

Article

A Rapidly Self-Healing Superhydrophobic Coating Made of Polydimethylsiloxane and N-nonadecane: Stability and Self-Healing Capabilities

Qin Hu *, Ziyuan Hu , Xingliang Jiang, Hang Yang, Yuhao Liu and Yaya An

Xuefeng Mountain Energy Equipment Safety National Observation and Research Station, Chongqing University, Chongqing 400044, China; huziyuan@stu.cqu.edu.cn (Z.H.); xliang@cqu.edu.cn (X.J.); anyaya@stu.cqu.edu.cn (Y.A.)

* Correspondence: huqin@cqu.edu.cn; Tel.: +86-15902350007

Abstract: Superhydrophobic surfaces have garnered significant attention in various industrial applications, such as photovoltaic power generation, anti-icing, and corrosion resistance, due to their exceptional water-repellent properties. However, the poor durability of conventional superhydrophobic coatings has severely impeded their practical implementation. To achieve the dual self-recovery of microscale and nanoscale surface structures and maintain low surface energy after damage to superhydrophobic coatings, thereby enhancing their durability, a rapidly self-healing superhydrophobic coating was developed using polydimethylsiloxane (PDMS) and n-nonadecane in this study. The coating surface demonstrated exceptional hydrophobic characteristics, as evidenced by a water contact angle (WCA) of 157.5° and a sliding angle (SA) of 4.2° achieved at optimized proportions. Through scanning electron microscopy, it was observed that the coating surface exhibited a rough structure at both the microscale and nanoscale. The stability test results showed that the WCA only decreases by 5.7° and the SA only increases by 3.6° after 100 instances of external friction. The stability test results demonstrated that the superhydrophobic coating maintains excellent hydrophobicity under mechanical external forces and in acidic and alkaline environments. The results of the self-healing capability test showed that the WCA rebounded to 151.5° and 149.5° after we subjected the samples to 20 MPa of vertical pressure damage and chloroform exposure for 4 h, respectively. The coating regained a robust hydrophobic state even after experiencing repeated mechanical and chemical damage. The above results indicate that the resulting coating demonstrates outstanding durability, including high resistance to friction, stability against acids and alkalis, and the ability to self-recover hydrophobicity after repeated damage.

Keywords: superhydrophobic coating; stability; self-healing; mechanical durability; acid and alkali resistance



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1. Introduction

Superhydrophobic surfaces are characterized by a static water contact angle greater than 150°. Due to their outstanding water repellency, superhydrophobic surfaces have garnered significant attention in industrial production [1–10]. Prevo et al. [11] prepared a permeation-enhancing superhydrophobic coating with silica nanoparticles, resulting in a substantial reduction in reflected sunlight and a 17% increase in solar cell efficiency. Zhu et al. [12] investigated a superhydrophobic coating of PDMS nanoparticles using the heat treatment method. The results revealed that the material exhibited exceptional hydrophobicity and delayed the ice coverage rate, with test samples demonstrating a 71% delay in ice coverage compared with untreated glass. Qiao et al. [13] combined epoxy resin, PDMS, and hexadecyltrimethoxysilane (HDTMS)-functionalized Al₂O₃ nanoparticles to formulate a superhydrophobic composite coating. The coating demonstrated excellent anti-corrosion performance in both salt spray corrosion and atmospheric corrosion tests, rendering it suitable for application on ship hulls, pipelines, and other corrosion-prone

substrates. In biomedicine, hydrophobicity significantly influences the circulation and distribution of polymers within organisms [14]. Biomimetic superhydrophobic surfaces facilitate precise drug delivery to target sites at optimal times, thereby reducing toxic side effects and enhancing drug utilization efficiency and clinical efficacy [15]. However, superhydrophobic surfaces are highly susceptible to microscale and nanoscale structural decomposition, collapse, and the absorption of high-surface-energy substances, which can compromise their superhydrophobic properties [16,17]. In practice, the hydrophobicity of superhydrophobic surfaces is highly constrained.

In order to solve the problem of superhydrophobic surface durability, researchers have made many attempts at material preparation. Celik et al. [18] proposed the use of waxes and alkoxy-silane-functionalized nanoparticles to construct lamellar structures with dual hierarchical features through evaporation-driven self-assembly, ensuring that the surface maintains its superhydrophobic properties despite exposure to water spray impact, water jet impact, and abrasion. Xiao et al. [19] described a straightforward spraying technique for preparing a hydrophobic coating comprising F-HPU resin with La_2O_3 , highlighting its notable durability. Huang et al. [20] employed a one-step electrochemical process to achieve a chemically stable superhydrophobic copper surface. While there have been advancements in developing hydrophobic surfaces with mechanical or chemical durability, durable superhydrophobic surfaces can only endure minimal surface damage. However, their hydrophobic properties may diminish in more demanding usage scenarios.

Artificially endowing materials with self-healing functions has become one of the ideas to solve the durability problem of superhydrophobic surfaces. Most of the self-healing superhydrophobic coatings studied rely on the migration of low-surface-energy substances and molecular chain flipping [21–24]. By contrast, the replication of the microscale and nanoscale rough structures [25–27] of superhydrophobic surfaces and the subsequent achievement of superhydrophobic self-healing function have been infrequently documented. Restoring surface microscale and nanoscale rough structures is challenging compared with repairing low-surface-energy materials. The current self-healing process necessitates additional external conditions, such as heat and light, and does not constitute a genuine self-healing process.

Inspired by the superhydrophobic self-healing mechanism of epidermal cell diffusion and the regeneration of epidermal wax crystals in lotus leaves after being squeezed following damage [28], in this study, a self-healing superhydrophobic coating was prepared using PDMS, known for its good stability [29–31], and n-nonadecane, recognized for its low surface energy and good hydrophobicity [32]. The substrate structure was initially created by transferring micron-scale structures onto a PDMS template surface with the templating method, whereas the rough coating structure was formed by incorporating n-nonadecane into the preparation solution containing PDMS and epoxy resin. The coating enables the concurrent regeneration of microscale and nanoscale rough structures and facilitates low-surface-energy diffusion. In comparison with other research results, the coating can better restore hydrophobicity after mechanical and chemical damage repeatedly without external excitation and rapidly. This study aims to determine the optimal formulation of PDMS, epoxy resin, and n-nonadecane to develop a self-healing superhydrophobic coating that exhibits durability and hydrophobicity. This research is expected to advance the application of superhydrophobic surfaces in outdoor equipment defense and biomedical diagnosis.

2. Materials and Methods

2.1. Materials

Sylgard184 PDMS and curing agent were purchased from Dow Corning Co. in Shanghai, China, while neopentyl glycol diglycidyl ether, polyether amine, and epoxy resin were all purchased from Chongqing Xingguang Chemical Glass Co. in Chongqing, China. Ethanol (99.7%) was purchased from Donghang Reagent Co. in Dongguan, China. Deionized water was prepared in the laboratory. A Polytetrafluoroethylene (PTFE) plate was purchased from the Shanghai Xinhai Rubber and Plastic Products Factory in Shanghai,

China, and various grades of sandpaper were acquired from the local market. All materials and reagents were used directly without any prior treatment.

2.2. Preparation of Micrometer-Groove Negative Template

The PTFE plate is cut into a sample measuring $4\text{ cm} \times 4\text{ cm} \times 0.5\text{ cm}$ in size and then sanded with both 500-mesh and 2000-mesh sandpaper to achieve a smooth surface. The sample is ultrasonically cleaned using anhydrous ethanol and then with deionized water for 10 min each, ensuring the removal of all organic impurities from the PTFE surface. Microcolumn arrays are then processed onto the sample surface using an infrared picosecond laser etching device. The laser power output is set to 10 W, while the etching area covers an area of $2.5\text{ cm} \times 2.5\text{ cm}$. Because the laser etching process must remain coherent to effectively etch grooves in the surface, the protruding part of the surface within the etching range is carved to $20\text{ }\mu\text{m} \times 20\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$, with intervals of $10\text{ }\mu\text{m}$ between the protrusions. After completing the laser processing, the sample undergoes another round of ultrasonic cleaning. Figure 1 illustrates the preparation process for PDMS-negative templates. PDMS and its curing agent are meticulously mixed in the recommended mass ratio of 10:1. The PTFE template is placed in a mold, and the PDMS mixture is poured onto the template surface for casting, allowing it to fully immerse into the microscale and nanoscale structures. Subsequently, a drying oven is preheated to $80\text{ }^{\circ}\text{C}$, and the mold is placed inside and heated for two hours to allow PDMS crosslinking to cure. Finally, the replicated PDMS-negative template with micrometer-groove structures is carefully removed.

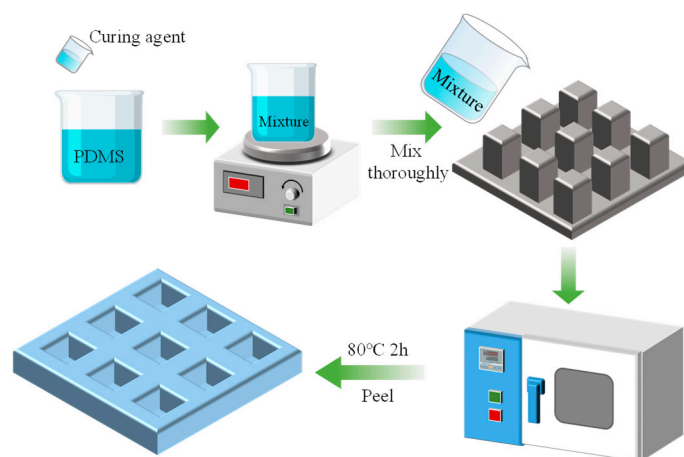


Figure 1. PDMS-negative template preparation process.

2.3. Preparation of Rapidly Self-Healing Superhydrophobic Coating

Figure 2 illustrates the process of preparing a rapidly self-healing superhydrophobic coating. Initially, 2 g of epoxy resin, 0.6 g of neopentyl diglycidyl ether, and 0.94 g of polyether amine are placed in 50 mL of anhydrous ethanol based on their respective molar ratios. The solution is stirred using a magnetic stirring apparatus at room temperature for 30 min until the three substances are completely dissolved. PDMS and its curing agent are thoroughly mixed in the recommended mass ratio of 10:1 and then added to the previous solution and mixed well, waiting for use. Next, the PDMS-negative template from the previous step is placed in a mold, and the mixture is cast onto the micrometer grooves of the template, allowing the mixture to fully immerse in the microscale and nanoscale structures. Subsequently, the entire mold is placed in a drying oven set to $80\text{ }^{\circ}\text{C}$, allowing the mixture to crosslink for 2 h, and then, the temperature is increased to $100\text{ }^{\circ}\text{C}$ for an additional hour to cure the mixture. Finally, the PDMS-negative template is removed to reveal a shape memory polymer composed of epoxy resin. The superhydrophobic coating is created by allowing the material to stand at room temperature for 24 h following n-nonadecane diffusion.

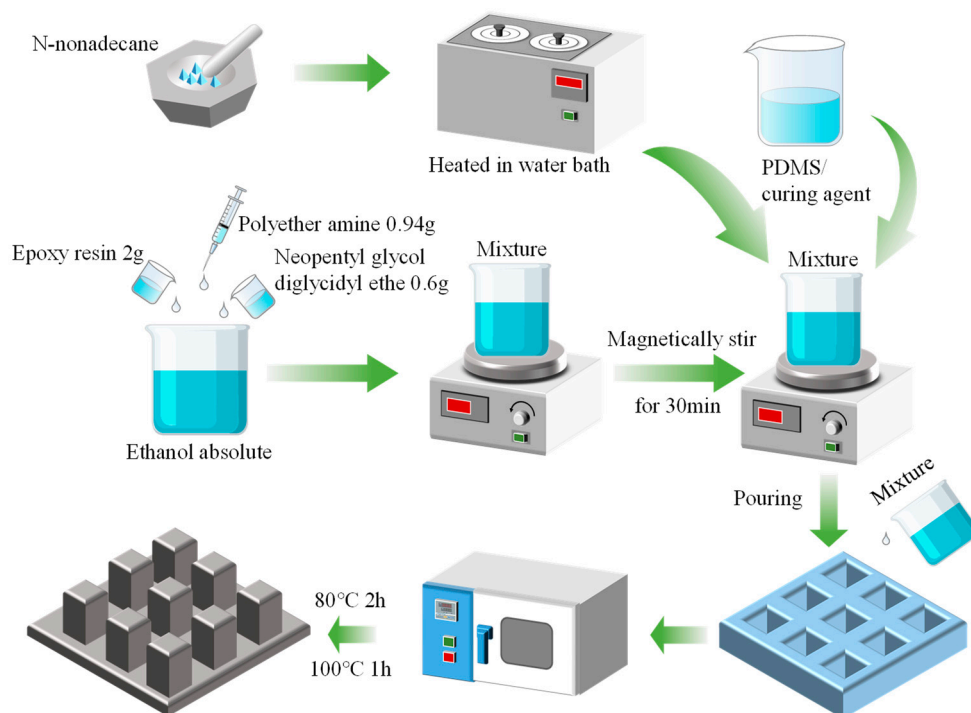


Figure 2. Preparation of rapidly self-healing superhydrophobic coating.

2.4. Surface Characterization

The surface morphology and roughness of the coating are observed and measured using a scanning electron microscope (SEM, QuattroS, Thermo Fisher Scientific, Waltham, MA, USA) at an electron accelerating voltage of 20 kV and various magnifications (200 $\times$, 1000 $\times$, 2000 $\times$, and 50,000 $\times$). X-ray photoelectron spectroscopy (XPS, Thermo escalab 250Xi, Thermo Fisher Scientific, USA) is employed to analyze the chemical components of the coating, operating at 1486.6 eV with 150 W Al K α radiation.

2.5. Surface Wettability

Typically, the volume of test water droplets for contact angle measurement is set at 5 μ L [33], but the water droplets are unable to rest on the hydrophobic coating surface. This occurs because the adhesion between the hydrophobic solid surface and the water droplets is weaker than the adsorption force of the micro-needle to the droplets. Based on our references [34,35], a droplet volume of 20 μ L of deionized water is used in the test. Surface wettability is measured using the optical contact angle meter (SDC-100, Huashitong Precision Instrument Co., Foshan, China) to assess the WCA and SA of deionized water on the surface. To minimize errors due to variations in measurement points, three distinct points on the surface are tested, and their average value is considered the test result.

2.6. Mechanical Durability Test

As per the reciprocating motion abrasion test method specified in ISO8251-2011 [36], the test is conducted by pushing the sample with a load of 5 Kpa (500 g weight, Changzhou Fuyue Weights Co., Liyang, China) at a constant speed of 7 cm/s over a distance of 20 cm on sandpaper (400-grit, Anjichang Grinding Technology Co., Shanghai, China). The completion of this recorded displacement constitutes one abrasion cycle. Both the sandpaper and sample surfaces are kept free of loose powder or wear debris throughout the test. The WCA and SA of the samples after 20, 40, 60, 80, and 100 instances of mechanical abrasion are tested using an SDC-100 optical contact angle meter.

2.7. Acid and Alkali Resistance Test

According to the GB/T9274-1988 [37] standard for determining the liquid medium resistance of color paints and varnishes, the acid and alkali resistance of superhydrophobic coatings is tested using the immersion method. Solutions of sulfuric acid, deionized water, and ammonia with pH levels of 5, 7, and 9 are prepared. Four samples are placed in each of the three solutions and immersed for 1, 2, 4, and 7 days. After removal and drying, the WCA and SA of the samples are tested using an SDC-100 optical contact angle meter.

2.8. Test of Surface Hydrophobicity Self-Healing following Mechanical Damage

The coating sample is placed in a pressure mold at 0 °C and removed after exposure to 20 MPa for 5 min; the hydrophobicity of the coating surface is then tested. The hydrophobicity of the coating surface is assessed before and after compression and at various recovery intervals following damage. Subsequently, the surface undergoes multiple instances of mechanical damage to assess its hydrophobicity self-healing capability.

2.9. Test of Surface Hydrophobicity Self-Healing following Chemical Damage

The sample surface is immersed in n-hexane for 30 s to fully dissolve the n-nonadecane coating in chloroform. Following the dissolution of n-nonadecane on the coating surface, the sample is then removed. The chemically damaged surface is achieved after the natural evaporation of n-hexane on the coating surface. Hydrophobicity is tested before and after chemical damage and at various recovery intervals following damage. Ambient temperature should be maintained at 0 °C during the recovery process. Subsequently, the surface undergoes multiple instances of chemical damage to assess its hydrophobic self-healing capability.

3. Results and Discussion

3.1. Optimal Ratio of PDMS to Epoxy Resin

In this experiment, n-nonadecane is excluded to determine the optimal epoxy resin-to-PDMS volume ratio. The superhydrophobic coating is prepared as described above, and the mixture is adjusted to various volume ratios of epoxy resin to PDMS: 5:1, 4:1, 3:1, 2:1, 1:1, 1:2, 1:3, 1:4, and 1:5. Hydrophobicity is measured for each of the nine samples separately, and Figure 3a illustrates the WCA and SA across different volume ratios.

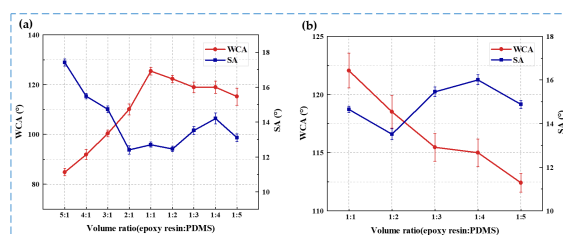


Figure 3. (a) Hydrophobicity of samples with different epoxies and PDMS volume ratios; (b) hydrophobicity of samples with different epoxies and PDMS volume ratios after 50 instances of wear.

As shown in Figure 3a, the hydrophobicity of the coating first increases and then decreases as the volume ratio of PDMS in the mixture increases, and the decrease is small. The experimental results indicate that there is no significant difference in the SA among volume ratios of 2:1, 1:1, or 1:2, with all ratios performing equally well compared with the other samples. Specifically, the WCA reaches its optimum value of 125.4° across all samples when the volume ratio is 1:1. Therefore, the optimally integrated hydrophobicity is achieved when the epoxy resin-to-PDMS volume ratio is 1:1. Moreover, within the above volume ratios, none of the contact angles could decrease to below 10°. While the PDMS surface possesses micrometer-scale roughness and provides a certain degree of low surface energy, the absence of nanostructures provided by nonadecane results in a failure to form the microscale and nanoscale rough structures required for superhydrophobic surfaces.

Mechanical durability tests are continued on samples with volume ratios of 1:1, 1:2, 1:3, 1:4, and 1:5, and hydrophobicity tests are repeated on each of the four samples after sandpaper abrasion. The results are depicted in Figure 3b. The results indicate that the sample with a 1:1 volume ratio of epoxy resin to PDMS maintained good WCA and SA after 50 wear cycles. Considering both hydrophobicity and abrasion resistance, a volume ratio of 1:1 provides the best combined result for both properties. Consequently, a 1:1 volume ratio of epoxy resin to PDMS is selected for material preparation during subsequent studies.

3.2. Optimum Quality Fraction of N-nonadecane

Ten different n-nonadecane mass fractions (2%, 4%, 6%, 8%, 10%, 12%, 14%, 16%, 18%, and 20%) are employed in the coating preparation to determine the optimal n-nonadecane mass fraction. Due to the large number of samples, lotus leaf slices were directly used as templates in the preparation process to expedite the procedure. The initial samples are depicted in Figure 4b. After a 24 h resting period, the surface hydrophobicity of these 10 samples was individually tested.

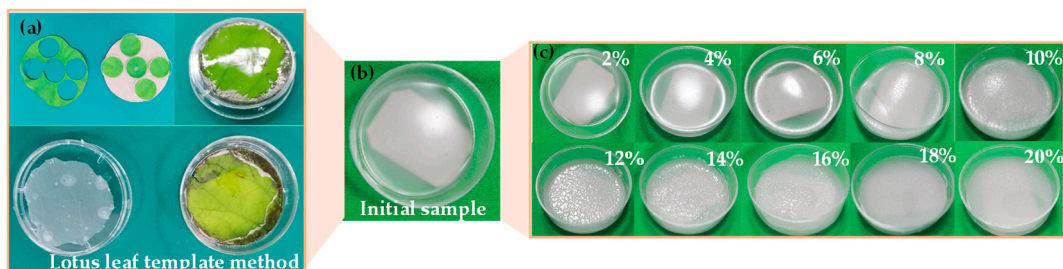


Figure 4. (a) Lotus leaf template; (b) initial sample; (c) the samples after 24 h.

The test results in Figure 4c indicate that n-nonadecane precipitated from all 10 samples after 24 h of rest, and the surface roughness initially increased and then decreased with the gradual increase in n-nonadecane content. The test results in Figure 5 also show that the static WCA increases and then decreases with increasing n-nonadecane content. At a mass fraction of 10% n-nonadecane, the coating exhibits a WCA of 149.3° and an SA of 8.3° , both of which simultaneously reach optimal levels among all tested samples, demonstrating superior hydrophobicity. Therefore, an n-nonadecane mass fraction of 10% is selected to participate in the preparation of rapidly self-healing superhydrophobic coating.

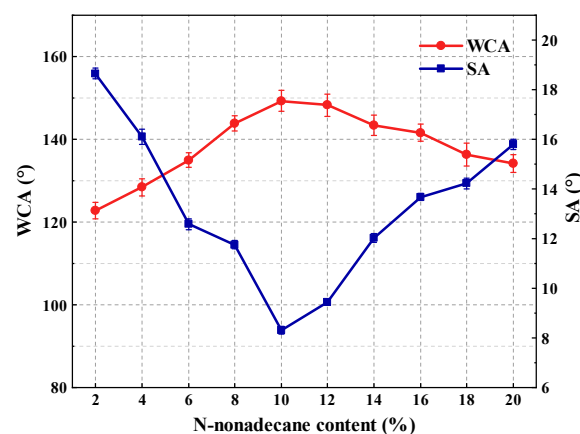


Figure 5. Hydrophobicity test of the samples after resting for 24 h.

As n-nonadecane diffuses into the coating's surface, driven by concentration differences between the surface and substrate interior, it forms a rough structure. With low n-nonadecane content, it is completely encapsulated by PDMS, insufficient for forming micro–nanostructures or generating adequate air pockets, resulting in lower coating hydrophobicity. When the n-nonadecane content is too high, the micron structure of the

coating surface becomes insufficient for accommodating all the n-nonadecane, leading to agglomeration. The limited PDMS cannot effectively provide low surface energy for the excessive n-nonadecane, resulting in lower coating hydrophobicity [38]. The maximum WCA of the coatings does not reach 150° in this exploratory preparation, possibly because laser-etched PTFE is not used as a template, resulting in insufficient micron-scale roughness.

3.3. Surface Morphology and Component Analysis

XPS and SEM are used to examine the surface morphology and analyze the components of the coating. Figure 6 illustrates the XPS elemental analysis of the coating, which shows the characteristic absorption peaks of elements such as C, O, Si, and N. The XPS result shows the presence of C, O, Si, N, and other elements in the coating, proving the presence of PDMS, epoxy resin, and n-nonadecane in the coating.

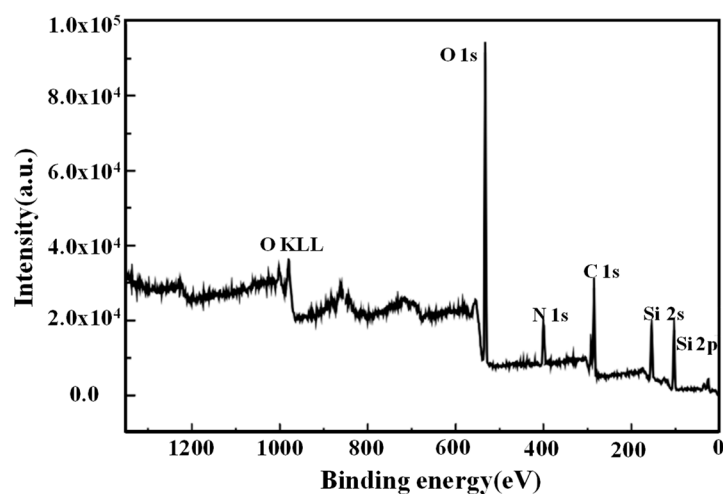


Figure 6. XPS elemental analysis of the coating.

Figure 7 shows the morphology of the rapidly self-healing superhydrophobic surface at different scales. In Figure 7a, the spacing between the micrometer columns measures approximately $10\ \mu\text{m}$, and rough structures are visible within this spacing. Zooming in on the macroscopic morphology, nanoscale rough structures can be observed on the micrometer columns, as shown in Figure 7c–e. The SEM results show that the surface of the prepared coatings exhibits microscale protrusions with n-nonadecane particles adhering to them. The microscale columnar structures originate from the PDMS-negative templates, and the rough structures between the spacings are caused by the laser etching of the PTFE templates. Thus, n-nonadecane, along with microscale and nanoscale columns, collectively forms a dual microscale and nanoscale structure on the coating surface.

According to Cassie's model [39],

$$\cos \theta_{CB} = f(1 + \cos \theta) - 1 \quad (1)$$

Here, θ_{CB} is the apparent contact angle in the Cassie–Baxter state, while f is the solid-phase contact surface fraction, and θ is the single-phase contact angle. A high contact angle on the surface can be achieved by minimizing the solid-phase contact fraction according to Equation (1). The rough microscale and nanoscale structure of the sample surface reduces the solid–liquid contact fraction, f , resulting in a larger apparent contact angle, θ_{CB} . Consequently, the roughness results in the enhanced hydrophobicity of the coating.

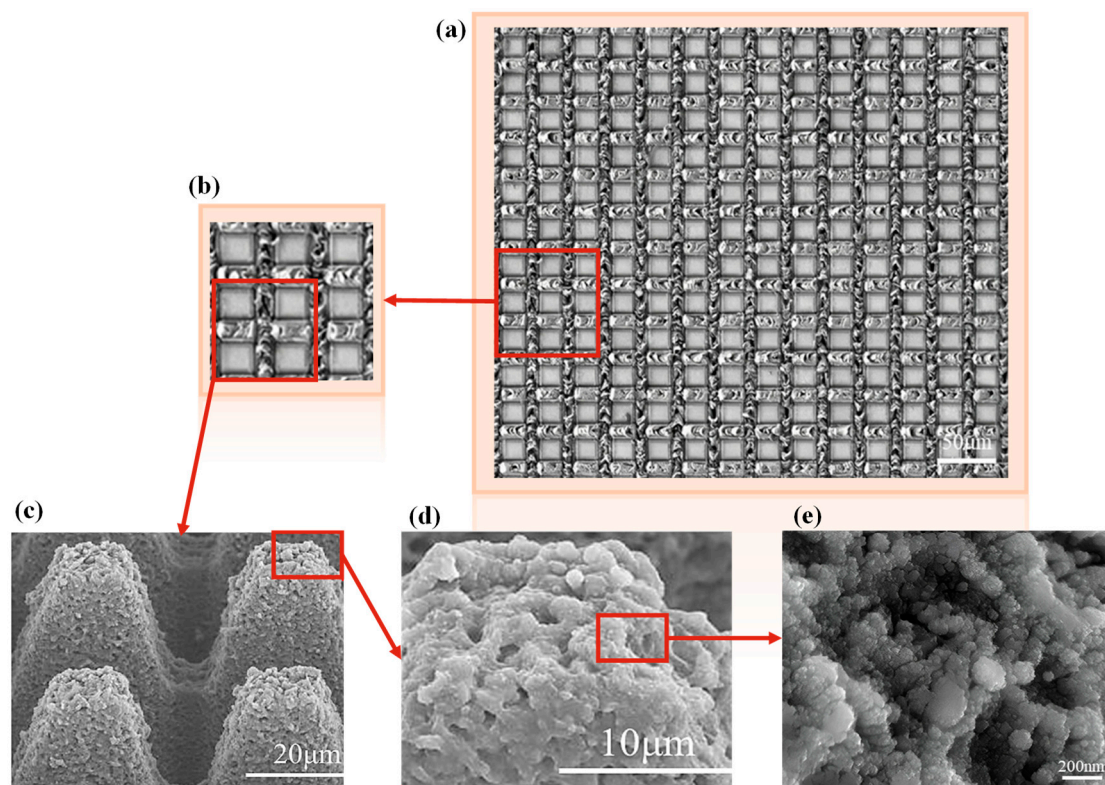


Figure 7. (a) Surface morphology of rapidly self-healing superhydrophobic coating; (b) partial enlargement of the coating; (c) apical structure of a micrometer column; (d) n-nonadecane particles on top of a microscale protrusion; (e) nanoscale roughness structure.

3.4. Stability

The analysis of stability performance consists of two primary parts: mechanical durability and acid and alkali resistance. The first aspect examined is the mechanical stability of the coating (Figure 8a). The hydrophobicity test results for the prepared sample after varying friction cycles are presented in Figure 8b. The hydrophobicity of the prepared superhydrophobic coatings diminishes with an increase in the number of frictions, but the reduction is not substantial. The WCA decreases by a maximum of 5.7° , and the SA increases by a maximum of 3.6° . Even after 100 friction cycles, the surface of the coating remains highly hydrophobic and can reach the superhydrophobic standard. This implies that the roughness and low surface energy of the coating surface decrease due to mechanical damage as the number of frictions increases, but the remaining polymer coating still maintains a level of hydrophobicity.

To analyze the changes in hydrophobicity of the coating in different pH solutions, an acid and alkali resistance test is conducted, and the results are presented in Figure 9a–c. The findings indicate that the coating maintains strong hydrophobicity after prolonged immersion in acidic, alkaline, and neutral solutions. Specifically, the WCA and SA of the coating are nearly constant in the neutral solution, suggesting that the neutral solution does not cause corrosion to the coating and that the coating can maintain hydrophobicity. In acidic or alkaline solutions, the hydrophobicity of the sample decreases slightly. The WCA decreases by up to 8.1° , and the SA increases by up to 1.3° .

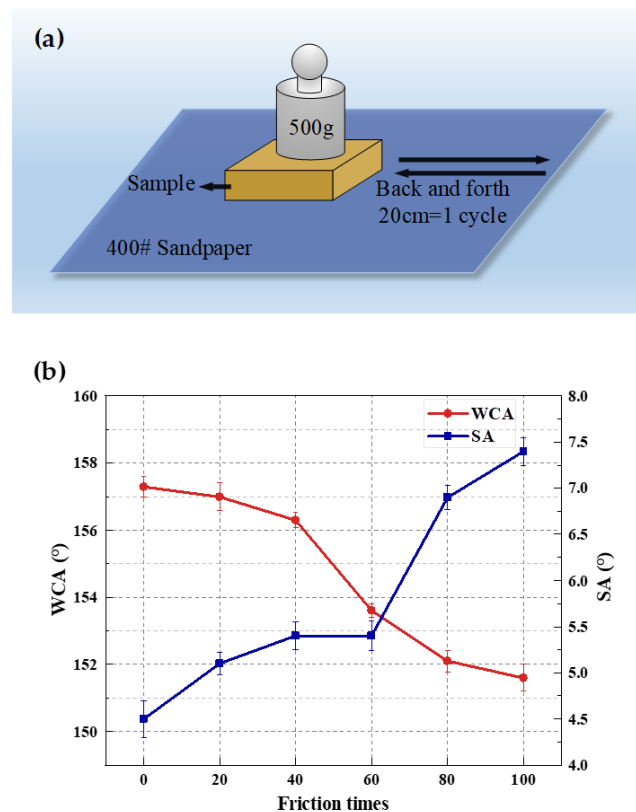


Figure 8. (a) Mechanical durability test diagram; (b) surface hydrophobicity after different friction times.

The hydrophobicity of the coating decreases slightly in acidic solutions, but the WCA is still greater than 150° . The decrease in hydrophobicity occurs because, when the raw coating material is incompletely crosslinked, acidic conditions catalyze the hydrolysis of PDMS, leading to the formation of polymers like dimethylsilanediol [40], which possess a slightly higher surface energy. However, the epoxy resin in the coating has excellent acid resistance, and n-nonadecane is insoluble in sulfuric acid. Therefore, during the immersion process, the component particles of the coating do not react with the acidic solution, and these particles are able to migrate to the surface of the resin to act as a shielding barrier so that the coating maintains excellent hydrophobicity. On the other hand, the roughness structure of microscale and nanoscale particles embedded in the resin forms numerous air cavities that act as a protective layer, preventing acidic liquids from infiltrating the interior and maintaining the coating's hydrophobicity. The small decrease in the hydrophobicity of the coating following immersion in alkaline solutions is due to the presence of siloxane groups in PDMS. The reaction of siloxane groups with water in alkaline solutions results in the alkaline hydrolysis of siloxane groups and the formation of silicates. This chemical reaction may result in the degradation of PDMS [41]. The reaction process of PDMS in alkaline solutions within the coating is depicted in Figure 10. Therefore, the degradation of PDMS and the formation of silicates reduce the hydrophobic durability of the coating in alkaline solutions compared with acidic solutions.

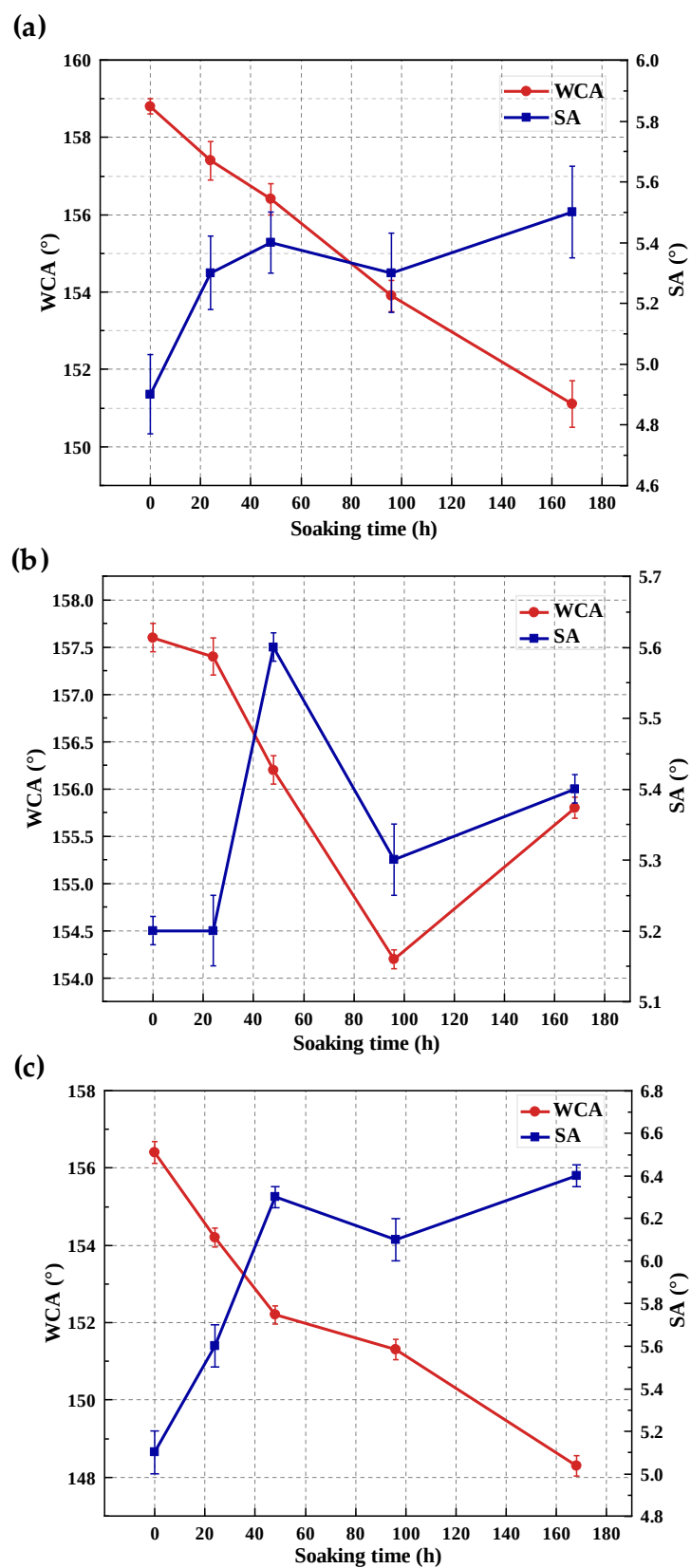


Figure 9. (a) Hydrophobicity changes in acidic solution; (b) hydrophobicity changes in neutral solution; (c) hydrophobicity changes in alkaline solution.

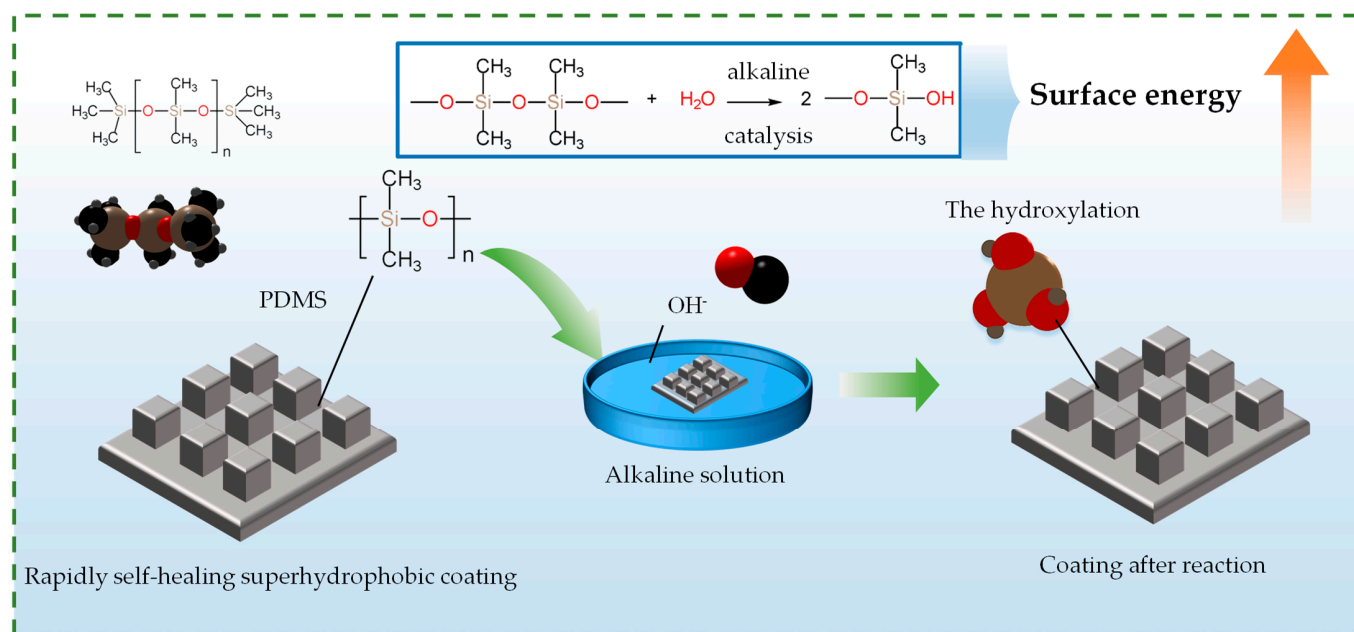


Figure 10. Reaction of PDMS in alkaline solutions.

3.5. Self-Healing Capability

A hydrophobicity self-healing test after mechanical damage is used to evaluate the self-healing capability of the coating. As shown in Figure 11a, the hydrophobicity of the coating deteriorates dramatically when pressure is applied perpendicularly to the surface, and the WCA decreases to 121.6° when the pressure is withdrawn. This suggests that the height of the microscale protrusions composed of epoxy resin and PDMS is compressed under continuous pressure, resulting in decreased roughness. After the pressure is withdrawn, the WCA rapidly recovers, taking only 4 h to return to 151.5° . The SA rises to 18.6° after the damage, as the nanostructures formed by *n*-nonadecane are disrupted under pressure. These nanostructures begin to recover gradually as *n*-nonadecane diffuses after the pressure is withdrawn, and the recovery process takes longer than that of the microscale protrusions. The SA recovers to below 10° within 24 h. Figure 11b,c show the test results for the recovery of the WCA and SA after the coating is mechanically damaged multiple times. The results illustrate that the prepared coatings can quickly recover to a state of strong hydrophobicity even after repeated mechanical damage, indicating that the coating possesses excellent self-healing capability.

Figure 11d illustrates the self-healing process of hydrophobicity following chemical damage. The WCA is measured at 142.5° post-damage, representing a minimal decrease from the initial WCA, and it can be restored to 149.5° within 4 h after damage. This outcome indicates that the height of microscale protrusions composed of epoxy resin and PDMS remains largely unaltered following chemical damage. Microscale protrusions significantly influence the static contact angle. Hence, the reduction in WCA can be attributed to *n*-hexane displacing *n*-nonadecane from the coating surface. The SA rises sharply to 25.8° post-damage. This is primarily because *n*-hexane dissolves *n*-nonadecane, causing the complete loss of the nanoscale surface structure. The nanostructure begins to gradually recover with the diffusion of *n*-nonadecane post-damage. Repeated chemical damage tests were conducted to evaluate the recovery of WCA and SA. The results are presented in Figure 11e,f. The results illustrate that the coatings can quickly recover to a robust hydrophobic state after repeated chemical damage, showcasing the excellent self-healing capability of the coating.

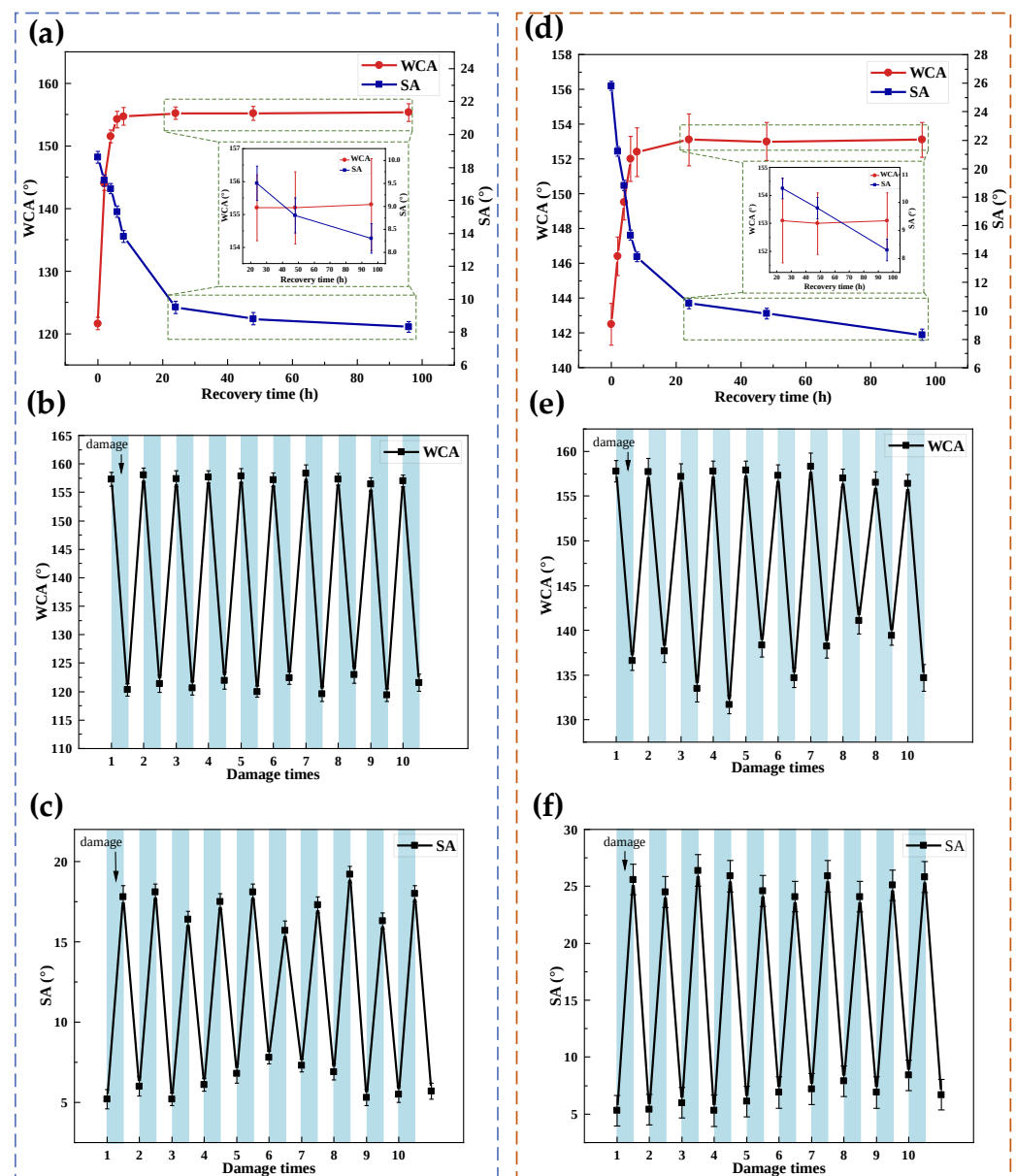


Figure 11. (a) Hydrophobic self-healing of the coating following mechanical damage; (b) the WCA following different mechanical damage cycles; (c) the SA following different mechanical damage cycles; (d) hydrophobic self-healing of the coating following chemical damage; (e) the WCA following different chemical damage cycles; (f) the SA following different chemical damage cycles.

At room temperature, *n*-nonadecane forms a coarse solid structure on the coating surface. When the surface is damaged, the *n*-nonadecane nanoparticles are stripped from the surface by mechanical or chemical damage, and the roughness decreases. Due to the significant concentration gradient of *n*-nonadecane between the interior and the surface of the coating, the diffusion rate of *n*-nonadecane from the interior to the surface increases. During the diffusion process, most of the nanoparticles are able to fill the voids on the surface. When the surface components are almost the same as those on the initially prepared coating surface, the coating surface restores the nanoscale rough structure formed by *n*-nonadecane, and the self-healing of *n*-nonadecane on the coating surface is achieved. As the surface nanostructures are regenerated and replenished, the concentration gradient of internal and external nanoparticles decreases, the diffusion rate decreases, and the rate of hydrophobicity recovery slows down gradually with increasing time. Therefore, the surface

hydrophobicity generally exhibits a trend of rapid recovery in the early stage followed by slower recovery in the later stage.

4. Conclusions

This paper employs the template method to prepare a rapidly self-healing superhydrophobic coating by combining PDMS and n-nonadecane. This study explores the factors influencing the coating; identifies the optimal ratio of PDMS, epoxy resin, and nonadecane; and investigates the coating's self-recovery performance after damage at 0 °C. The research conclusions can be derived as follows.

Using epoxy resin, PDMS, and n-nonadecane as raw materials, the template method is successfully employed to prepare a rapidly self-healing superhydrophobic coating. This study identified the optimal ratios for preparing the coating, revealing that the best volume ratio of epoxy resin to PDMS is 1:1, and the ideal mass fraction of n-nonadecane is 10%, resulting in the highest hydrophobicity.

The resulting coating exhibits excellent resistance to friction, acids, and alkalis. It retains good hydrophobicity even after 100 instances of sandpaper abrasion and shows virtually no change in hydrophobicity after being immersed in acid and alkaline solutions for seven days.

A mechanically and chemically damaged rapid self-recovery superhydrophobic coating was studied to understand the hydrophobicity recovery process. The results indicate that the coating temporarily loses its surface hydrophobicity under vertical pressure or after n-hexane dissolution. However, once the external conditions are removed, the coating can spontaneously recover without any additional stimuli, with a recovery time of approximately 4 h. Multiple damage tests demonstrate that the coating possesses the ability to repeatedly restore its hydrophobicity.

The developed coating exhibits the ability to restore its hydrophobicity multiple times after damage without requiring any external stimuli, thereby enhancing the durability of superhydrophobic materials. This coating shows promise for application in the field of biomedical smart diagnostics, where its superhydrophobic properties can reduce non-specific adsorption and improve the sensitivity of biosensors over extended use. Additionally, when applied to the surfaces of electrical equipment, this coating is expected to enhance the equipment's resistance to electrical hazards in harsh outdoor environments, such as icy or salt spray environments. However, specific application scenarios for the coating have not yet been experimentally studied. Future research should focus on analyzing and discussing the coating's anti-icing and anti-corrosion effects in the context of electrical equipment, particularly under severe outdoor conditions.

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