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Natural and biomimetic superhydrophobic surface: Review of the manufacturing techniques

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Abstract: Nature has produced many materials, things, and processes at all scales, from the large to the tiny. The newly growing area of biomimicry enables the development of materials, tools, and techniques with desired features by mimicking biology or nature. Consequently, the traits of animals, plants, and insects in nature have drawn much attention. Because of its surface roughness and epicuticular waxes, the lotus leaf, for instance, has a superhydrophobic surface. These surfaces feature a water-repellent effect and high and low-contact angle hysteresis. This essay briefly introduces the theoretical wetting process before describing some of the traits of several naturally occurring species. Next, a thorough analysis of artificial superhydrophobic surfaces made in the last five years utilizing the most popular fabrication methods is provided.

Keywords: Superhydrophobic surface, fabrication, durability issue

1. Introduction

Have you ever noticed that lotus leaves never get wet from water droplets? The answer to this phenomenon is superhydrophobicity (of the surface). There are a bunch of examples of superhydrophobic characters that exist in nature, which contain plants (rice leaves), animals (Sharkskin), and insects (Butterflies' wings and water-walking insects). The term "superhydrophobic" is well-known in today's society. The history of the superhydrophobic surface may be traced back to the period when Young's equation was discovered. However, there is further development, including Wenzel State and Casie-Baxter State, the Lotus Effect, and various techniques. Recently, more and more attention has been paid to manufacturing and applying bioinspired superhydrophobic surfaces. Over two decades have published over 50,000 papers about superhydrophobic posted. Mostly, they review the manufacture of biomimetic superhydrophobic surfaces such as molding, plasma treatment, sol-gel, etc. Also, increasingly advanced techniques that could produce superhydrophobic characteristics have been published in the last five years, which makes it easier to apply to various substrates, including cotton, glass, metal, and plastic. As a result, the superhydrophobic surface has a wide range of applications, such as energy conversion and conservation, ship manufacture, building construction, etc. However, some things still need to be fixed, blocking further development and application. Herein, we will start with fundamental wettability theories, such as surface tension and hysteresis. Moreover, we are reviewing some natural superhydrophobic surfaces' properties and surface chemistry. Finally, we are also trying to check the most common bioinspired superhydrophobic surface techniques from the last five years papers on bioinspired superhydrophobic surfaces, and their limitations are discussed.

1.1. Definitions
Molecules augment the energy of the surface tension of a liquid or solid because they bind to fewer molecules than those in bulk. Molecules have an attractive force that sticks together and attracts each other, called cohesion. For example, in a magnified view of the water's surface, the molecules are not surrounded by any other similar molecules above the surface. The surface of the water is therefore pulled in all directions by the cohesive forces between all the water molecules. The surface molecules, therefore, have more force pulling them towards the water molecules below and to the sides. In contrast, water molecules below the surface are subject to pulling troops from all directions. Therefore, surface tension is the cohesive force between molecules acting on the surface area.

The interaction with the same phases is called cohesive; however, with different stages called adhesive. Young's contact angle is formed by the plane of contact and the tangent to the liquid. Several variables, including the roughness of the solid's surface energy, might influence the contact angle [1-3]. Suppose the contact angle is $0° < \Theta < 90°$ when water wetting the surface; that surface is hydrophilic. At this stage, the feeling is just partially wet. The value of contact angle $\Theta > 90°$is hydrophobic the material would not be wetted. Superhydrophobic surfaces have a contact angle $\Theta > 150°$, whereas super hydrophilic surfaces have an angle of less than 5°[4] (Figure 1).

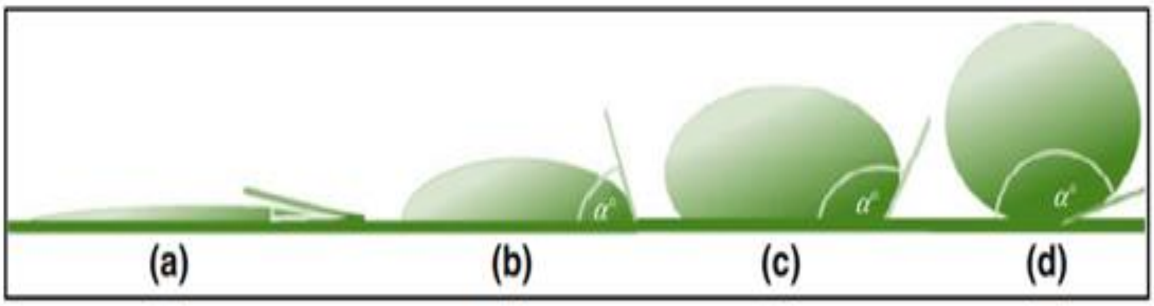

Figure 1. (a) Superhydrophilicity ($\Theta < 5°$), (b) hydrophilicity ($0° < \Theta < 90°$), (c) hydrophobicity ($\Theta > 90°$), and (d) superhydrophobicity 5 ($\Theta > 150°$)

Here there is an effect closely related to superhydrophobicity, known as the lotus leaf effect. In fluid flow, a typical superhydrophobic surface is inherently non-stick and shows a very low contact angle hysteresis. On such a surface, water droplets will slide off with minimal resistance [5]. This impact is usually advantageous to self-cleaning, as the water droplets travel downwards, and the droplets will always rake into contaminants. The contact angle in the front is called the advancing angle, while the angle in the back is called the receding angle. The angle of advancement is larger than the angle of retreat. The difference between the two angles shows the contact angle's hysteresis. Many factors influence the backward angle, for example, wetting roughness, chemical heterogeneity, and condensation near water droplets. Therefore, superhydrophobicity depends on the low and high contact angle hysteresis (Figure 2).

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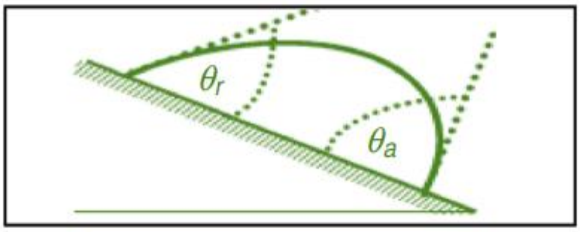

Figure 2. Advancing and receding contact angle [6]

1.1.1 The Wenzel model and the Cassie-Baxter model.

If the size of the droplet is smaller than the capillary length, the droplet is deemed less significant. For tiny droplets, ignoring gravity and surface tension dominates. Three interfaces exist when a tiny droplet is introduced onto an ideal horizontal solid surface. They are the Cassie-Baxter model, young's model, and Wenzel model, respectively. Furthermore, it contains three interfaces: vapor–solid, liquid–vapor, and solid-liquid. Therefore, are three interfacial surface tensions. In surface wettability studies, the most common ones are Cassie-Baxter and Wenzel states. In Figure 3, Wenzel anticipates the connection between contact angle and surface, which have different results for rough and smooth surfaces. However, airbags exist. Wenzel predicts the relationship between the contact angle and character, which have other effects on rough and smooth surfaces. Cassie and Baxter revealed that the model includes a gaseous phase between coarse solids to form a combination of solid-gas-liquid instead of only solid-liquid (Figure 3).

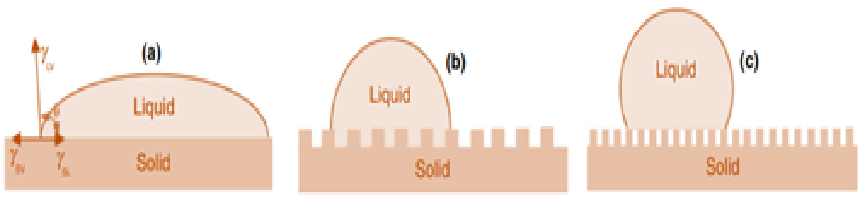

Figure 3. (a) Young's Model, (b) Wenzel Model, and (c) Cassie–Baxter Model

1.2 Contact angle definition

Surface atoms or molecules of liquids or solids have fewer chemical connections to neighboring atoms and, as a result, possess more incredible energy than equivalent atoms or molecules within. The surface tension or free surface energy γ reveals this extra energy. Surface tension is traditionally measured as a force per unit length and expressed in N m^{-1} or energy per unit area J m^{-2}. It equals the amount of work necessary to generate one square unit of a surface at constant pressure and temperature.

Equation 1:

$$W_{SL} = \gamma_{SA} + \gamma_{LA} - \gamma_{SL} \tag{1}$$

The WSLis adhesive per unit area and γSA and γSLare the surface energies of the solid against air and liquid, and γLA is the surface energy of fluid against air [1, 2].

When a liquid droplet lands on a plate and the liquid and solid surfaces combine, the total energy is Equation 2:

$$E_t = \gamma_{LA}(A_{LA} + A_{SL}) - W_{SL}A_{SL} \tag{2}$$

When they come to equilibrium, the angle is called the static contact angleθ0.ASL and ALA are the contact areas between solid and air. The first assumption is that the droplet density is smaller than the capillary length. The volume and pressure of the second are constant. For gravitational potential energy to be disregarded and volumetric energy to remain stable. So, at the equilibrium dEt = 0,

Equation 3:

$$\gamma_{LA}(dA_{LA} + dA_{SL}) - W_{SL}\, dA_{SL} = 0 \tag{3}$$

For a droplet with a constant volume,

Equation 4:

$$dA_{LA} \;/\; dA_{SL} = cos\ cos\ \theta_0$$

The young equation for finding the contact angle combines all 3 equations 2,4,5.

Equation5:

$$cos\ cos\ \theta_0\ = \frac{\gamma_{SA} - \gamma_{SL}}{\gamma_{LA}} \tag{4}$$

1.3 Wenzel and Cassie-Baxter equations

The majority of solid surfaces are rough. The Wenzel state defines the link between roughness and contact angle.

Equation6:

$$roughness = \frac{real\ surface\ area}{project\ surface\ area} \tag{5}$$

Because Young's equation only applies to absolutely smooth surfaces. Thereby, the roughness of a perfectly smooth surface is 1 [7].

When a liquid is in touch with a rough surface in a homogenous manner. Wenzel explains that increasing surface roughness improves the wettability produced by surface chemistry.

The Wenzel equation:

Equation7:

$$cos\ cos\ \theta\ = r\ cos\ cos\ \theta_0 \tag{6}$$

Θ is the contact angle between a liquid droplet and a rough solid surface. Θ_0 for the homogenous interface (Figure 4).

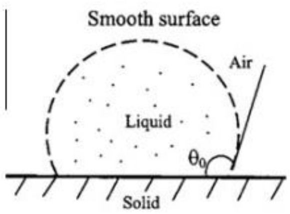

Figure 4. A diagram of a liquid droplet contacting a smooth solid surface (contact angle, Θ_0).

Figure 5 illustrates the contact angle and the surface roughness factory (Figure 5).

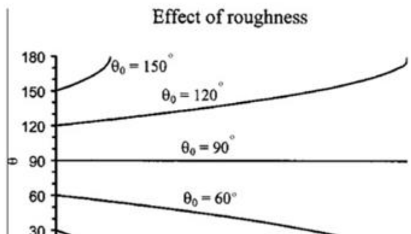

Figure 5. Contact angle for rough surface (Θ) as a function of the roughness factor (r) for various contact angles of the smooth surface (Θ_0)

For Wenzel, when $\Theta_0 < 90°$ the surface becomes more hydrophilic with an increase of roughness, and $\Theta_0 > 90°$the surface becomes more hydrophobic with an increase of roughness (Figure 6).

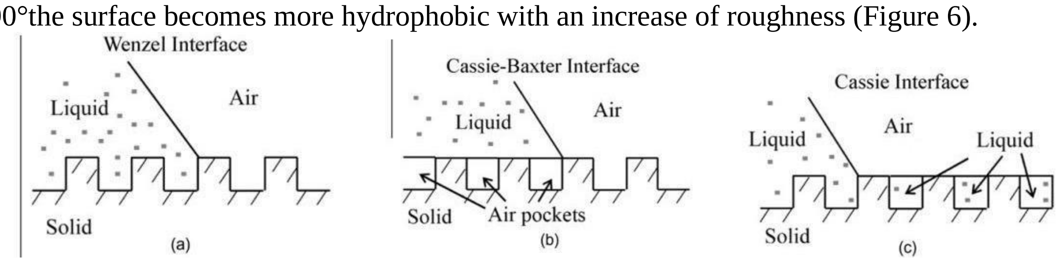

Figure 6. Figures are shown by (a) the homogeneous interface in the Wenzel equation, (b) the

composite interface with air pockets for Cassie–Baxter equation, and (c) the homogeneous interface in the Cassie equation [8].

On the other hand, the contact angle between heterogeneous interfaces, for the surface, there are two fractions. f_1 is the solid fraction, and f_2 is the fraction of the air. Also $f_1 + f_2 = 1$.
Cassie equation [9]:
Equation8：

$$cos\, cos\, \theta \ = f_1\, cos\, cos\, \theta_1 \ + f_2\, cos\, cos\, \theta_2 \tag{7}$$

When $f_1 = f_{SL}$ and $\theta_1 = 0$, for figure 7 (c) the surface consists of the solid-liquid fraction. When $f_2 = 1 - f_{SL}$, $cos\, cos\, \theta_2 = -1$the surface consists of the liquid-air fraction.
Cassie-Baxter equation[9]：
Equation9：

$$cos\, cos\, \theta \ = rf_{SL}\, cos\, cos\, \theta \ + f_{SL} - 1 \tag{8}$$

Here is a particular state when f_{SL} is close to 1 that will become the Wenzel model.

2. Superhydrophobic surface in nature

2.1 Rice leaf
There is another plant that has similar properties as the lotus leaf, which is the rice leaf. The rice leaf has many similar properties to the lotus leaf, which grows in humid and mushy environments. So that they have self-cleaning properties that they can clean dirty; for example, wet soil would remain on the leaves, which can influence their photosynthesis and absorb nutrition from the air [10]. So, the rice leaf surface images were taken with a large-scale SEM image. Papillae are arranged regularly and parallel to each other, and their spacing is similar so that water droplets will slide from a greater distance [11] (Figure 7).

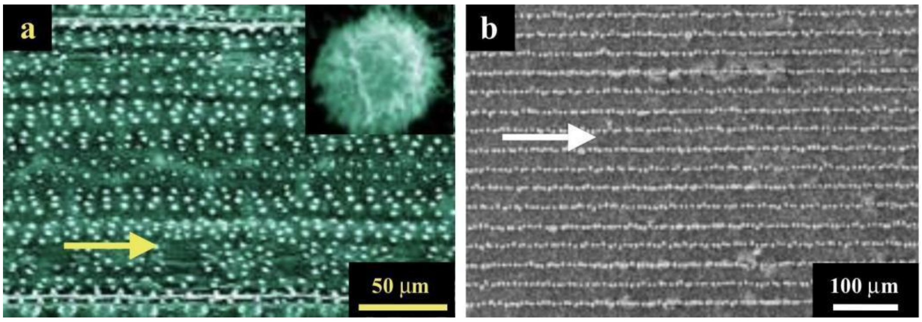

Figure 7. SEM images of rice leaf [11]

2.2 Sharkskin
Shark skin is superhydrophobic with drag reduction and anti-fouling. These SEM images show that the sharks' skin is rough and irregular. The sharks' scale has a groove shape, which reduces the area of water contact with sharks to reduce the resistance of water to sharks so that sharks can move faster [12]. Moreover, this groove shape can also reduce the attachment of sea life to sharks because sharkskin is rough, and Balanus is difficult to adhere to, keeping the sharkskin clean (Figure 8).

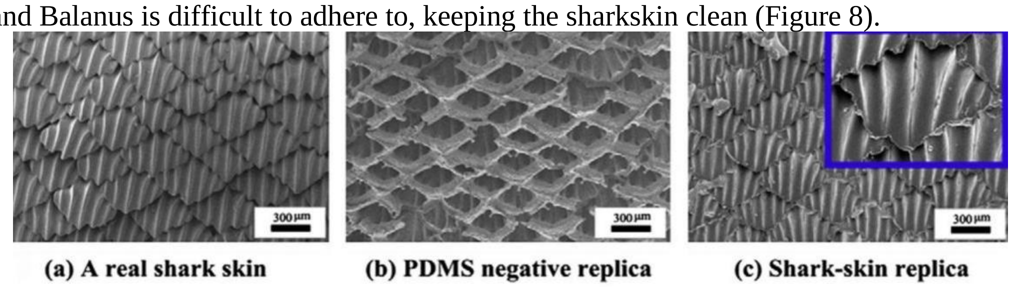

Figure 8. SEM images of shark skin [12]

2.3 Butterflies' wing

Since butterflies are fragile and unable to clean their wings, the hydrophobicity of insect wings is beneficial to reduce dust particles and improve insects' flying ability. According to related studies, their wings are covered in wax, which is hydrophobic. Looking at a butterfly's wings at the microscopic level, it is evident that the scales of the wings are aligned in one direction and overlap each other. Anisotropy is a word when water droplets condense on a butterfly's wing. The droplets travel in one order and not closer to the main body, protecting the safety of the butterfly's flight ability and skill [13] (Figure 9).

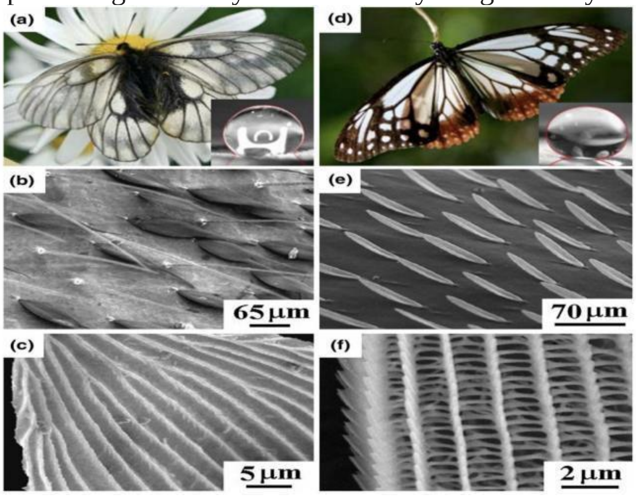

Figure 9. SEM images of butterflies' wings [13]

2.4 Water-walking insect

Many insects can glide across the water, such as water striders. In addition, arthropods that walk on water are governed by surface tension, which makes insects buoyant [14-16]. Their legs, which are 30 mm long at the surface and about 1 mm in diameter at the base of their legs, help them walk on water, but they will sink if placed on the water with low surface tension, such as oil. Furthermore, these hairs are also made up of wax. So, these crucial conditions allow the insects' legs and the water surface to form a Cassie-Baxter state, with low adhesion and a high volume of air bubbles (Figure 10).

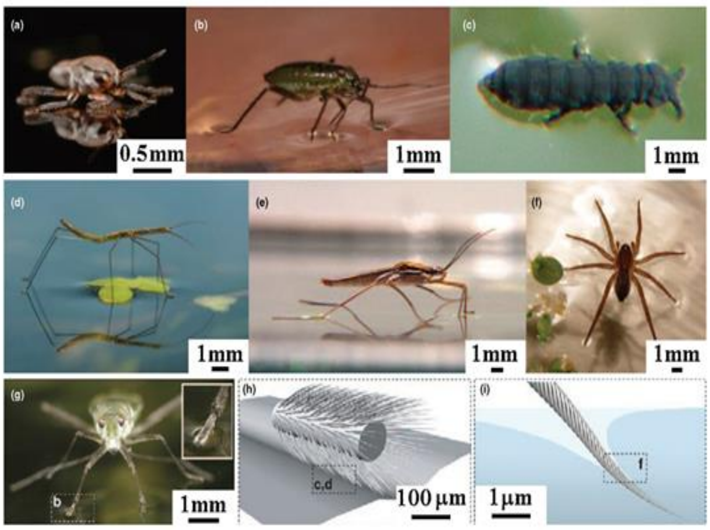

Figure 10. Pictures of diverse water-walking arthropods; (g–i) images of a leg at changing magnifications [17]

3. Fabrications

Superhydrophobic surface fabrication has received much attention since the mid-1990s. In this case, we reviewed the most frequent papers from the last five years and developed the following manufacturing techniques that appeared most common in the previous five years.

3.1 Template/Molding

Applying desired pattern or roughness to the substrate through templating is a standard technique for producing superhydrophobic surfaces. Both natural and artificial surfaces can serve as templates. After choosing the original template (Master template), the desired polymer resin is added. The template is then pressed against the spaces to leave the opposite of its pattern (negative template) on the substrate. Finally, the patterned negative template is used to recreate the original template using the same procedure (Figure.11) [18]. A patternable superhydrophobic surface can be created using the negative template and replica birth. Zhou et al. [19] demonstrated how superhydrophobic materials with customizable surface morphologies and wetting characteristics might be made fast using a low-cost templating approach. After being created by photopolymerization NIPAM, the templates were used to duplicate PDMS samples with correspondingly high roughness levels. Contact angle measurements, which reveal that the WCAs of the PDMS samples changed from 114° to 154°, are used to verify the method's effectiveness.

Furthermore, the patterned PDMS materials were resistant to external mechanical deformation for up to 100 cycles. Similarly, using a fresh lotus leaf as a template and PDMS, Wang, and associates [20,21] produce a surface that resembles a lotus leaf. A WCA of 157 degrees, which was very close to a natural lotus leaf (160 degrees), was used to illustrate the superhydrophobicity of lotus-like surfaces. The authors concluded that this behavior could be caused by the rougher wood surfaces' more significant amounts of micro/nano-papillate hills (Figure 11).

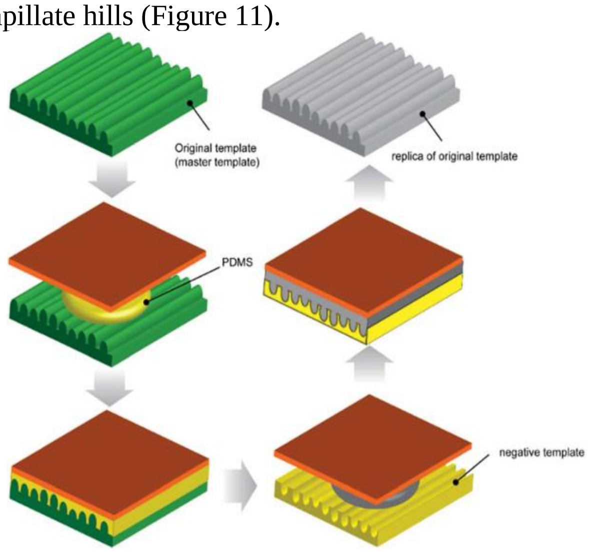

Figure 11. Schematic illustration of the templating technique to produce superhydrophobic materials with a micro/nano-patterned surface

3.2 Spray coating

Spray coating is the popular one because it is cost-effective and large-scale. According to Zhi et al.'s [22] report, they use simple spray or dip coating on various substrates, depending on one's shape, to obtain a large-scale fabrication of superhydrophobic surfaces. First, they receive hydrophobic silica nanoparticles mixed with others to get SiO2/polyurethane (PU) coatings. Then, spray the coating with a spray gun on the substrate. Then, prepare silica/epoxy resin and spread it on a substrate. The WCA is approximately 150° in all substrates. However, the high temperature during testing damages the coating, demonstrating that the weld is stable below 150°.

Furthermore, all the substrates show good mechanical, chemical, and UV resistance through induced management. Finally, it is a fluorinated-free surface, which is environmentally friendly. Also, Spray coating could help to obtain a high WCA. According to Keying Feng's [23] report, the first step to making their high-performance spray coating is the preparation of POS@HNTs by causing the hydrolytic condensation of silanes reacting on the surface of HNTs. Then, using a spray gun to spray-

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coating the POS@HNTs toluene suspension onto the various substrates, with the WCA 170°, the water droplets (10 L) could be nearly spherical in 100% coating.

3.3 Dip coating

Like spray coating, simple dip coating is a facile way to do superhydrophobic coating and can potentially be applied to large-scale manufacturing processes. In Latthe et al [24] reports exploring the feasible industrial applications of self-cleaning superhydrophobic coatings, A hydrophobic silica nanoparticle suspension was coated on various substrates. First, they clean the substrate of exterior dirt. Depending on the substrate shape, they use dip or spray coating to do the surface coating. In dip coating, each will coat ten layers, each layer is 1 minute long. The WCA in dip-coated glass is 160°, and hysteresis is less than 6°. In Figure 12, the SEM graph shows the surface morphology, on which nanoparticles are evenly spread, and confirmed self-cleaning properties (Figure 12).

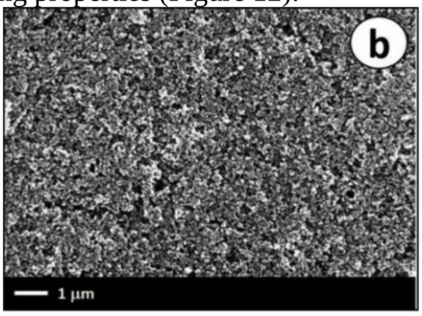

Fig 12. SEM graph [24]

Also, some reports find ways to develop fluorinated-free surfaces and other techniques to improve resistance. For example, according to Zhu et al [25], after applying PDMS to create an adhesive layer, ZnO nanoparticles were deposited onto the fabric's surface using an oil bath coating method after applying PDMS to form an adhesive layer. Finally, PDMS-ZnO-PDMS layers were successfully created on top of the cotton fibers using a repetitive dip-coating method. The WCA after two times of coating is 160°.

3.4 Electrospinning

Utilizing electricity, the electrospinning technique turns polymer melts and solutions into continuous filaments. To create a non-woven fabric network with a nanoscale structure, the produced fibers can be

randomly distributed on the collecting device. So this is mainly in the medical field, nanosensors, protective clothing, and so on, all of which are sustainable industries in the future. Electrospinning is a cheap and easy-to-implement method, which means it is facile to obtain without many requirements for raw materials. Moreover, electrospinning is easier and more convenient to control fiber diameter, surface, and arrangement, and it is used in modern society on a large scale [26,27].

In figure 13, the Metering pump is equipped with a liquid, such as a polymer solution, and is connected to the needle, which is connected to the high-voltage power supply. As a result, the liquid elongates into a cone form known as a Taylor cone, and the electric field produces a force opposing the surface tension of the solution. Bundles of liquid fly out of the cone when the voltage is strong enough to break the surface tension. The drink goes straight at first, but due to the instability of the electric field behind it, the path of the fluid behind it is messy and irregular, called the whipping motion. Finally, when the liquid solidifies in the collector, a non-woven pad of fine fibers is formed [28] (Figure 13).

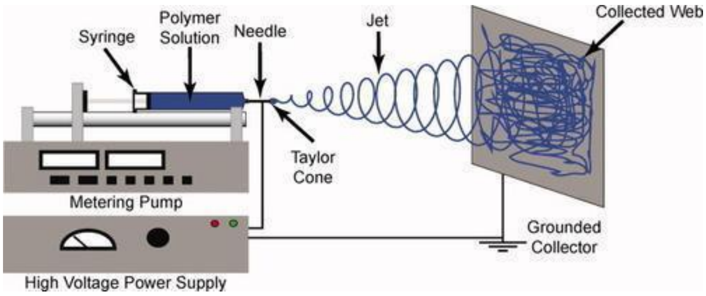

Figure 13. Electrospinning process [27]

3.5 Electrochemical Deposition

Electrodeposition is a commonly used metal deposition technology that generally covers metal surfaces, thus improving metals' appearance, wear resistance, and corrosion resistance. Electrodeposition devices include positive and negative electrodes immersed in electrolytes containing metal ions, usually in aqueous solutions. When the power supply is turned on, there is a current at the beginning of the two electrodes, such that at the anode, the metal dissolves into metal ions. The metal ions are reduced at the negative electrode to create a metal coating that makes the metal superhydrophobic and protects the metal. Its nature can be intentionally modified [28,29] (Figure 14).

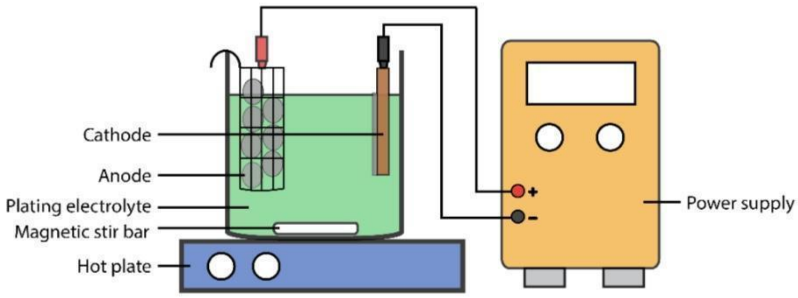

Figure 14. Equipment of Electrochemical deposition and its process [29]

3.6 CVD

Chemical vapor deposition (CVD) is the name given to a group of procedures in which a solid substance is deposited from a vapor via a chemical reaction on or near the surface of a substrate. According to Carlsson & Martin: The CVD technique is distinguished by its excellent throwing power, which creates consistently thick coatings with little porosity even on complexly formed surfaces. Another essential feature is the ability to do local or selective deposition on patterned surfaces [30].

Chemical vapor deposition can also be used in the processing of superhydrophobic surfaces. The surface exhibits extremely high hydrophobicity by coating poly perfluoroalkyl ethyl methacrylate (PPFEMA) onto the surface. Moreover, PPFEMA-coated PCL mats have extremely low surface energies, which are soft enough to cause oleophobicity (Figure 15) [31].

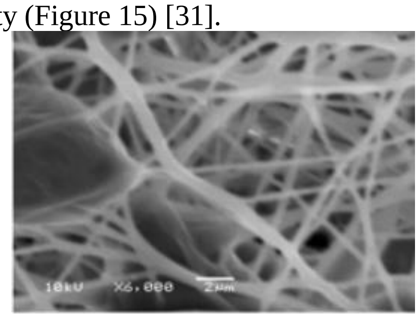

Figure 15. SEM images of the sample after CVD coating [31]

3.7 Sol-gel

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The sol-gel is a cost-effective technique that could be applied to industrial superhydrophobic manufacture. It could be used to large-scale manufacturing. According to Su et al. [32], sol-gel reactions could fabricate a flame-retardant superhydrophobic surface on cotton, which is cost-effective. As the figure shows, the whole manufacturing process starts with getting clean fiber and is activated by Oxygen plasma. Then treated cotton will be immersed in processed ethanol suspension. The TEOS and HPDMS in situ sol-gel synthesis was then started to produce the PDMS-silica hybrid under the catalysis of ammonia (PDMS-silica). The WCA and SA were 162 degrees and 8 degrees when surface-coated the PDMS-silica was in combination with the APP particles. It shows relatively good mechanical durability and chemical durability. Under the Microscale combustion calorimetry (MCC) and vertical flame test, according to ASTM D6413, the surface offers an excellent flame-retardant property (Figure 16).

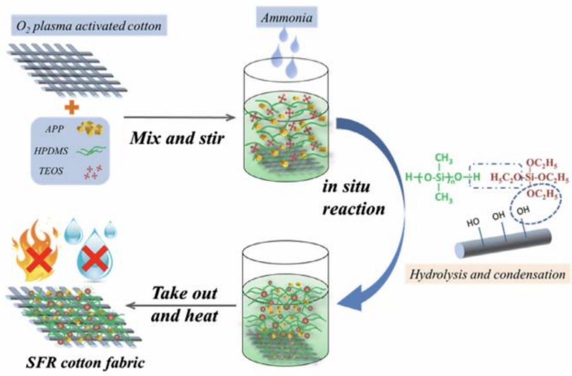

Figure 16. process of manufacturing superhydrophobic surface via sol-gel

Su et al. [32], report a vapor-liquid sol-gel method, which could create a superhydrophobic surface on polyester fabrics. It is based on using TEOS to produce silica through hydrolysis and condensation, causing the gradual construction of micro-aggregated silica with sufficient roughness, formed by the extreme polarity difference between silica and PDMS(OH). In addition, subsequent crosslinking reactions of Si-OH groups between micro-aggregated silica and PDMS (OH) also help to enhance the surface roughness. When the polyester textile was fabricated with the mass ratio of TEOS to PDMS(OH) at 3, the WCA reached its highest number, which is 160°. After that, the WCA started to decrease. This surface also shows good chemical durability, mechanical durability, and oil-water separation by testing with solid acids and bases; ultrasonic tests; laundering tests, abrasion tests; and absorption of oil from water in a practical perspective.

3.8 Layer-by-layer

Layer-by-layer (LbL) assembly is an effective solution-processing technology for producing multilayer films with coatings consisting of monolithic films and layered materials with nanoscale thickness control. Traditionally, LbL films are made by alternately covering polyelectrolyte multilayers using soluble polymers with opposite charges. However, the technology is adaptable and adjustable for processing other valuable materials. LbL has been extended from classical polyelectrolytes to dendrimer polyelectrolytes, polymer brushes, and inorganic charged nanoparticles such as MMT, CNT, and colloids. LbL has been raised from aqueous media to organic solvents and ionic liquids. Because LbL assembly meets versatility, simplicity, and modularity, it is feasible to produce multilayer materials with controllable thickness and composition and customizable characteristics and structure [33,34]. Even enabling control of the film's design, construction, and consistency at the molecular level, this technology is so essential that it is reflected in many applications, for example, sensors, separation membranes, superhydrophobic surfaces, and contact lenses. It is also used in many fields, such as biomedicine, optoelectronic devices, and the design of unique films.

Figure 17 shows the process of traditional LbL assembly. Initially, a charged material is adsorbed onto the surface of a substrate with the opposite charge. Then the substrate with the first polymer layer (in figure 17, the red solution). Next, rinse the surface. This step is necessary because unbound

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polyelectrolyte molecules may be removed from the multilayers when adsorbing oppositely charged layers, forming inter-polyelectrolyte complexes in the solution [35]. Thus, put it into a second polymer solution (in figure 17, the blue key), which has the opposite charge to the first solution. Then rinse again to prevent cross-contamination. Finally, repeat these steps until the desired thickness is achieved. Many factors influence the LbL assembly, for instance, the strength of the ions in the solution, the solvent's nature, and the solution's pH value (Figure 17).

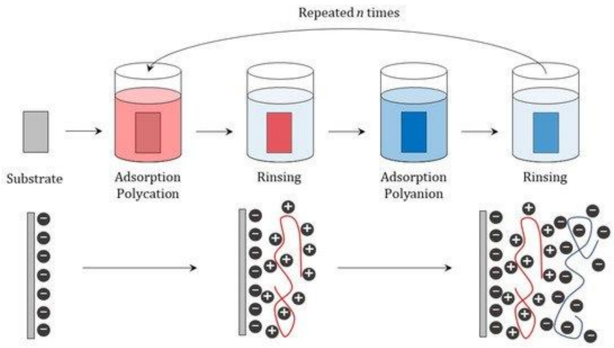

Figure 17. A graphic illustrating the usual process for fabricating Layer-by-Layer (LbL) multilayers on a flat substrate using immersion deposition [36].

The standard methodology of the LbL assembly method is inexpensive and straightforward to fabricate the multilayer structures. The LbL assembly has a significant disadvantage, but this can be partially solved by adding organic solvents such as dimethylformamide or dimethyl sulfoxide to the layering solvent, which takes too long to prepare each layer. With these solvents, it is possible to allow a de-wetting process to take place, thus reducing the rising step and increasing the speed of LbL assembly by 30-fold [37,38]. In conclusion, although technology is simple, it will play an essential role in many areas and drive technological progress as time progresses and technology advances.

3.9 Hydrothermal method

Hydrothermal synthesis refers to the numerous procedures for crystallizing compounds from high-temperature aqueous solutions at high vapor pressures. The hydrothermal synthesis method is based on mineral solubility in hot water under high pressure. The entire reaction takes place in a vessel known as an autoclave. The temperature differential between the two ends of the growing chamber is maintained. The seed crystal is deposited at the more excellent end, growing the desired crystal, while it dissolves on a nutrient solute at the hotter end. K. H. Tam et al. state that: the hydrothermal method is particularly interesting since it is a low-cost, environmentally friendly method of making nanosheets [39]. Applying this technique to superhydrophobic surface production, the resulting surface exhibits excellent corrosion resistance. According to Yunxiao wan et alhydrothermal treatment designs the superhydrophobic cover on copper. This superhydrophobic surface has CA 157.7 1°. Furthermore, in a 3.5 wt% aqueous NaCl solution, this surface demonstrated a corrosion inhibition efficacy of 99.81% [40].

4. The comparison between different techniques for mechanical durability

Contrary to naturally occurring surfaces, artificial superhydrophobic materials have the significant flaw of swiftly losing their usefulness in challenging mechanical environments. Because of this, their potential usage in new industrial applications is constrained. The literature now accessible demonstrates that superhydrophobic coating materials go through many diagnostic procedures utilizing various tools to ascertain their ability to survive challenging circumstances.

4.1. Structure stability and durability issue

Superhydrophobic materials cannot maintain a stable structure for a long time, especially nanoscale, where the strands behave like wet noodles and quickly wind and matte, losing their superhydrophobic characteristics. Under some extreme application situations, the low-surface-energy chemicals and micro-nano rough structures are degraded rapidly. The surface morphology and chemistry may change due to precipitation, sand particles, and mechanical abrasion, resulting in a partial or total loss of the superhydrophobic qualities. Furthermore, bonding any superhydrophobic nanoparticle without destroying its superhydrophobic characteristics is challenging. Durability and superhydrophobic behavior are somewhat contradictory [41].

4.2. Cost issues

Raw materials and other expensive processes make super hydrophobic surface manufacturing extraordinarily costly. Furthermore, creating large-area substrates with nanostructured surfaces is impossible using typical procedures, such as lithography and the template approach. Therefore, making tiny chip dies and joining them together can raise the price [41,42].

4.3. Challenges of impacting water droplets

Superhydrophobic surfaces are often difficult to apply in practical engineering, such as aircraft anti-icing and energy production, where high-intensity droplet impacts occur. Superhydrophobic coatings are typically thin layers applied to material surfaces or surface effects. Simple rubbing or a targeted high-pressure water jet can remove such coatings or products [43,44].

4.4. Vapor condensation issues

Although the superhydrophobic layer is waterproof, it does not protect against vapor. Condensation occurs when the surface temperature of hydrophobic material is low. In this case, the hydrophobicity of the coating will be significantly reduced while the surface is wetted [45]. According to Mockenhaupt et al., as the temperature decreases, condensation leads to a reduction in contact angle, increased sliding angles, and a significant reduction in hydrophobicity.[46]

4.5. Environmental risks

To achieve superhydrophobic qualities on metal substrates with hydrophilic surfaces, a micro-nano rough structure must be formed on the surface and then modified using low surface energy materials. Unfortunately, the processes or raw materials utilized to produce the graded roughness frequently result in undesired side effects. Chemical etching procedures, for example, necessitate a corrosive approach, with H2SO4, HCl, HNO3, and NaOH solutions being utilized, which severely impact the environment.[43]

5. Conclusion

This review discusses the natural superhydrophobic surface and recent advances in the superhydrophobic surface generation field. Many animals, insects, and plants in nature exhibit excellent superhydrophobicity, and many superhydrophobic characters were invented by the inspiration of these natural surfaces. These superhydrophobic surfaces have achieved various properties, such as adhesion, corrosion, and self-cleaning, and have a wide range of industrial applications. Although much research has been done in this field, it is still limited to the laboratory level and has not been used in commercial products and real-world applications. While various biomimetic superhydrophobic surfaces have been developed, researchers must address challenges such as cost and durability. It is a significant difficulty for researchers and scientists to produce commercially viable semi-permanent and permanent superhydrophobic surfaces with all the needed qualities on all base materials. Furthermore, fluorine-based products and other non-biodegradable chemicals endanger human and environmental health and must be replaced with safer alternatives.

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