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Recent Innovations in the Design of Hydrophobic Coatings to Prevent Equipment Icing

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Abstract

The accumulation of ice on critical infrastructure, which includes elements such as airplanes, automobiles, buildings, power grids, wind turbines, airplanes and offshore platforms, poses considerable safety risks as well as significant economic challenges. This problem can lead to network failures, road and air accidents, and interruptions in energy production, thus affecting not only the operation of these infrastructures, but also the economy as a whole. The costs associated with these risks include unforeseen maintenance expenses, material damage and a decrease in the reliability of services, which underlines the need to develop adapted solutions to manage and prevent these ice accumulations. This review analyzes the hazards associated with surface icing, emphasizing the risks it poses and its impact on various materials. It also evaluates current de-icing methods, while exploring the mechanisms of icing and the interactions between ice and materials. Among the main points discussed, we find the coating strategies developed to repel the ice. This includes an examination of superhydrophobic coatings that prevent ice adhesion through highly hydrophobic surfaces. In addition, the review discusses liquid-infused slippery surfaces (SLIPS), which utilize layers of liquid to reduce ice buildup. The effectiveness of these different solutions is highlighted, as well as their mechanisms of action, thus providing a detailed perspective on advances in the field of combating surface icing.

Keywords

Icing, Coating, Adhesion, Hydrophobic Surface, Superhydrophobic Surface, Slippery Surface

1. Introduction

Icing of surfaces is a critical issue for several sectors as well as for the safety of people [1]-[4]. Traditional de-icing methods, such as mechanical scraping, chemical de-icing, and electrothermal de-icing, have proven effective in reducing the consequences of ice buildup. However, these techniques are often costly and require regular maintenance. This underscores the urgent need for research and development of new de-icing and anti-icing technologies that are not only more effective but also environmentally friendly in order to sustainably address the challenges posed by icing in these industries. Hydrophobic coatings represent a significant advancement in surface protection, offering excellent moisture resistance through high contact angles that reduce wetting [5]. These coatings contribute to corrosion protection, facilitate self-cleaning, and enhance other functional properties. The effectiveness of hydrophobic material protection is determined by the composition and manufacturing methods, which affect surface morphology, adhesion, and durability [5]. Solution immersion, spraying, and dipping are among the methods commonly used for manufacturing hydrophobic coatings. The design of low-wettability surfaces is heavily inspired by biomimicry (**Figure 1**), using nanometric topography methodologies to achieve Cassie-Baxter wetting states. These surfaces, mimicking the structures of animals and plants, have generated increasing interest and led to the development of smart, functional materials characterized by high hydrophobicity and diverse applications [6]. Studies show that these surfaces offer various properties, such as drag reduction, anti-reflective and anti-fouling characteristics, oil-water separation capabilities, and corrosion protection for metals [7]. Modern scientific research has revealed that surfaces with pronounced superhydrophobic properties are capable of effectively removing water droplets before they freeze at sub-zero temperatures [8] [9]. Both hydrophobic and superhydrophobic coatings exhibit high frost resistance, making them promising for use in extreme weather conditions. Interest in passive anti-icing strategies based on superhydrophobic surfaces has significantly dominated research in this area in recent years [10] [11]. These materials, characterized by low surface energy and a fine micro-nano structure, play a crucial role in preventing ice formation [12] [13]. Their design reduces ice adhesion, which helps slow heat transfer. Thus, the use of superhydrophobic surfaces makes ice formation more difficult, which may have potential applications in various fields, such as aeronautics, construction and transport systems, where icing can pose significant problems.

Modern water-repellent surfaces are inspired by lotus leaves, which are naturally hydrophobic. However, materials derived from this inspiration have not yet achieved the desired performance because, although they repel water, they are not oil-resistant, cannot withstand physical stress, are not self-healing, and remain expensive. Slippery liquid-impregnated porous surface (SLIPS) technology, inspired by Nepenthes pitchers, offers a unique coating for industrial and medical surfaces. It uses a porous material impregnated with a lubricating fluid, creating smooth, water-repellent, and self-cleaning surfaces. These slippery surfaces repel a wide variety of contaminants, such as bacteria, ice, oil, and dust. First introduced in 2011 by Wong *et al.* [16], SLIPS remains repellent under extreme conditions and possesses good self-healing properties, thus distinguishing it from superhydrophobic surfaces. This method uses surface irregularities to retain a lubricant by capillary action. If the surface energies are appropriate and the roughness well chosen, the lubricant fills the irregularities, forming a continuous liquid film that stabilizes the interface. This allows compressible air pockets to be replaced by a less compressible liquid, providing a smooth surface capable of withstanding pressure, while also facilitating the removal of any immiscible external liquid resting on this lubricant layer. Liquid-impregnated surfaces show promise for applications such as anti-icing, anti-corrosion, and drag reduction [17]. However, challenges remain, including lubricant loss due to evaporation, displacement, fouling, or other mechanisms.

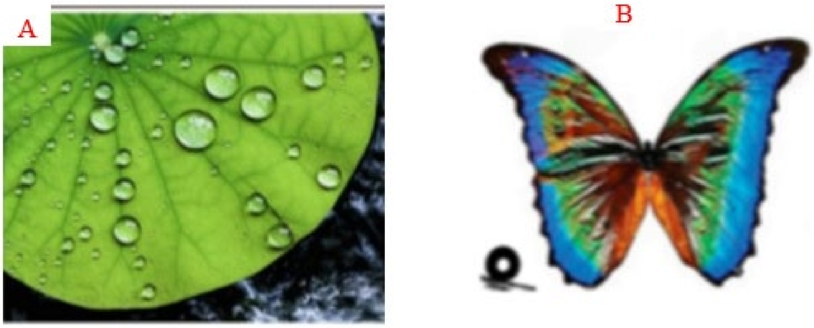

Figure 1. Natural superhydrophobic surfaces: (A) lotus leaf [14] and (B) image of an iridescent blue butterfly [15].

This review examines recent technological advances in the field of superhydrophobic coatings, offering an in-depth analysis of their fundamental principles and mechanisms of action. It also highlights the crucial role of nanomaterials in the integration of these coatings. Furthermore, the review addresses the diverse applications of these coatings in various industries. A focus is also placed on the development of liquid-impregnated slippery surface coatings, which present an innovative alternative to superhydrophobic surfaces for anti-icing applications.

2. Concepts, Mechanisms and Applications of Superhydrophobic Surfaces

Superhydrophobic surfaces have seen significant progress over the past two decades, driven by strong demand in various industrial sectors. The global market for superhydrophobic coatings, valued at approximately US$19.5 million in 2021, is projected to reach approximately US$120 million by 2030, with a compound annual growth rate (CAGR) of 25.6% between 2022 and 2030 [18]. Artificial superhydrophobic surfaces are created using biomimetic techniques inspired by nature, such as the lotus leaf and butterfly wings. These surfaces, with a static contact angle greater than 150˚ and a contact angle hysteresis of less than 10˚, exhibit exceptional properties (hierarchical micro/nanostructures and surface chemistry) characterized by their ability to effectively repel water [19] [20]. This phenomenon, known as the superhydrophobicity effect, results in the formation of almost spherical water droplets when they interact with the surface, minimizing adhesion and greatly facilitating their removal. These unique properties are due to the interaction between low surface energy materials and multi-level surface roughness [21]. This dual-scale structure traps air pockets beneath a liquid, reducing solid-liquid contact and promoting droplet rolling, thus giving the surface hydrophobic and self-cleaning properties. However, artificial superhydrophobic micro/nanostructures are brittle under mechanical stress during practical use [22]. Surface micro/nanostructures and air layers can be permanently damaged, causing irreversible degradation of the surface's superhydrophobicity, which is a major obstacle to the industrial development of these surfaces [23]. Researchers have investigated methods to enhance the durability of brittle micro-nanostructures, including developing composite micro-nanostructures that protect the surface against mechanical wear [24].

The use of low surface energy materials such as fluorinated compounds or silanes is also essential to achieve superhydrophobicity and decrease adhesion with water molecules [14]. Understanding these characteristics is crucial for creating advanced materials with diverse industrial and environmental applications. Superhydrophobic surfaces find varied applications in several industrial sectors, including aerospace, automotive, construction, energy, textiles, architecture, and medical devices. Their development continues, offering innovative solutions to reduce maintenance efforts while improving the durability and performance of the products and infrastructure involved. Interest in self-sustaining hybrid surfaces based on TiO_2 is growing due to their photocatalytic properties, which are well-suited to harsh environments. Semiconducting metal oxides, such as TiO_2, generate photogenerated electron-hole pairs when exposed to high-energy ultraviolet radiation, giving them excellent photocatalytic properties. However, maintaining the long-term stability of superhydrophobic TiO_2-based coatings is challenging because the organic SH components degrade under UV exposure, destroying their anti-wetting properties. Polymer materials, such as PDMS, are valued for their durability and mechanical properties thanks to their stable cross-linked structure. Their hydrophobicity, chemical inertness, high elasticity, ease of processing, and environmental friendliness make them common choices in many everyday objects. Superhydrophobic composite materials, composed of hydrophobic polypropylene, TiO_2 nanorods, SiO_2 nanoparticles, and PDMS, resist wear while maintaining a self-similar rough structure even after destruction of the surface micro-nanostructure, thus preserving hydrophobicity. Furthermore, superhydrophobic surfaces with self-healing properties increase their durability and longevity. Wang *et al.* [25] developed a UV-stable superhydrophobic (SH) coating from polydimethylsiloxane (PDMS) and TiO_2 nanoparticles, applied by spraying onto various substrates. Long *et al.* [26] achieved the modification of polypropylene (PP) to increase its hydrophobicity without losing its structural integrity by creating m-SiO_2/PP composites, using modified silica to obtain a 140˚ water contact angle on a polytetrafluoroethylene (PTFE) substrate. This represents a 44% increase compared to pure PP. Analysis reveals that the m-SiO_2 migrates to the face pressed against the PTFE, due to the substitution of hydrogen atoms by fluorine atoms, forming a protective layer. The self-cleaning properties of the material make it an ideal candidate for dust and oil protection applications.

The use of superhydrophobic surfaces shows promise for reducing ice formation and facilitating de-icing and anti-icing. These surfaces prevent ice nucleation and adhesion, thus improving safety and operational efficiency in cold environments. Wang *et al.* [27] developed nanocomposite films of polydimethylsiloxane (PDMS) and single-walled carbon nanotubes (SWNTs) with hydrophobic properties due to the low surface energy of PDMS and the conductivity of SWNTs. The films switch between hydrophobic anti-icing and low-voltage electrothermal de-icing. Infrared thermometry showed low droplet contact with the superhydrophobic nanocomposite surface, confirming its properties. Joule effect heat distribution analysis demonstrated the nanocomposite's ability to heat up for active de-icing, which was confirmed experimentally. Deng *et al.* [28] presented hydrophobic polydimethylsiloxane (PDMS) aggregates loaded with mesoporous silica (mSiO_2) incorporated into a silicone resin with carbon nanotubes (CNTs) to create a near-infrared-sensitive anti-icing/de-icing coating. This coating offers micrometric roughness and low surface energy due to the PDMS@mSiO_2, while the CNTs add a hierarchical micro-nano structure. The coating exhibits superhydrophobic character with a contact angle of 154.3˚ and a delayed freezing time of 440 s at −20˚C, representing significantly superior performance compared to aluminum plates. Furthermore, it maintains strong adhesion and stable anti-icing properties, promising robustness and durability for anti-icing modifications of rotor blades. Jiang *et al.* [29] developed a layered coating combining polyvinylidene fluoride (PVDF) and carbon nanotubes (CNTs) for improved anti-icing properties. The coating exhibits a contact angle of 163˚, a frost-delay time of 584 s, and low ice adhesion (13.2 kPa). Its multilayer structure, formed by PVDF and CNT particles, ensures robust performance, even after abrasion and chemical exposure. The melting of the PVDF upon heating creates a continuous network, and the use of CNTs enables efficient photothermal conversion, facilitating de-icing at low temperatures under illumination.

Understanding the physicochemical characteristics of salt-based freezing and adhesion solutions in the context of their application to de-icing processes is a crucial aspect of developing effective and environmentally sound strategies. Yao *et al.* [30] analyzed the ice-adhesion strength (IAS) of NaCl and $NaCH_3COO$ salts on bituminous surfaces at various concentrations and temperatures. The results showed that a 0.5% saline solution can reduce IAS by 40% - 50% compared to pure water, and the adhesion failure threshold is temperature-dependent. The latent heat of fusion (hf) of NaCl solutions (0.5% to 2.5%) increased successively by 45.3 J/g, 63.1 J/g, 79.9 J/g, 90.0 J/g and 117.6 J/g relative to pure water and the freezing temperature (T_F) of $NaCH_3COO$ and NaCl solutions decreased by 1.3˚C and 1.6˚C, respectively. The reduction in T_F and hf increased the nucleation energy barrier (ΔG^*) and the increase in salinity transformed the quasi-liquid layer (QLL) of the droplets into a film, thus reducing the contact area. Luo *et al.* [31] explored how salinity influences ice adhesion at sub-zero temperatures. In their study, they observed that the adhesion of salt ice decreases with increasing salinity. Brine at temperatures above −21.2˚C acts as a lubricant, significantly reducing this adhesion. At −25˚C, below the eutectic temperature, strong adhesion is noted. Hydrophobicity on smooth surfaces also reduces adhesion, with a hydrophobic silicon wafer exhibiting an adhesion strength of 2.4 ± 1.8 kPa at −10˚C with a saline solution. In contrast, seawater ice exhibits an adhesion of approximately 12 kPa even at −25˚C. These results highlight the importance of considering temperature, salinity, and surface characteristics when designing materials that minimize icing of marine infrastructure.

2.1. Aircraft

Air accidents due to icing often occur on wings and tails, caused by the presence of supercooled water and ice particles in clouds. This ice buildup damages equipment and disrupts aircraft operation, potentially leading to an accident. Modern de-icing systems, such as thermal, mechanical, and chemical systems, consume significant amounts of energy and increase fuel consumption; they are also harmful to the environment due to the chemicals they release. Ice formation on an aircraft poses significant risks to aviation safety [32]. It can lead to mechanical failures, including malfunctions of power-generating cables and blades, and in extreme cases, it could cause irreversible harm to human life. Anti-icing and hydrophobic coatings are used to prevent ice formation on aircraft surfaces by delaying freezing time and lowering the freezing point of supercooled water [33]. This allows the condensed water to drain away before freezing under the effect of external forces.

In aerospace, superhydrophobic coatings reduce ice buildup on aircraft, thereby improving aerodynamics and safety, while also decreasing the use of chemical de-icing and snow removal agents. Piscitelli [34] presented the development of a superhydrophobic coating, applicable as a paint on various aeronautical materials, that protects aircraft parts by reducing surface free energy and adhesion of treated substrates by more than 90%. Tong *et al.* [35] described a cost-effective, fluorine-free method for creating a superhydrophobic anti-icing coating using the self-assembled deposition of nanoparticles on an aeronautical composite. Analysis of the coating reveals a multiscale structure and low surface energy. It offers excellent hydrophobicity, high resistance to acids and bases, and surpasses previous coatings in durability and mechanical stability. The coating delays ice buildup for 120 minutes with an adhesion strength of 53.6 kPa, making it promising for applications on airfoil profiles and wind turbine blades. To counter the risk of aircraft icing, a method for spraying a superhydrophobic photothermal coating was proposed by Yang *et al.* [36], aiming to optimize anti-icing protection systems. This coating, with a hierarchical micro-nano structure, has a contact angle of 159.5˚ with water and demonstrates excellent stability after wear and corrosion tests. It allows droplets to detach quickly, delaying icing in cold environments and providing good anti-icing performance. Wind tunnel tests validated its effectiveness, proving its ability to significantly reduce ice thickness, thus contributing to the development of sustainable and energy-efficient anti-icing technologies.

2.2. Automotive

In the automotive industry, superhydrophobic coatings are used in various applications, including on windshields, side windows, and rearview mirrors, to improve visibility in adverse weather conditions. These water-repellent coatings allow rainwater to bead and run off, increasing driver safety and reducing the need for windshield wipers. They are also applied to the body to protect the paint from water, dirt, and other contaminants, helping to maintain a clean and glossy appearance and extending the lifespan of automotive components. Transparency is crucial for windshield coatings [37]. Surface roughness, optical transmittance, and superhydrophobicity are opposing properties: increased roughness improves hydrophobicity but decreases transparency, as light scattering reduces transmittance. A combination of micro/nanostructures could improve self-cleaning, but at the cost of making the surface opaque. Methods combining nanoparticles and low surface energy materials have been developed to create superhydrophobic coatings while preserving transparency.

Transparent superhydrophobic surfaces are used in exterior applications such as windshields, but their sensitivity to impacts limits their use. A new, environmentally friendly self-assembly process has been developed by Lyu *et al.* [38], creating resistant surfaces with a transmittance of 94.2% compared to pure glass. These surfaces withstand impacts from 600 g of sand and water jets of 8.6 m/s for 6 minutes, demonstrating their durability under heavy rain. Furthermore, they withstand corrosive environments such as sulfuric acid and UV radiation, making them attractive for applications requiring self-cleaning and environmentally stable properties. Luo *et al.* [39] proposed an innovative method for creating transparent, microstructured, multilayer superhydrophobic coatings. These coatings exhibit a contact angle of ~153.6˚ and a glide angle of ~3.2˚. A microstructured, UV-cured photosensitive resin framework ensures their durability, while modified silica nanoparticles, anchored in the microcavities by an epoxy adhesive, provide their superhydrophobicity. These surfaces are abrasion-resistant and retain their hydrophobic properties after various resistance tests, such as water impact, acid immersion, and mechanical bending. Furthermore, they exhibit antireflective characteristics while maintaining high transparency. Syafiq *et al.* [40] synthesized transparent, self-cleaning coatings from polydimethylsiloxane (PDMS) and calcium nanocarbonate ($CaCO_3$). These coatings, applied by spraying and cured at room temperature, are designed to be economical and easy to produce. After four months of outdoor exposure, it was observed that the light transmission of the substrate with 0.8% nano-$CaCO_3$ was only slightly degraded (7%), demonstrating a good self-cleaning effect. A higher nano-$CaCO_3$ loading rate increases capillary pressure, exacerbating the pressure during rain and fog, but results in only a 2% degradation of the water contact angle, providing excellent anti-fog properties.

Corrosion caused by prolonged exposure to the elements impairs vehicle performance and lifespan, affecting their appearance and damaging associated equipment, resulting in high maintenance costs and a safety risk. One approach to improving the corrosion resistance of metal surfaces is to create superhydrophobic coatings, which generate an air gap between the surface and the solution, thus forming a protective barrier against the corrosive environment (**Figure 2**).

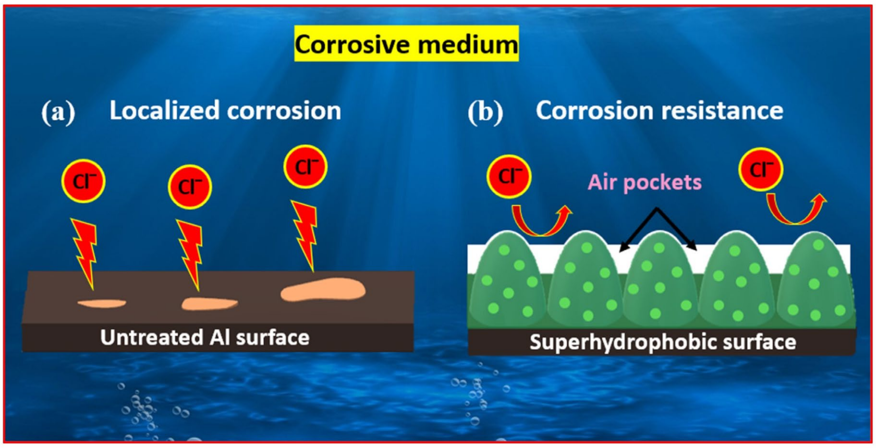

Figure 2. The anti-corrosion mechanism of the superhydrophobic surfaces [18].

Hu *et al.* [41] presented a rough zinc coating on carbon steel, coated with a polyaniline/TiO_2 composite and stearic acid, creating a superhydrophobic SPTC-Zn coating. The coating exhibits a contact angle of 159.8˚ and a slip angle of 6.2˚, indicating significant superhydrophobicity. It also possesses superior scratch, flake, and abrasion resistance, as well as corrosion protection. The coating's performance results from the synergistic effect of the hierarchical structure, the formation of hydrophobic complexes, and a composite passivation film, suggesting strong potential for industrial applications. Huang *et al.* [42] developed an environmentally friendly, superhydrophobic, polyaniline-titanium oxide (PANI-TiO_2) nanocomposite alternative to chromium-based corrosion protection coatings. This new coating, produced by surfactant-free nanoprecipitation, exhibits superior water repellency (contact angle > 150˚) and improved corrosion resistance compared to traditional epoxy coatings. A positive correlation between TiO_2 content and thermal conductivity was observed, confirming that this coating offers optimal performance as an anti-corrosion coating. Lv *et al.* [43] described a cost-effective method combining chemical substitution, thermal oxidation, and stearic acid modification, resulting in a superhydrophobic and oleophilic coating with contact angles of 157.3˚ and a slip angle of 3.6˚. This coating exhibits low adhesion and excellent self-cleaning properties. Mechanical analyses showed that the stability of the micro/nanostructures and air pockets influence interfacial adhesion. Tests reveal that the coating retains its properties even after peeling, abrasion and chemical exposure, notably with a corrosion current density of 0.77×10^{-7} A/cm^2 in NaCl medium, lower than that of the 6061-aluminum substrate (7.18×10^{-7} A/cm^2).

2.3. Buildings

In civil engineering, superhydrophobic coatings offer significant potential for functional applications in the maintenance of building materials. Exposure of these materials, such as concrete, stone, glass, brick, tile, metal surfaces, and mortar, to external conditions leads to degradation that can cause significant structural, functional, and aesthetic problems in buildings. Superhydrophobic surfaces stand out as multifunctional protective coatings, primarily due to their properties that prevent the adhesion and penetration of liquids. For example, treated concrete surfaces absorb less water, thus limiting freeze-thaw damage in cold climates. Furthermore, they promote self-cleaning and inhibit bacterial adhesion, thereby enhancing their potential for protecting and extending the lifespan of structures [44]. This technology provides an innovative solution to the challenges of material degradation in the construction industry.

Superhydrophobic coatings show promise in architecture due to their ability to combat pollution thanks to their self-cleaning properties [37]. They help overcome the challenges posed by temperature variations, UV radiation, humidity, and mechanical wear affecting building exteriors. Under prolonged exposure to the elements, superhydrophobic coatings in buildings can be damaged or flake off due to their fragile micro/nanostructure. Therefore, the design of durable and robust coatings is essential for their use in this field. Zhi *et al.* [45] developed a silica-polymer (SiO_2/PU) spray coating that offers characteristics such as superhydrophobicity, mechanical durability, chemical stability, and UV resistance. It retains its superhydrophobic properties after 175 hours of UV irradiation, heating to 150 ˚C, and exposure to strong acids and bases. Mechanical durability was tested using various methods, including scraping and 100 peel-off cycles. Furthermore, a sponge treated with this coating achieved an oil-water separation efficiency of over 95% for various liquid hydrocarbons using a vacuum system. Zulfiqar *et al.* [46] presented a simple method for creating durable, superhydrophobic surfaces on building materials that are restorable after abrasion. These surfaces, made from hydrophobic silica nanoparticles treated with trimethylchlorosilane (TMCS) and a spray adhesive (3 M Super 77), were applied to brick, marble, and glass. This process creates durable, self-healing superhydrophobic coatings with contact angles of 168˚, 166˚, and 163˚, respectively. These coatings withstood sand impacts at 11.26 km/h and regained their superhydrophobic properties through acetone treatment after significant damage. Buildings exposed to high temperatures due to solar radiation increase their energy consumption, with a third of this consumption attributed to air conditioning, particularly in summer. To improve energy efficiency, it is important to enhance the thermal insulation of buildings with superhydrophobic coatings. These heat-reflecting coatings contribute to energy savings and can be applied to facades and roofs, while also improving durability and reducing maintenance costs. Wang *et al.* [47] obtained a durable, self-cleaning, ultraviolet-reflective, superhydrophobic exterior coating based on white Portland cement, incorporating room-temperature vulcanized silicone rubber and titanium dioxide. Applied by brush, the coating demonstrates excellent self-cleaning properties and mechanical strength after 24 hours of curing. It is resistant to dust and food liquids and withstands temperature cycles between −40˚C and 100 ˚C. The measured infrared and solar reflectances were 0.867 and 0.67, respectively, with a decrease of less than 3% after abrasion tests. Tang *et al.* [48] developed environmentally friendly coatings based on ground calcium carbonate (GCC) and titanium dioxide (TiO_2) on a cementitious substrate using a one-step spray method. The resulting superhydrophobic coating (GCC/TiO_2) exhibited a contact angle of 158˚ ± 1.1˚ and a slip angle of 5˚ ± 0.6˚ and retained its properties even after 2 m of abrasion and 50 applications. Its solar reflectance reached 0.895, reducing the surface temperature of the cement by nearly 10˚C, while also offering corrosion resistance, UV protection, and self-cleaning properties, suggesting its potential for building cooling. Inspired by concrete, Binrui *et al.* [49] developed a superhydrophobic coating from an organic/inorganic hybrid resin and micro/nanometric fillers. This resin improves hydrophobicity and robustness, with wear-resistant phases such as silica sand, aluminum nanoparticles, and PTFE. The surfaces thus created exhibit high abrasion resistance and retain their superhydrophobicity after abrasion and impact tests. The coating retained its superhydrophobicity after an abrasive test (180-grit sandpaper over 10 m and 600-grit sandpaper over 12.8 m, pressure 22.5 kPa) and exposure to sand (1400 g, height 30 cm). Adhesion to the substrateis 5B.

3. Coatings for Liquid-Impregnated Surfaces

The aerospace, automotive, and energy industries are experiencing increasing demand for durable surfaces with anti-fog, anti-freeze, and anti-fouling properties due to extreme conditions. Ice buildup and fogging affect flight safety, road traffic, and the efficiency of power generation. Conventional superhydrophobic surfaces using Cassie-type wetting to prevent ice formation have limited durability due to the inevitable transition to the Wenzel state at low temperatures and high humidity. They suffer from limitations due to a stable air layer, including poor stability under pressure and an inability to repel certain liquids [50]. To overcome these challenges, materials inspired by the carnivorous plant Nepenthes, called lubricant-impregnated porous surfaces (SLIPS), have been developed, providing a continuous and stable liquid layer. SLIPS improve anti-icing efficiency and offer an alternative to superhydrophobic surfaces (SHS) as an innovative anti-icing material [51]. SLIPS are slippery surfaces that prevent adhesion, allowing viscous liquids, gels, and emulsions to slide freely. Thanks to their anti-wetting and self-cleaning properties, SLIPS coatings are used in a variety of fields, including consumer goods, agrochemicals, electrical equipment, oil and gas, manufacturing, biomedical devices, pharmaceuticals, energy, and utilities [52]. Composed of solid and liquid materials, SLIPS coatings create a durable, wet, and slippery surface, unlike traditional coatings that dry to form a solid surface (**Figure 3**). The liquid layer seeps into the textured solid and remains functional throughout the product's lifespan, allowing for immediate operation after application. Innovation in this area highlights the importance of developing preservation and performance solutions in environments exposed to harsh climatic conditions, where ice management is critical.

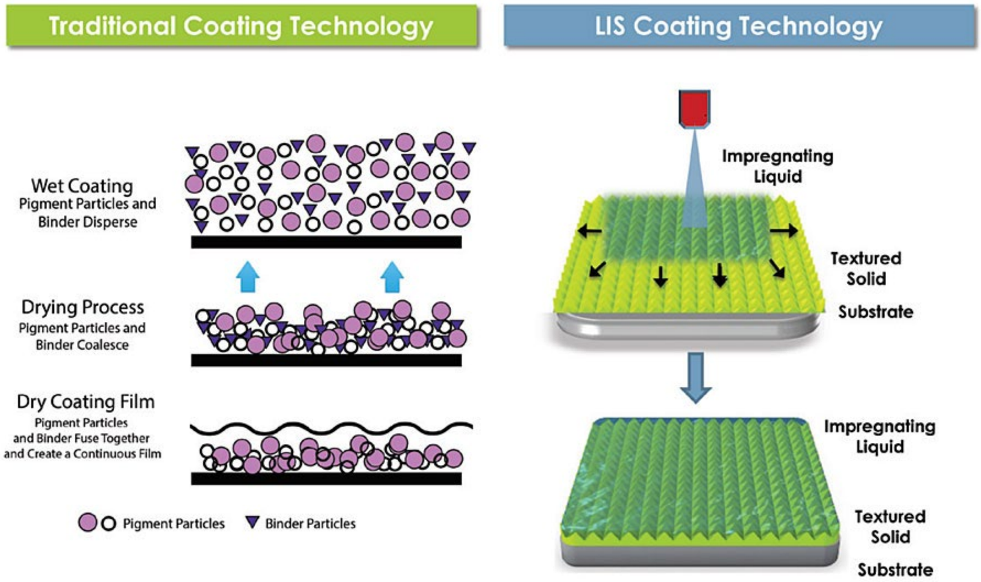

Figure 3. Coating technologies: (a) traditional and (b) SLIPS [53].

To create a slippery fluid-impregnated porous surface, a suitable lubricant must be selected that penetrates, spreads, and adheres to surface irregularities, taking into account both surface roughness and lubricant properties [17]. The resulting morphology depends on the properties of the liquid, the lubrication, and the surface. At a zero contact angle, a wetting layer forms, covering the solid surface. The durability of slips is a limiting factor in their practical use across various working environments [54]. Slip deterioration is primarily attributed to two factors: a reduction in the amount of oil present and the smoothing of the nanoporous functional layer [55]. This combination affects the effectiveness of slips in their lubrication function. Slip life can be extended by improving characteristics such as substrate roughness, chemical composition, the physical properties of the lubricant, and ambient conditions [56]. A thorough understanding of lubricant degradation mechanisms is essential for designing durable slips.

Xi *et al.* [57] presented the fabrication of a micro/nano-integrated, lubricant-impregnated surface with a network of conical microcavities and a porous TiO_2 nanostructure (P-SLIPS). Experimental results indicate that the anti-abrasion properties of P-SLIPS are significantly improved, demonstrating a decrease in ice adhesion after 7 sanding cycles. Icing is not observed on P-SLIPS even after 10 cycles, compared to only 3 cycles for SLIPS surfaces. This improvement is attributed to the micro-cone structure, which protects the coating during icing and polishing operations, thus enhancing the anti-icing durability of P-SLIPS. Zheng *et al.* [58] designed microstructures on SLIPS substrates using direct laser interference lithography (DLIL), followed by a lubricating oil coating to create DLIL-impregnated SLIPS (DLIL-SLIPS). These structures efficiently retain the oil, allowing self-feeding after multiple icing/de-icing cycles, and thus improving anti-icing performance, durability, and robustness. Tests demonstrate that DLIL-SLIPS exhibit improved ice adhesion with an apparent contact angle of 143˚ and an adhesion force of 7.16 kPa, while reducing the coefficient of friction by 63.3% compared to the substrate. Ge *et al.* [59] developed a durable SLIPS using a microcone composite micropillar (MCMA) structure created by femtosecond laser writing and a thermosensitive polymer transfer method. The MCMA adjusts its anti-icing properties according to temperature by releasing and absorbing lubricant, and can self-regenerate the lubricant to maintain its properties even after depletion. It offers an optimal static icing delay time of 1033 seconds and a low ice adhesion of 2.51 kPa. Its mechanical and chemical durability is high, maintaining an adhesion of less than 20 kPa after 50 de-icing cycles. Yuan *et al.* [60] analyzed the self-healing performance of SLIPS via icing-repair and abrasion-repair cycles. A stable lubricating layer is obtained by the infiltration of silicone oil into a silanized porous surface. SLIPS exhibit low ice adhesion, even after icing, and the ice slides off under the influence of gravity. Adhesion does not exceed 100 kPa, and the coating withstands 150 icing/de-icing cycles and 100 abrasion cycles, demonstrating the durability of its anti-icing properties, which makes it promising for applications in durable anti-icing materials for aircraft.

Networked surface structures improve the robustness and durability of SLIPS [61]. Studies have shown that the use of textured surfaces, including interconnected microchannels and cross-linked nanosheets, promotes better retention and efficient liquid storage. This advance in surface design significantly improves their performance by offering both strength and efficiency in liquid handling. Wei *et al.* [62] prepared a slippery liquid-infused phosphate network-like surface (SLIPNS) whose texture is modulated by the phosphating time. This structure allows for excellent oil storage and retention, extends the freezing time of sessile droplets to 436 seconds—nearly ten times longer than an untreated aluminum foil—and reduces ice adhesion tenfold compared to untreated substrates. SLIPNS is distinguished by its durability, antifouling effectiveness, and potential for long-term de-icing/anti-freezing solutions. Li *et al.* [63] presented the preparation of a superhydrophobic surface by spraying a sepiolite/ZEF-8 hybrid material with a three-dimensional (3D) fibrous porous network structure layered on a magnesium alloy. The injection of silicone oil generates a self-regenerating SLIPS system, providing a reservoir and channel structure for the lubricant. In addition to its self-regenerating and protective properties, SLIPS demonstrates superior corrosion resistance compared to the superhydrophobic surface, thanks to continuous lubrication that blocks the infiltration of corrosive ions. Finally, the corrosion stability of SLIPS remains excellent after 30 days of immersion in a 3.5% NaCl solution.

Aluminum and its alloys, used in various sectors, face contamination and corrosion problems due to their hydrophilicity. Lv *et al.* [64] propose a fluorine-free method for creating a lubricated porous surface (SLIPS) by chemically etching aluminum to obtain a honeycomb structure, followed by modification with 1-octadecanethiol and silicone oil. This surface exhibits a 3˚ sliding angle for various liquids, displaying superior corrosion resistance compared to the original aluminum. SLIPS surfaces also demonstrate better anti-icing performance and remarkable durability in extreme tests, thus opening up new applications in the marine industry.

To improve the wetting of a substrate by a lubricant, it is essential to increase the chemical affinity between them [65]. This can be achieved by reducing the surface energy of the substrate using a hydrophobic coating, which stabilizes the lubricant layer. Alternatively, modifying the substrate with functional groups or adding adhesive groups can also promote the stabilization of this layer. Lubricant layer stabilization is traditionally achieved by silanization, a process that removes hydroxyl (–OH) groups from the substrate using silane, resulting in the formation of covalent bonds between the silicon and the substrate via Si-O-M bonds (where M represents the substrate). The incorporation of functionality into silica can be achieved by various methods, depending on the type of functionalization and its properties (**Figure 4**). Traditional surface modification techniques are based on post-synthetic grafting, using compounds such as organosilanes, silazanes and chlorosilanes, which react with free silanol groups on the surface [66].

He *et al.* [67] proposed a novel sol-gel process for creating lubricant-impregnated surfaces, avoiding the use of multiple polyelectrolytes and post-treatments previously required. The process is based on the layer-by-layer assembly of nanostructured titanium dioxide onto 316 L stainless steel substrates, using a titanium (IV) butoxide solution in an ethanolic medium. The surfaces are then functionalized with fluorinated silanes and impregnated with a fluorinated lubricant, providing excellent liquid-repellent and antifouling properties. The resulting physicochemical characteristics enhance the antifouling performance of the surfaces. Zhang *et al.* [68] developed a surface functionalization strategy to make lubricants compatible with the surface by grafting a layer of polydimethylsiloxane (PDMS), thereby stabilizing a silicone oil layer. Jing and Guo [69] prepared lubricant-immobilized sliding surfaces (LISS) by grafting polydimethylsiloxane onto

ZnO nanorods, using silicone oil as the lubricant. The silicone oil adheres firmly to the zinc oxide, allowing a sliding angle of less than 3°. The LISS exhibit high omniphobia at room temperature and excellent sliding with hot liquids. In high-temperature tests, the liquids slide at angles of less than 4°. Under extreme conditions (shear speeds up to 7000 rpm, 400 hours of immersion, and in the presence of strong acids or bases), the LISS maintains remarkable stability and exhibits corrosion resistance, anti-icing, and anti-fouling properties, promoting its practical applications. Zhang *et al.* [70] fabricated a novel oil-in-water emulsion-type "armor" structure that allows for the spray deposition of an ultra-slippery coating made of polydimethylsiloxane (PDMS), silicone oil (SO), and waterborne epoxy resin (WEP). This flexible-rigid system, in which the WEP encapsulates the silicone oil and the PDMS gel, maintains 81.2% of its oil film even at 5000 rpm, while preserving its slippery properties. Furthermore, the PDMS gel enhances the adhesion between the WEP layer and the substrate, significantly increasing the coating's tensile strength to 38 N compared to 12 N for a pure PDMS coating. This solution improves lubricant retention and durability, while also providing superior corrosion resistance and antifouling performance. Xing *et al.* [71] designed a durable polydimethylsiloxane/silicone oil (PDMS-oil) system exhibiting mechanical strength and self-healing properties. Applied to a magnesium alloy, the PDMS-oil coating is formed by the polymerization of a PDMS layer followed by the diffusion of dimethyl silicone oil. An optimal oil concentration of 50 wt% ensures low shear strength, less than 30 kPa, after 20 freeze-thaw cycles. With a slip angle of approximately 30° under normal pressure of 10 kPa, the coating also demonstrates excellent corrosion resistance and self-healing capacity, remaining intact after 20 days in a 3.5 wt% aqueous NaCl solution.

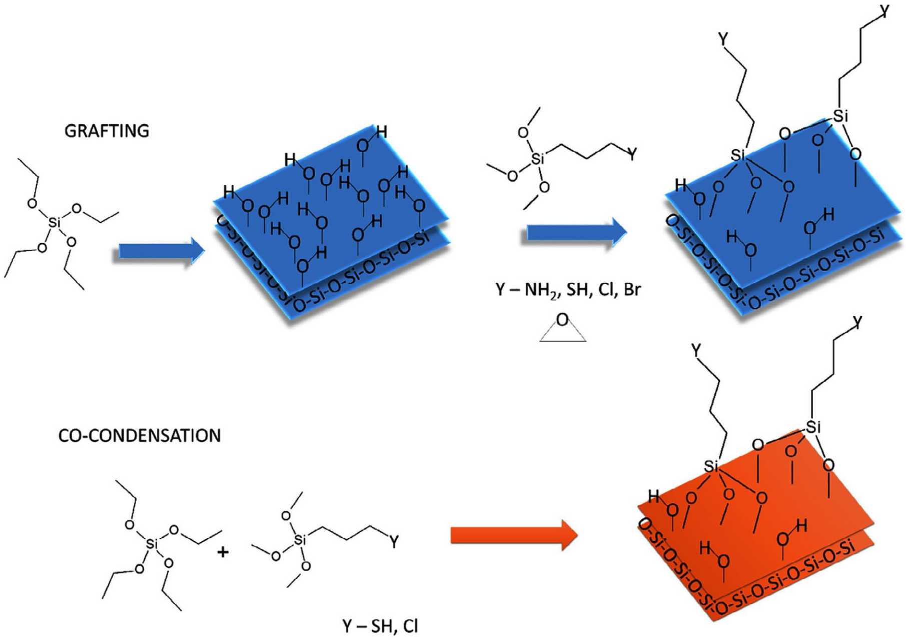

Figure 4. Scheme for obtaining organosilanes by grafting and co-condensation [66].

4. Conclusions

Superhydrophobic coatings hold great promise for a variety of industrial applications due to their exceptional properties. These coatings are self-cleaning, anti-fog, reduce drag, and offer corrosion resistance, as well as anti-icing characteristics. The development of superhydrophobic surfaces with anti-icing and de-icing properties represents a significant advancement in materials science. By integrating functional nanomaterials and strategically designing surface structures, these surfaces provide effective solutions against icing. This progress contributes to improved safety and efficiency in various industrial sectors, further solidifying their usefulness in applications where water management and icing prevention are critical.

Liquid-impregnated surfaces (SLIPS) offer great potential for antifouling coatings, repelling various liquids and facilitating self-cleaning. Created by impregnating a low-surface-tension liquid, they possess a smooth and homogeneous interface. These surfaces are stable under pressure and self-healing, but their performance depends on the amount of lubricant, which can be depleted through evaporation, drainage, or shearing. Understanding the mechanisms and pathways of lubricant depletion allows us to target the factors contributing to lubricant wear and failure, which is crucial for the development of more durable and efficient SLIPS materials. The surface topography is critically important in lubricant retention. Pore dimensions and surface porosity are key factors influencing the wetting behavior of SLIPS surfaces. Another significant method for optimizing lubricant retention is to increase the affinity between the substrate and the lubricant. This can be achieved by applying surface modifiers or polymers that act as crosslinking agents. Despite significant advances, the commercialization of SLIPS remains a distant goal. One of the main challenges is maintaining lubricant retention in surface protrusions. Among the most promising solutions are the creation of functionalized surfaces to increase the durability of SLIPS. Furthermore, integrating several strategies could offer additional benefits.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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