org/10.1021/ie05320a024

Wenzel, R.N.: Surface roughness and contact angle. J. Phys. Colloid Chem. 53, 1466–1467 (1949). https://doi.org/10.1010/j150474a015

Whale, T.F., Rosillo-Lopez, M., Murray, B.J., Salzmann, C.G.: Ice Nucleation properties of oxidized carbon nanomaterials. J. Phys. Chem. Lett. 6, 3012–3016 (2015). https://doi.org/10.1021/acs.jpclett.5b01096

Wong, T.S., Bang, S.H., Tang, S.K.Y., Smythe, E.D., Hatton, B.D., Grinthal, A., Aizenberg, J.: Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity. Nature 477, 443–447 (2011). https://doi.org/10.1038/nature10447

Work, A., Lian, Y.: A critical review of the measurement of ice adhesion to solid substrates. Prog. Aerosp. Sci. 98, 1–26 (2018). https://doi.org/10.1016/j.paerosci.2018.03.001
Wu, X., Chen, Z.: A mechanically robust transparent coating for anti-icing and self-cleaning applications. J. Mater. Chem. a. 6, 16043–16052 (2018). https://doi.org/10.1039/c8ta05692g

Wu, M., An, N., Li, Y., Sun, J.: Layer-by-layer assembly of fluorine-free polyelectrolyte-surfactant complexes for the fabrication of self-healing superhydrophobic films. Langmuir 32, 12361–12369 (2016a). https://doi.org/10.1021/acs.langmuir.6b02607

Wu, X., Fu, Q., Kumar, D., Ho, J.W.C., Kanhere, P., Zhou, H., Chen, Z.: Mechanically robust superhydrophobic and superoleophobic coatings derived by sol-gel method. Mater. Des. 89, 1302–1309 (2016b). https://doi.org/10.1016/j.matdes.2015.10.053

Wu, Y., Jia, S., Wang, S., Qing, Y., Yan, N., Wang, Q., Meng, T.: A facile and novel emulsion for efficient and convenient fabrication of durable superhydrophobic materials. Chem. Eng. J. 328, 186–196 (2017). https://doi.org/10.1016/jecej.v.2017.07.023

Wu, X., Zheng, S., Bellido-Aguilar, D.A., Silberschmidt, V.V., Chen, Z.: Transparent icephobic coatings using bio-based epoxy resin. Mater. Des. 140, 516–523 (2018). https://doi.org/10.1016/j.matdes.2017.12.017

Wu, X., Silberschmidt, V.V., Hu, Z.T., Chen, Z.: When superhydrophobic coatings are icephobic: role of surface topology. Surf. Coatings Technol. 358, 207–214 (2019). https://doi.org/10.1016/j.surfcoat.2018.11.039

Xiu, Y., Xiao, F., Hess, D.W., Wong, C.P.: Superhydrophobic optically transparent silica films formed with a eutectic liquid. Thin Solid Films 517, 1610–1615 (2009). https://doi.org/10.1016/j.tsf.2008.09.081

Xu, Q., Zhang, W., Dong, C., Sreeprasad, T.S., Xia, Z.: Bimimetic self-cleaning surfaces: synthesis, mechanism and applications. J. R. Soc. Interfaces. 13, 20160300 (2016). https://doi.org/10.1098/rsif.2016.0300

Xue, C.H., Ma, J.Z.: Long-lived superhydrophobic surfaces. J. Mater. Chem. A 1, 4146–4161 (2013). https://doi.org/10.1039/c2ta01073a

Yan, Y.Y., Gao, N., Barthlott, W.: Mimicking natural superhydrophobic surfaces and grasping the wetting process: A review on recent progress in preparing superhydrophobic surfaces. Adv. Colloid Interface Sci. 169, 80–105 (2011). https://doi.org/10.1016/j.cis.2011.08.005

Yang, P., Wang, X.: COVID-19: a new challenge for human beings. Cell. Mol. Immunol. 17, 555–557 (2020). https://doi.org/10.1038/s41423-020-0407-x

Yang, S., Qiu, R., Song, H., Wang, P., Shi, Z., Wang, Y.: Slippery liquid-infused porous surface based on perfluorinated lubricant/iron tetradecanoate: preparation and corrosion protection application. Appl. Surf. Sci. 328, 491–500 (2015). https://doi.org/10.1016/j.apsusc.2014.12.067

Yang, X., Song, J., Liu, J., Liu, X., Jin, Z.: A twice electrochemical-etching method to fabricate superhydrophobic-superhydrophilic patterns for biomimetic fog harvest. Sci. Rep. 7, 1–12 (2017). https://doi.org/10.1038/s41598-017-09108-1

Yang, C., Wu, L., Li, G.: Magnetically responsive superhydrophobic surface: in situ reversible switching of water droplet wettability and adhesion for droplet manipulation. ACS Appl. Mater. Interfaces. 10, 20150–20158 (2018). https://doi.org/10.1021/acsami.8b04190

Yao, Y., Li, C., Zhang, H., Yang, R.: Modelling the impact, spreading and freezing of a water droplet on horizontal and inclined superhydrophobic cooled surfaces. Appl. Surf. Sci. 419, 52–62 (2017). https://doi.org/10.1016/j.apsusc.2017.04.085

Yarin, A.L.: Drop impact dynamics: splashing, spreading, receding, bouncing. Annu. Rev. Fluid Mech. 38, 159–192 (2006). https://doi.org/10.1146/annurev.fluid.38.050304.092144

Yeerken, T., Wang, G., Li, H., Liu, H., Yu, W.: Chemical stable, superhydrophobic and self-cleaning fabrics prepared by two-step coating of a polytetrafluoroethylene membrane and silica nanoparticles. Text. Res. J. 89, 4827–4841 (2019). https://doi.org/10.1177/0040517918792795

Yıldırım Erbil, H., Elif Cansoy, C.: Range of applicability of the wenzel and cassie-baxter equations for superhydrophobic surfaces. Langmuir 25, 14135–14145 (2009). https://doi.org/10.1021/la902098a

Yin, X., Zhang, Y., Wang, D., Liu, Z., Liu, Y., Pei, X., Yu, B., Zhou, F.: Integration of self-lubrication and near-infrared photothermogenesis for excellent anti-icing/deicing performance. Adv. Funct. Mater. 25, 4237–4245 (2015)

Young, T.: An essay on the cohesion of fluids. Philos. Trans. 95, 65–80 (1805). https://doi.org/10.1098/rstl.1805.0005

Yuan, Z., Chen, H., Tang, J., Gong, H., Liu, Y., Wang, Z., Shi, P., Zhang, J., Chen, X.: A novel preparation of polystyrene film with a superhydrophobic surface using a template method. J. Phys. D. Appl. Phys. 40, 3485–3489 (2007). https://doi.org/10.1088/0022-3727/40/11/033

Zahid, M., Mazzoon, G., Athanasissiou, A., Bayer, I.S.: Environmentally benign non-wettable textile treatments: a review of recent state-of-the-art. Adv. Colloid Interface Sci. 270, 216–250 (2019). https://doi.org/10.1016/j.cis.2019.06.001

Zhan, X., Yan, Y., Zhang, Q., Chen, F.: A novel superhydrophobic hybrid nanocomposite material prepared by surface-initiated AGET ATRP and its anti-icing properties. J. Mater. Chem. A 2, 9390–9399 (2014). https://doi.org/10.1039/c4ta00634h

Zhang, J., Kwok, D.Y.: Contact line and contact angle dynamics in superhydrophobic channels. Langmuir 22, 4998–5004 (2006). https://doi.org/10.1021/la053375c

Zhang, P., Lv, F.Y.: A review of the recent advances in superhydrophobic surfaces and the emerging energy-related applications. Energy 82, 1068–1087 (2015). https://doi.org/10.1016/j.energy.2015.01.061

Zhang, R., Farokhirad, S., Lee, T., Koplik, J.: Multiscale liquid drop impact on wettable and textured surfaces. Phys. Fluids. 26, 082003 (2014). https://doi.org/10.1063/1.4892083

Zhang, Z.-X., Yang, R., Ye, M., Boonkerd, K., Zhang, Z.-X., Li, Y., Ye, M., Boonkerd, K., Vollmer, D., Kim, J.K., Deng, X.: Fabrication of superhydrophobic surface by a laminating exfoliation method. J. Mater. Chem. A 2, 1268–1271 (2014b)

Zhang, S., Ouyang, X., Li, J., Gao, S., Han, S., Liu, L., Wei, H.: Underwater drag-reducing effect of superhydrophobic submarine model. Langmuir 31, 587–593 (2015). https://doi.org/10.1021/la504451k
Zhang, B., Lei, Q., Wang, Z., Zhang, X.: Droplets can rebound toward both directions on textured surfaces with a wettability gradient. Langmuir 32, 346–351 (2016a). https://doi.org/10.1021/acs.langmuir.5b04365

Zhang, X., Zhu, W., He, G., Zhang, P., Zhang, Z., Parkin, I.P.: Flexible and mechanically robust superhydrophobic silicone surfaces with stable Cassie-Baxter state. J. Mater. Chem. A 4, 14180–14186 (2016b). https://doi.org/10.1039/c6ta06493k

Zhang, Y., Anim-Danso, E., Bekele, S., Dhinojwala, A.: Effect of surface energy on freezing temperature of water. ACS Appl. Mater. Interfaces. 8, 17583–17590 (2016c). https://doi.org/10.1021/acsami.6b02094

Zhang, S., Huang, J., Cheng, Y., Yang, H., Chen, Z., Lai, Y.: Bioinspired surfaces with superwettability for anti-icing and ice-phobic application: concept, mechanism, and design. Small 13, 1–20 (2017a). https://doi.org/10.1002/smll.201701867

Zhang, L., Xue, C.H., Cao, M., Zhang, M.M., Li, M., Ma, J.Z.: Highly transparent fluorine-free superhydrophobic silica nanotube coatings. Chem. Eng. J. 320, 244–252 (2017b). https://doi.org/10.1016/j.cej.2017.03.048

Zhang, X., Si, Y., Mo, J., Guo, Z.: Robust micro-nanoscale flowerlike ZnO/epoxy resin superhydrophobic coating with rapid healing ability. Chem. Eng. J. 313, 1152–1159 (2017c). https://doi.org/10.1016/j.cej.2016.11.014

Zhang, X., Wu, X., Min, J.: Freezing and melting of a sessile water droplet on a horizontal cold plate. Exp. Therm. Fluid Sci. 88, 1–7 (2017d). https://doi.org/10.1016/j.expthermflusci.2017.05.009

Zhang, X., Wu, X., Min, J., Liu, X.: Modelling of sessile water droplet shape evolution during freezing with consideration of supercooling effect. Appl. Therm. Eng. 125, 644–651 (2017e). https://doi.org/10.1016/j.applthermaleng.2017.07.017

Zhang, Z.H., Wang, H.J., Liang, Y.H., Li, X.J., Ren, L.Q., Cui, Z.Q., Luo, C.: One-step fabrication of robust superhydrophobic and superoleophobic surfaces with self-cleaning and oil/water separation function. Sci. Rep. 8, 1–12 (2018a). https://doi.org/10.1038/s41598-018-22241-9

Zhang, J., Zhang, W., Lu, J., Zhu, C., Lin, W., Feng, J.: Aqueous epoxy-based superhydrophobic coatings: fabrication and stability in water. Prog. Org. Coatings. 121, 201–208 (2018b). https://doi.org/10.1016/j.porgcoat.2018.04.012

Zhang, F., Qian, H., Wang, L., Wang, Z., Du, C., Li, X., Zhang, D.: Superhydrophobic carbon nanotubes/epoxy nanocomposite coating by facile one-step spraying. Surf. Coatings Technol. 341, 15–23 (2018c). https://doi.org/10.1016/j.surfcoat.2018.01.045

Zhang, R., Hao, P., Zhang, X., He, F.: Supercooled water droplet impact on superhydrophobic surfaces with various roughness and temperature. Int. J. Heat Mass Transf. 122, 395–402 (2018d). https://doi.org/10.1016/j.ijheatmasstransfer.2018.01.076

Zhang, Y., Yin, M.-J., Ouyang, X., Zhang, A.P., Tam, H.-Y.: 3D μ-printing of polytetrafluoroethylene microstructures: a route to superhydrophobic surfaces and devices. Appl. Mater. Today. 19, 100580 (2020a)

Zhang, X., Liu, X., Wu, X., Min, J.: Impacting-freezing dynamics of a supercooled water droplet on a cold surface: Rebound and adhesion. Int. J. Heat Mass Transf. 158, 119997 (2020b). https://doi.org/10.1016/j.ijheatmasstransfer.2020.119997

Zhao, Y., Tong, T., Delzeitz, L., Kashani, A., Meyyappan, M., Majumdar, A.: Interfacial energy and strength of multi-walled-carbon-nanotube-based dry adhesive. J. Vacuum Sci. Technol. B Microelectron. Nanomot. Struct. Process. Measure. Phenom. 24, 331–335 (2006). https://doi.org/10.1116/1.2163891

Zhao, H., Law, K.Y., Sambhy, V.: Fabrication, surface properties, and origin of superoleophobicity for a model textured surface. Langmuir 27, 5927–5935 (2011). https://doi.org/10.1021/la104872q

Zhao, H., Park, K.-C., Law, K.-Y.: Effect of surface texturing on superoleophobicity, contact angle hysteresis, and “robustness.” Langmuir 28, 14925–14934 (2012). https://doi.org/10.1021/la302765t

Zheng, L., Li, Z., Bourdo, S., Kedir, K.R., Asar, M.P., Ryerson, C.C., Biris, A.S.: Exceptional superhydrophobicity and low velocity impact icephobicity of acetone-functionalized carbon nanotube films. Langmuir 27, 9936–9943 (2011). https://doi.org/10.1021/la101548K

Zheng, S., Li, C., Fu, Q., Hu, W., Xiang, T., Wang, Q., Du, M., Liu, X., Chen, Z.: Development of stable superhydrophobic coatings on aluminum surface for corrosion-resistant, self-cleaning, and anti-icing applications. Mater. Des. 93, 261–270 (2016). https://doi.org/10.1016/j.matdes.2015.12.155

Zhong, M., Zhang, Y., Li, X., Wu, X.: Facile fabrication of durable superhydrophobic silica/epoxy resin coatings with compatible transparency and stability. Surf. Coat. Technol. 347, 191–198 (2018). https://doi.org/10.1016/j.surfcoat.2018.04.063

Zhong, H., Zhu, Z., Lin, J., Cheung, C.F., Lu, V.L., Yan, F., Chan, C.-Y., Li, G.: Reusable and recyclable graphene masks with outstanding superhydrophobic and photothermal performances. ACS Nano (2020). https://doi.org/10.1021/acsnano.0c02250

Zhu, L., Xiu, Y., Xu, J., Tamirisra, P.A., Hess, D.W., Wong, C.P.: Superhydrophobicity on two-tier rough surfaces fabricated by controlled growth of aligned carbon nanotube arrays coated with fluorocarbon. Langmuir 21, 11208–11212 (2005). https://doi.org/10.1021/la0514104

Zu, Y.Q., Yan, Y.Y.: Single droplet on micro square-post patterned surfaces-theoretical model and numerical simulation. Sci. Rep. 6, 1–12 (2016). https://doi.org/10.1038/srep19281

Zu, Y.Q., Yan, Y.Y., Li, J.Q., Han, Z.W.: Wetting behaviours of a single droplet on biomimetic micro structured surfaces. J. Bionic Eng. 7, 191–198 (2010). https://doi.org/10.1016/S1672-6529(09)60202-X

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.