

Review

Stretchable Superhydrophobic Surfaces: From Basic Fabrication Strategies to Applications

Wendong Liu ^{1,*} , Xiaojing Wang ¹, Siyuan Xiang ², Yuechang Lian ¹ and Shengyang Tao ^{1,*}

¹ School of Chemistry, Dalian University of Technology, Linggong Road 2, Dalian 116024, China; wxj2022@mail.dlut.edu.cn (X.W.); 13102968173@mail.dlut.edu.cn (Y.L.)

² Academy of Food Interdisciplinary Science, School of Food Science and Technology, Dalian Polytechnic University, Qinggongyuan 1, Dalian 116034, China; xiangsiyuan0903@outlook.com

* Correspondence: liuwendong@dlut.edu.cn (W.L.); taosy@dlut.edu.cn (S.T.)

Abstract: Superhydrophobic surfaces find extensive applications in various fields, including self-cleaning, liquid manipulation, anti-icing, and water harvesting. To achieve superhydrophobicity, the surfaces are designed with hierarchical nano- and/or microscale protrusions. These structures result in a static contact angle above 150° and a sliding/rolling-off angle below 10° when water droplets deposit on the surface. The combination of hierarchical structures and low-surface energy materials contributes to this unique liquid-repellent property. In addition to liquid repellency, the durability of these surfaces is crucial for practical applications, which has prompted the exploration of stretchable superhydrophobic surfaces as a viable solution. The flexibility of these surfaces means that they are effectively safeguarded against mechanical damage and can withstand daily wear and tear. Over the last decade, considerable research has been dedicated to developing stretchable superhydrophobic surfaces to expand their potential applications. This review provides an overview of stretchable superhydrophobic surfaces, specifically emphasizing current processing strategies and their prospective applications. Additionally, we present a forward-looking perspective on future fabrication methods to create robust superhydrophobic surfaces, further enhancing their practicality and versatility.

Keywords: superhydrophobic surface; stretchable; elastomer; low surface energy; strain sensing; anti-corrosion; oil–water separation; anti-icing



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1. Introduction

Drawing inspiration from nature's super-liquid-repellent phenomena, such as lotus leaves and moth eyes, superhydrophobic surfaces possess exceptional water-repellent properties. When water droplets are deposited on these surfaces, they exhibit almost perfect spherical shapes due to the high receding contact angle, typically above 150°, and a sliding or rolling-off angle below 10° [1–3]. The superhydrophobicity of these surfaces is primarily attributed to the combination of micro/nano/hierarchical physical structures and low-surface energy materials. This synergistic integration enables water droplets to establish a *Cassie–Baxter* contact state, wherein an air layer forms between the droplet and the solid substrate. This unique wetting status ensures that the droplets maintain their spherical morphology while preventing the liquid from wetting the rough protrusions [4,5]. Thus, retaining the *Cassie–Baxter* contact with an air layer is crucial for mechanical durability and operational stability when fabricating superhydrophobic surfaces.

Due to their low liquid adhesion and the extremely small contact area between water droplets and the solid substrate, superhydrophobic surfaces hold significant potential in diverse fields, including antifouling [6–9], oil–water separation [10–15], self-cleaning [16–18], and anti-corrosion applications [19,20], among others [21–27]. Researchers have already

explored various strategies to achieve superhydrophobic surfaces [28–35]. However, significant limitations for practical applications still exist due to cost-intensive manufacturing processes and the durability drawbacks associated with rigid and fragile inorganic micro/nano/hierarchical structures [36–39]. Consequently, the development of superhydrophobic surfaces with enhanced durability is a significant challenge.

In contrast to rigid and brittle inorganic materials, soft materials, such as polymers, rubbers, and elastomers, can maintain their properties after experiencing mechanical deformations such as bending, pressing, and stretching. This distinctive feature offers an opportunity to create soft superhydrophobic surfaces with greatly improved durability. Based on this, stretchable superhydrophobic surfaces have emerged in recent years [40–46]. The primary objective is to extend the lifetime of super hydrophobic surfaces in practical applications and expand their use in wearable electronics, strain sensors, and other flexible devices [47–51]. The fundamental principle behind developing stretchable surfaces involves incorporating soft materials into fabrication. The incorporation imparts flexibility to the superhydrophobic surfaces, enabling them to withstand mechanical deformations and be applied on curved or irregular surfaces, thereby widening their range of applications. The incorporation of soft materials also facilitates the recovery of intrinsic hydrophobicity after mechanical deformation, ensuring that the micro/nanostructures revert to their rough surface topography. This, in turn, bestows the superhydrophobic surfaces with improved durability and sustainability.

In this paper, we first reviewed strategies used to prepare stretchable superhydrophobic surfaces. We then highlighted representative applications of stretchable superhydrophobic surfaces with enhanced durability. The introduction of soft materials into the manufacturing process unlocks new possibilities for utilizing superhydrophobic surfaces in various industries. Finally, a conclusion and a forward-looking perspective on evolving fabrication techniques for stretchable superhydrophobic surfaces was presented, offering valuable insights for future research endeavors.

2. Strategies for Achieving Stretchable Superhydrophobic Surfaces

A stretchable superhydrophobic surface employs soft materials (elastomers) as integral components, providing the necessary flexibility to withstand mechanical deformation while maintaining its surface properties. Based on the way that elastomers integrate, the fabrication strategies can be categorized into three main categories: covering elastomers with a layer of rough and low surface energy materials; hybridizing functional materials in elastomers; and directly manufacturing rough surfaces utilizing bulk elastomers (Figure 1).

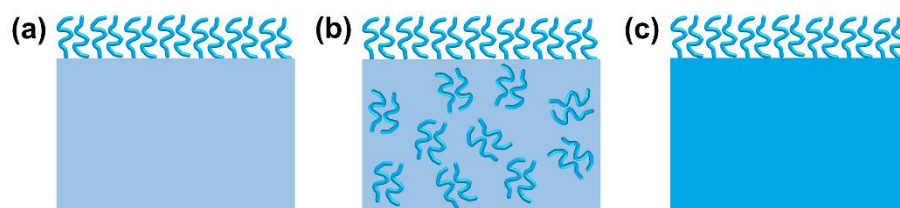


Figure 1. Schematic of the strategies for stretchable superhydrophobic surface manufacturing: (a) covering elastomers with a layer of rough and low surface energy materials, (b) hybridizing functional materials in elastomers, and (c) directly manufacturing rough surfaces utilizing bulk elastomers.

2.1. Covering Elastomers with a Layer of Rough and Low Surface Energy Materials

When the superhydrophobic surface suffers a large mechanical deformation, such as bending, compression, and stretching, the rough structures change significantly, resulting in the wetting transition from *Cassie–Baxter* to *Wenzel* or even in the loss of superhydrophobic characteristics. Therefore, maintaining the critical surface roughness in stretchable superhydrophobic surfaces under mechanical deformation is crucial to retain their water repellency. Covering elastomers with a layer of rough and low surface energy materials offers an efficient solution to meet this requirement. As demonstrated in Figure 1a, an

additional layer of materials possessing specific physical structures and low surface energy is covered on top of the elastomer substrate. The post-covered layer endows the complex surface with the necessary physical roughness and surface chemistry for achieving superhydrophobicity. Meanwhile, the elastomer imparts flexibility to the surface and endows the obtained complex surface with stretchability. The structured layer adheres firmly to the substrate, preserving low surface tension materials and physical roughness even when the surface undergoes stretching, enhancing superhydrophobicity durability.

By employing a spray-coating technique, Zhou et al. achieved a breakthrough in fabricating stretchable superamphiphobic surfaces by manipulating deformable structures induced by mechanical forces [52]. The pre-stretched cis-1,4-polyisoprene substrate was coated with silicone nanofilaments through spray coating. This technique led to the creation of sub-microscale re-entrant structures anchored to the substrate by a layer of poly(dimethylsiloxane) (PDMS) acting as a binding agent. After a subsequent fluorination step with trichloro (1H,1H,2H,2H-heptadecafluorodecylsilane), the resultant surface was proficient not only in repelling water but also low surface tension liquids (i.e., n-hexadecane). Evidenced by contact angles for water and n-hexadecane, both larger than 150° , the surface demonstrated superamphiphobicity (Figure 2a). The spraying process engendered rearrangeable hierarchical configurations by taking advantage of the inherent structure of silicon nanofilaments. Subsequently, upon the release of substrate tension following fabrication, the surface underwent the formation of relatively compact structures. This amalgamation of looser and denser structural attributes aligning with the prerequisites for liquid-repellent surfaces conferred the composite surface with an innate stretchability. The orchestrated interplay between the reconfiguration of surface structures (involving the disintegration of prominent nanofilament clusters and the orchestrated movement of hierarchical components with each other) combined harmoniously with the presence of the PDMS-binding layer, endowing the surface with heightened resistance to surface deformation, culminating in unwavering liquid repellency and sustained surface morphology, even after enduring a rigorous regimen of 1000 cycles of stretching (100%) and release (Figure 2b). This remarkable achievement, stemming from the ingenious manipulation of deformable structures and strategic binding, not only upholds the promise of versatile lab-on-a-chip applications but also holds the potential for significant cost savings, opening up new horizons in various scientific and technological domains.

Lin et al. introduced an exceptionally stretchable superhydrophobic surface, denoted as F/Ag/MWCNTs/G-PDMS (FAMG), assembled in a layered configuration using a layer-by-layer spray-coating approach. The surface was used for the creation of ultra-sensitive strain sensors [53]. The FAMG sensor was meticulously fabricated by applying a sequential spray-coating of 3-(aminopropyl) triethoxysilane (APTES) and a composite of multi-walled carbon nanotubes/graphene (MWCNTs/G) onto a flexible elastomeric PDMS substrate. The APTES and MWCNTs/G layers served as a binding agent and a conductive layer, respectively. This three-layered arrangement was then further modified with the integration of silver (Ag) nanoparticles and (heptadecafluoro-1,1,2,2-tetradecyl) trimethoxysilane (FAS, F in short) to achieve the desired structure (Figure 2c). MWCNTs/G alongside Ag nanoparticles on the surface led to crucial physical roughness, while the FAS modification introduced low surface energy. The careful orchestration of these physical and chemical attributes ensured that water droplets adopted a *Cassie–Baxter* wetting state when deposited onto the surface, thereby conferring superhydrophobic characteristics to the surface. Notably, liquid droplets of various substances, such as green tea, black tea, orange juice, cola, milk, HCl, NaOH, and NaCl, displayed nearly spherical morphologies, accompanied by static contact angles of 154° , 154° , 155° , 156° , 153° , 156° , 156° , and 157° , respectively. The innovative design of the FAMG sensor harnessed the microbridge effect of MWCNTs and the APTES/MWCNTs/G slippage to accommodate a wide strain range. The inherent flexibility of unbonded overlapping graphene layers within the core facilitated surface structural movements and adjustments, enabling the complex surface to maintain its superhydrophobicity even under stretching conditions. Meanwhile, the binding layer

ensured maintenance of the physical structure under external deformation. Impressively, the superhydrophobicity of the FAMG surface persisted up to a strain of 170%, wherein the aforementioned liquid droplets deposited on the surface exhibited contact angles of 155° , 154° , 156° , 155° , 154° , 158° , 158° , and 157° , respectively. The liquid-repellent properties were maintained even after undergoing a thousand strain cycles, ranging from 0% to 170% stretching. Moreover, the FAMG sensor demonstrated extraordinary ultrasensitivity with a maximum gauge factor of 1989 within a strain range from 0.1% to 170%. Notably, the sensor's response time was 150 ms, rendering it suitable for real-world applications in monitoring a diverse array of human movements. This groundbreaking innovation opens doors for practical implementations across various domains, showcasing its potential to revolutionize the realm of ultrasensitive strain sensing technology.

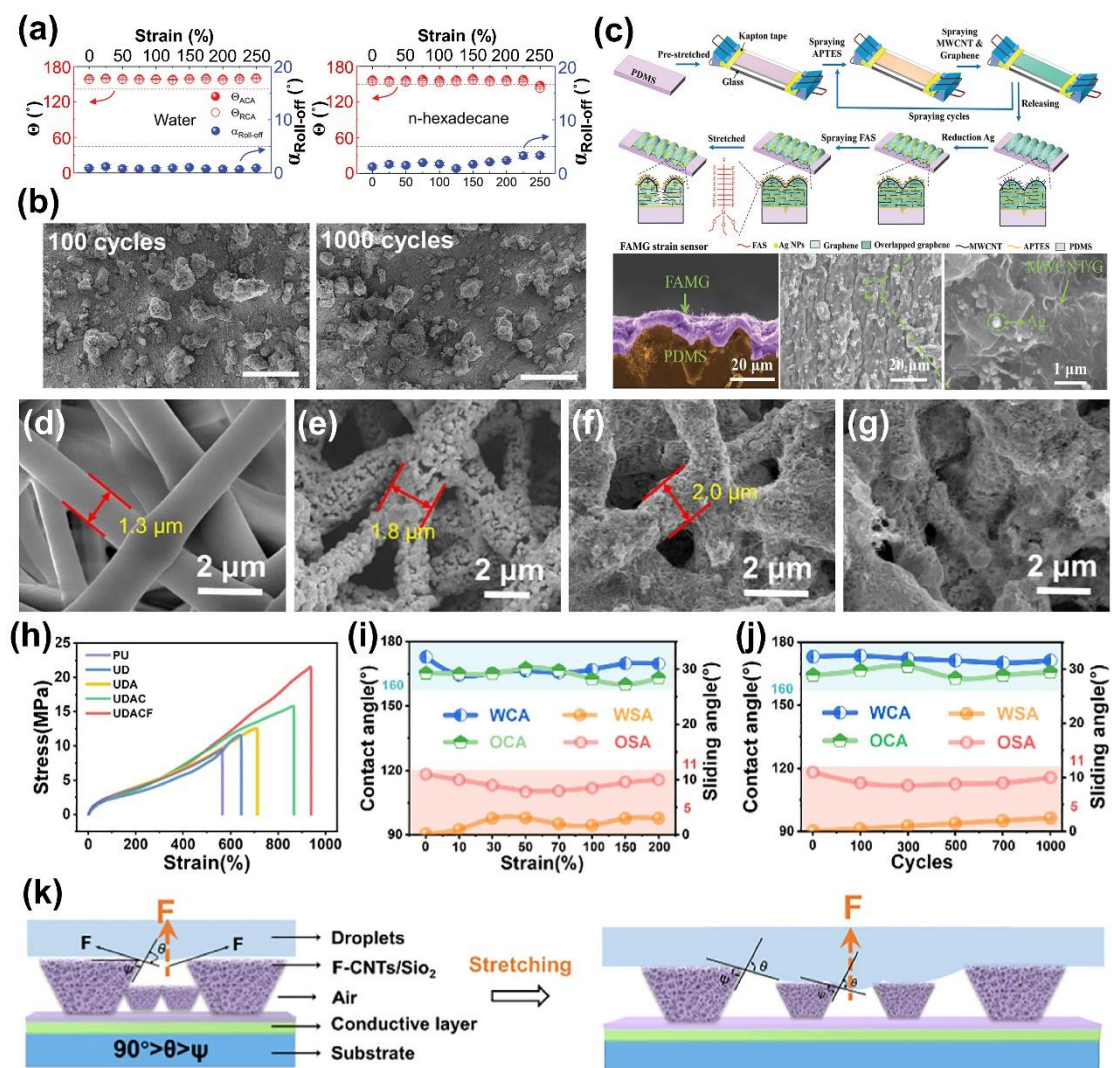


Figure 2. (a,b) Superamphiphobicity and durability of the superhydrophobic surface: (a) advancing and receding contact angles and roll-off angles of water and n-hexadecane on the NFSS surface with different tensile strains; (b) SEM images of the superhydrophobic surface after 100 and 1000 stretch-release cycles. Scale bar: 100 μm [52]; and (c) procedure for fabricating FAMG resistant to liquid interference and characterization of the FAMG strain sensor: from left to right are high-magnification cross-sectional, overhead view, and high magnification overhead view SEM images, respectively [53]. (d–g) SEM images of: (d) PU; (e) UDA; (f) UDAC; and (g) UDACF. (h) The stress-strain curves of PU and its composite materials (i,j): the influence of (i) strain; (j) different cycles at a strain of 50% on WCA, OCA, WSA, and OSA (soybean oil); and (k) schematic illustration of surface re-entrant structure mechanism [54].

Sahoo et al. successfully achieved a superhydrophobic and stretchable 3D hierarchical wrinkled surface by applying hydrophobic carbon nanotubes to a wrinkled PDMS film [55]. Their work initiated the fabrication by treating thermoplastic PS films with CHF_3 plasma for various durations. Subsequently, an annealing step was performed at 115°C for 1 h to generate 3D wrinkled PS templates. The PDMS precursor, mixed with a crosslinker, was applied to the template to create the desired superhydrophobicity, effectively transferring the wrinkled structure onto a transparent and stretchable PDMS film. This step provided the essential physical roughness required for superhydrophobic properties. The wrinkled PDMS film was then treated with oxygen plasma to convert it into a hydrophilic surface. Subsequently, a carbon nanotube (CNT) solution was spray-coated onto the surface to yield a wrinkled PDMS/CNT film. After the solvent was fully evaporated through incubation at 70°C for 3 h, hydrogen bonds formed between the hydrophilic groups on the CNTs ($-\text{SO}_4$ group) and the hydrophilic regions of the wrinkled PDMS surface ($-\text{OD}$ and $-\text{COOH}$), ensuring solid adhesion of the CNTs to the wrinkled film. The synergy between the exposed hydrophobic groups of the CNTs and the hierarchical wrinkled structure led to the composite film exhibiting superhydrophobicity, with a remarkable maximum water-contact angle of $165 \pm 2^\circ$. The composite film's durability in maintaining superhydrophobicity during stretching was due to the robust nanowrinkles and the strong adhesion between the CNTs and the PDMS surface. Even under various forms of surface deformation, such as bending (0° – 140°) and twisting (0° – 100°), the 3D structural hierarchy and liquid repellency remained intact. Under stretching conditions, the superhydrophobicity persisted, even at stretching strains of 0% to 80%. After subjecting the film to 5000 stretching–relaxing cycles, despite a slight reduction, the water-contact angle remained above 150° . This resilience indicated the potential suitability of the stretchable superhydrophobic surface for a wide array of applications in wearable devices and robotics.

Another way is generating the additional layer by in situ growth. By the method mentioned above, Tian et al. designed and fabricated a robust and stretchable surface through the combination of in situ growth of silver nanoparticles (AgNPs)/acid-modified carbon nanotubes (ACNTs) conductive networks and 1H,1H,2H,2H-perfluorodecyltriethoxysilane functionalized carbon nanotubes-silica nanoparticles (FCNTs- SiO_2) [54]. During the fabrication process, the elastic substrate, thermoplastic PU (polyurethanes, Figure 2d), was first modified with a uniform and dense layer of polydopamine (PDA) by immersing it into 2 mg/mL dopamine solution to be used as an adhesive agent between the substrate and the additional coating layer. Then, the modified textile (UD) underwent in situ growth of silver nanoparticles in an AgNO_3 aqueous solution. With the presence of glucose, AgNPs were synthesized on the UD surface, forming TPU/PDS/AgNPs film (UDA) (Figure 2e). Subsequently, the UDA was subjected to oxygen plasma treatment, and ACNTs dissolved in ethanol were spray-coated onto the surface. This step created a TPU/PDA/AgNPs/ACNTs composite film (UDAC), where the ACNTs filled in the voids and surfaces, connecting the discrete AgNPs (Figure 2f). Finally, FCNTs- SiO_2 was uniformly spray-coated onto the composite film, introducing the necessary physical re-entrant structures to confer superhydrophobic properties (Figure 2g), resulting in the formation of an UDACF (TPU/PDA/AgNPs/ACNTs/FCNTs- SiO_2 film) film with a robust reentrant nanotopography. The cross-section analysis of the UDACF textile revealed a PU film thickness of approximately $110\text{ }\mu\text{m}$ and a coating thickness of about $20\text{ }\mu\text{m}$.

Tensile testing confirmed the exceptional mechanical characteristics of the as-prepared UDACF textile. The elongation at the point of fracture exhibited remarkable improvement, increasing from an initial value of 560% to an impressive 939%. This enhancement can be attributed to the interaction of hydrogen bonds, which contribute additional physical crosslinking effects among the components when subjected to stretching forces. Simultaneously, the tensile strength of the UDACF textile increased significantly, rising from 9.65 MPa to 21.7 MPa, as illustrated in Figure 2h.

By combining the reentrant hierarchical structure with the low surface energy properties of FCNTs- SiO_2 , the resulting surface exhibited superamphiphobic characteristics. Water

and oil droplets on this surface adopted spherical shapes, and the water-contact angle (WCA) and oil-contact angle (OCA) exceeded 165° . Even under strain levels of 0–200%, the WCA consistently remained above 165° , with a slight variation of WSA less than 5° observed, while the OCA remained above 160° with an OSA below 11° (Figure 2i). Such performance underscores the surface's remarkable ability to maintain superamphiphobicity, even when subjected to stretching. In addition, the liquid-repellent properties of the composite textile endured repeated stretching and releasing cycles. Across 0 to 1000 stretch-release cycles, the WCA, OCA, WSA, and OSA exhibited minimal fluctuations, consistently measuring around 170° , 165° , 5° , and 11° , respectively (Figure 2j). This maintenance of liquid repellency is attributed to the reentrant hierarchical structure created by FCNTs-SiO₂. Figure 2k illustrates the mechanism model of the surface's reentrant structure (where $90^\circ > \theta > \psi$), with θ representing Young's contact angle and ψ being the partial geometric angle of the structure. This structure allows for the upward liquid traction of the liquid/air interface, pushing the liquid upward to achieve a stable *Cassie* state. Even when the material is stretched, the hierarchical fluorinated carbon nanotubes and silica nanoparticles maintain this reentrant structure, resulting in a robust superamphiphobic surface. Moreover, this superamphiphobic surface was adaptable to extreme conditions such as temperature variations ranging from -60°C to 60°C and exposure to corrosive and non-polar liquids. When applied to the stretchable superhydrophobic surfaces for flexible strain sensors, it exhibited ultra-high gauge factors (6.6×10^4), a broad strain range (0.1–155%), rapid response times (62 ms), excellent cycle durability (over 5000 cycles), and the capability to monitor high-frequency movements. These superior properties are attributed to the conductive paths formed by ACNTs-bridged AgNPs, which offer novel possibilities for human exercise health monitoring, such as cyclist training, or in extreme environments.

Jia et al. introduced a straightforward method for fabricating highly stretchable superhydrophobic conductive textile by the in situ growth of silver nanoparticles (AgNPs), followed by the reduction in surface tension using a poly(dimethylsiloxane) (PDMS) layer, showcasing the potential for application as a wearable heater for thermal management [56]. Initially, the pristine textile exhibited a characteristic micro-rough surface structure comprising smooth microscale fibers ($\sim 12\ \mu\text{m}$ in diameter) (Figure 3a). Subsequently, the textile was treated with an Ag precursor solution containing 15 wt% silver trifluoroacetate (STA) in ethanol and then air-dried at 25°C for 30 min. Following this, a chemical reduction step was carried out using L-Ascorbic acid (LAA), followed by drying at 80°C for 60 min, forming AgNPs on the textile surface. This process yielded a composite AgNP/Textile (Figure 3b), with the AgNP content controlled by the weight of the coated Ag precursor solution. The in situ growth of AgNPs led to the formation of a textile surface covered with closely packed nanoparticles (~ 100 to $150\ \text{nm}$ in diameter) that formed interconnected networks (Figure 3b). AgNPs were chosen as the conductive nanomaterial to provide a highly electrically conductive path and to regulate surface roughness, meeting the necessary structural requirements for superhydrophobicity. The achievement of a superhydrophobic surface was realized by modifying the AgNP/Textile with PDMS, a drop-casting process using a mixture of prepolymer, curing agent, and ethyl acetate, followed by drying at 25°C for 30 min and curing at 100°C for 30 min. PDMS, as a low-surface-energy compound, was employed to reduce the surface tension of the composite textile. A thin protective layer was observed on the AgNP coating in the PDMS-AgNPTextile (Figure 3c), serving as a protective barrier to stabilize the AgNP coating.

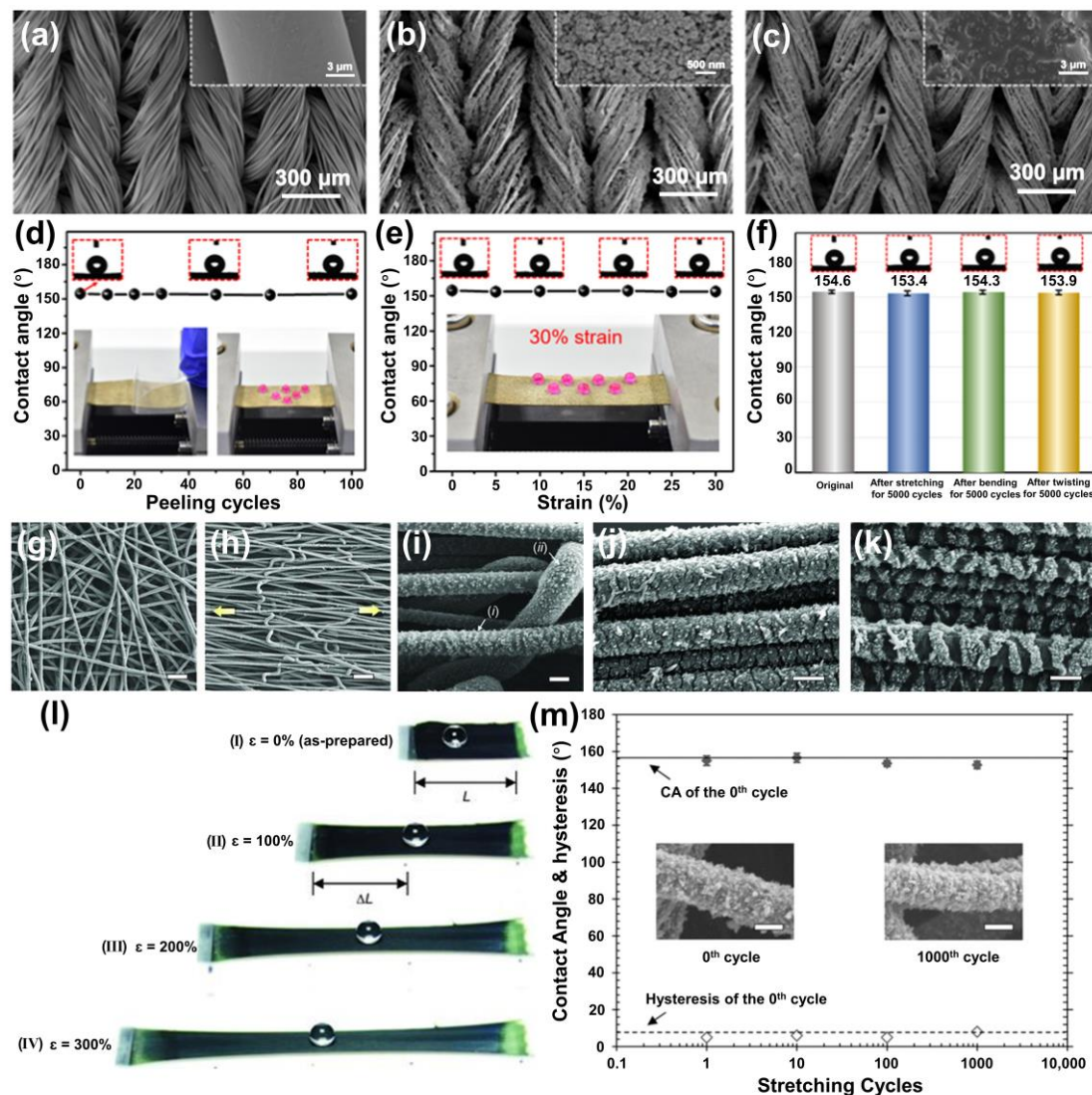


Figure 3. (a–c) Surface morphology of: (a) pure textile; (b) the AgNP/Textile with 4.5 vol % AgNP content; and (c) Ag-IV. (d–f) CA variation of Ag-IV with: (d) peeling cycles; (e) first stretching–releasing cycle; and (f) before and after stretching–releasing (30% terminal strain), bending–releasing (2.0 mm bending radius), and twisting–releasing (360° twisting angle) for 5000 cycles, respectively [56]; (g) SEM image of randomly oriented nanostructured PU fibers (as-prepared). Scale bar: 10 μm . (h) PU fibers shown in: (g) horizontally stretched by 200%, the arrows showed the stretching directions. Scale bar: 10 μm ; (i) magnified image of (h); (j) 0% stretched fibers oriented in one direction, produced by a parallel collector. Scale bar: 1 μm ; (k) 100% stretched image of (j). Scale bar: 1 μm ; (l) optical images of the superhydrophobic membrane under various strains, $\epsilon = \Delta L/L \cdot 100$, ranging from 0 to 300%; and (m) CAs and CAHs of the stretchable membrane after a stretching cycle (a strain of 100% $\rightarrow$ 300% $\rightarrow$ 100%). The insets are SEM images of a 0-cycle stretched fiber and a 1000-cycle stretched fiber. Scale bar: 1 μm [57].

The resulting composite surface exhibited remarkable superhydrophobicity through the combination of micro-nano roughness achieved by the in-situ-grown AgNPs and the low surface energy provided by the post-modified PDMS. It featured a water-contact angle of $\sim 155^\circ$, a minimal sliding angle of $\sim 6^\circ$, and facilitated easy water flow runoff at a slight incline. The surface's durability was evident, as a mechanical peeling test confirmed the firm adhesion of the PDMS-AgNP coating to the underlying substrate, even when subjected to external disturbances. Even after 100 peeling cycles, the prepared surface maintained its superhydrophobicity, with a high water-contact angle of 154° (Figure 3d). Furthermore,

this surface displayed increased tolerance to mechanical deformations due to the unique distribution of the AgNP networks. This distribution ensured the retention of surface roughness and the PDMS layer, enhancing interfacial adhesion and firmly anchoring the AgNP networks to the fibers. As illustrated in Figure 3e, the composite surface's liquid-repellent property remained unchanged, with a water-contact angle of 153° even when subjected to stretching up to 30%. The stretching–releasing cycle test demonstrated that the surface maintained its superhydrophobicity, featuring a water-contact angle of 153° even after 5000 strain cycles (Figure 3f). Similarly, the superhydrophobicity endured bending and twisting, remaining intact after 5000 bending–releasing and twisting–releasing cycles (Figure 3f). Leveraging the conductivity of the incorporated AgNPs, the composite surface also exhibited a stable, high electrical conductivity of 861.3 S/m. This excellent electrical-heating performance was characterized by a high saturation temperature of 63.6°C at an ultralow supplied voltage of 1.2 V. Consequently, it holds significant promise as a wearable heater for efficient thermal management. It assures long-term reliable operation under challenging environmental conditions.

Lim et al. recently reported the development of a mechanically robust superhydrophobic surface with exceptional stretchability [57]. Elastic polyurethane fibers, approximately $1\ \mu\text{m}$ in diameter, were fabricated via electrospinning as the flexible substrate. Then, this substrate was coated with hairy polyaniline (PANI) nanostructures using a dilute polymerization technique [58]. These hairy nanostructures exhibited high-aspect ratio geometries, with diameters ranging from 20 to 40 nm and lengths of approximately 100 nm. This unique structure minimized the contact area between droplets and the solid substrate, creating the physical roughness necessary for liquid repellency. Finally, the authors dip-coated the membrane with a polytetrafluoroethylene (PTFE) layer to reduce surface energy and achieve superhydrophobicity.

The resulting membrane displayed excellent anti-wetting properties, as water droplets deposited on the surface adopted a *Cassie* state, where the droplets resided on a composite surface consisting of solid and trapped air. This characteristic enabled the surface to block falling droplets and even water jets. Even after continuous jetting, no water residue was observed. Due to the surface roughness, the average CA of the PANI-nanostructured PU membranes reached 160° . The CAH (contact angle hysteresis) significantly decreased from ~ 106.7 to $\sim 9.7^\circ$ for the PANI-nanostructured PU membranes. Thanks to the elastic properties of the PU matrix, the resulting superhydrophobic surface exhibited rubber-like hyperelastic behavior over the entire strain range, reaching a maximum strain breakpoint of 350% with a low modulus of approximately 1.4 MPa. Notably, the surface maintained superhydrophobicity throughout the strain range until the breaking point (Figure 3l).

As depicted in Figure 3g, the stretchable superhydrophobic surface possessed a microporous structure with micropores exceeding $5\ \mu\text{m}$. This structure was due to the arrangement of randomly oriented microfibers. During stretching, stress at the PANI-PU structure interface caused the surface to deform or fracture, primarily resulting from a Young's modulus mismatch and high strain conditions (Figure 3g–k). As the fibers stretched uniaxially, they aligned with the stretching direction, and this alignment improved with increasing strain, albeit with slight elongation and minor cracking of the fibers (Figure 3i). As shown in Figure 3j,k, the as-prepared fibers tolerated stretching levels of 0% and 100%, respectively. In both cases, the PANI structure repeatedly cracked orthogonally to the stretching direction along the entire fiber length, and the spacing between adjacent cracks increased with strain. At a strain of 300%, the average interval distance was approximately 520 nm, reaching a maximum distance of 550 nm at the breaking point ($\epsilon_{\text{max}} = 350\%$). The crack width remained in the range of 300 to 400 nm at various strain values. The combination of microscale fibers, sub-microscale cracks, and nanoscale PANI nanostructures resulted in a multiscale hierarchical structure, which was critical to the stability of the superhydrophobic surface. This structure allowed it to maintain stable superhydrophobicity. Figure 3m illustrates the wetting behavior after cyclic stretching, involving alternating low strain (100%) and high strain (300%) cycles, followed by a return to low strain (100%). Remarkably, even

after a thousand cycles, the CA and CAH for the membrane sustained an average of 156° and 8° , respectively, nearly as high as those observed at the initial (0th cycle) state. The surface morphology appeared unchanged, as shown in the insets of Figure 3m. The stability of the membrane structure was closely related to crack formation, which efficiently released interfacial stress during high deformation due to the modulus mismatch. Thus, the PANI nanostructure and PU fibers were firmly combined, and the fibrous architecture exhibited stable liquid repellency even under significant deformation. Additionally, the electrospun fibrous substrate featured numerous micropores that allowed for the penetration of gas, acoustic waves, and small particles, while effectively preventing water passage. This quality endowed the stretchable superhydrophobic surface with the potential for underwater gas sensing, safeguarding the gas sensor and electric circuit from exposure to water in various long-term applications.

In contrast to the instances mentioned above, where surface structural adaptability is harnessed to sustain superhydrophobicity under external stretching, an alternative strategy entails preserving a fixed physical structure atop an additional layer to fulfill surface roughness criteria across varying stretching states. This principle is the foundation for the work of Ju et al., who engineered a robust, highly stretchable, non-fluorinated superhydrophobic surface [59]. The fabrication commenced with creating a silicone-elastomer Ecoflex sheet by curing a dual-component mixture. Subsequently, the elastomer sheet underwent a 200% strain stretch, followed by the coating of silicone oligomers using the same mixing ratio. After a designated horizontal incubation period, silica microparticles were directly deposited onto the substrate. Excess particles were then meticulously eliminated, and the surface was subjected to a 10 h incubation at 100°C , solidifying the oligomers and immobilizing the silica particles. As illustrated in Figure 4a,b, the final curing process prompted the migration of silicone oligomers to the surface of the silica microparticles, facilitated by the contrast between the former's low surface energy and the latter's high surface tension. This phenomenon led to the physical encapsulation of the microparticles.

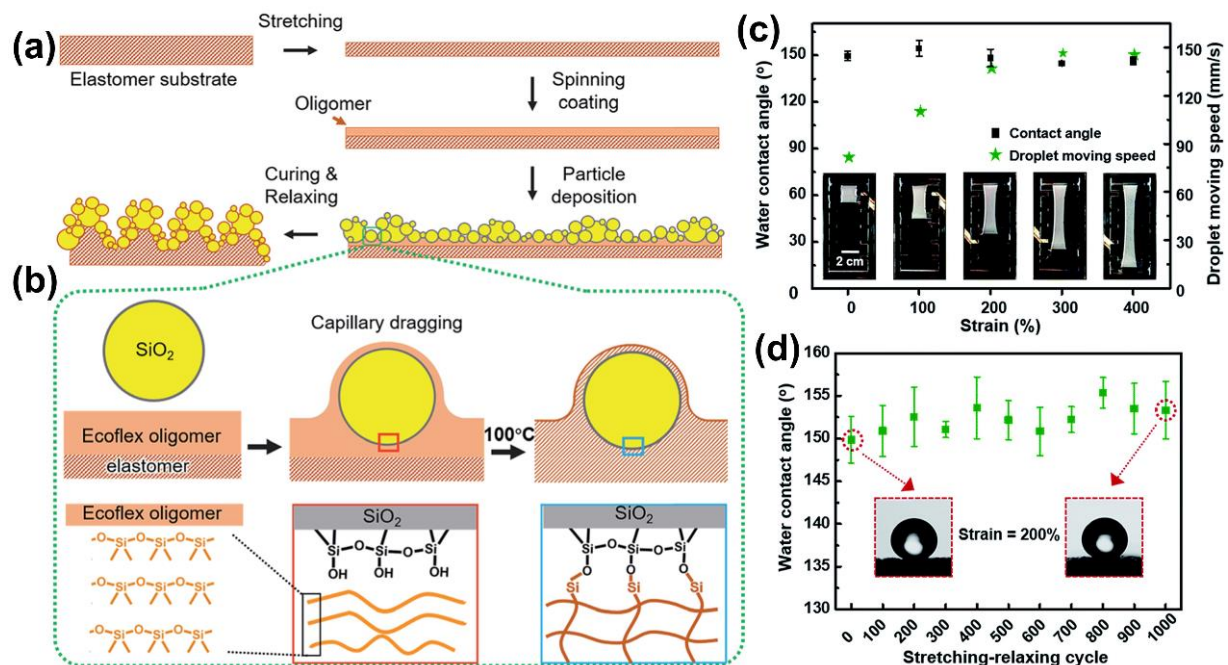


Figure 4. Silicone elastomer/silica microparticle based superhydrophobic surface (a,b) schematics showing: (a) fabrication; and (b) mechanism of the silicone elastomer/silica microparticle superhydrophobic surface; (c) water-contact angles and water-sliding velocities under different strains of the superhydrophobic surface; and (d) the hydrophobicity of the surface remains after 1000 cycles of stretching-relaxing, with strain = 200% [59].

Additionally, a chemical reaction occurred between the hydroxyl groups on the surface of the silica microparticles and the Si-O groups of the oligomers during the curing process, resulting in covalent chemical bonds forming between the silica and the silicone elastomer. Integration of the physical encapsulation and chemical bonding endowed the composite surface with superhydrophobic properties, even when stretched (Figure 4c). This unique configuration drew upon the indispensable physical roughness offered by the fixed silica particles and the inherent low surface energy of the elastomer. Upon release, the surface assumed wrinkled structures that successfully fulfilled surface roughness requirements. Crucially, the immobilized silica particles remained unaltered due to their firm anchorage in the elastomer. As a result, the surface maintained its superhydrophobicity even after undergoing at least 1000 cycles of stretching and relaxation, with the contact angle of a 5 μ L water droplet deposited on the surface consistently exceeding 150° (Figure 4d). Given that this highly stretchable superhydrophobic surface stemmed from the synergy of physical roughness and the low surface tension innate to the silicone elastomer, all in a non-fluorinated context, its potential applications in biomedicine, energy management, and electronics are endowed with distinct advantages. This pioneering advancement unlocks possibilities in diverse fields, promising innovative solutions to pertinent challenges.

Recently, Hou et al. reported a durable, stretchable superhydrophobic surface with the help of self-assembled hierarchical porous structures [60]. An alloy of poly(amide-imide) (PAI) and thermoplastic polyurethane (TPU) with a tensile strength of above 40 MPa and an elongation at a break approaching 300% was employed as an elastic substrate. Then, perfluorosilane-modified silica nanoparticles (F-SiO₂) were spray-coated, forming self-assembled porous structures to offer a stable *Cassie* state. The primer coating was then immersed in a PDMS solution to form a protective layer. Attributed to the introduction of good compatibility of the F-SiO₂ with the elastic substrate, accompanied by the adhesive action of PDMS, the obtained surface was highly stretchable, with a tensile strength of 41.4 MPa and an elongation at break approaching 3000%. When the surface was stretched, the grooves formed by the F-SiO₂ assembly became bigger and bigger, while the neighboring F-SiO₂ nanoparticles were still interconnected to provide the essential physical structure. The tight adhesion between the F-SiO₂ and the stretchable substrate enabled the superhydrophobic surface to bear 2000 cycles of stretching–releasing at a 30% strain without sacrificing the superhydrophobicity. In addition to stretchability, the surface is mechanically robust, as the TPU decorated with F-SiO₂ works as a binder to hold the F-SiO₂ together and as a bridge to anchor F-SiO₂ closely into the PAI-TPU substrate. The surface was treated with ultrasonic vibration at a frequency of 40 kHz and a power of 50 W for 100 h, and the surface was abraded with 120-grit sandpaper under a load of 100 g for 100 cycles (each cycle was conducted a movement of 5 cm), the superhydrophobicity remained without the superhydrophobic coating of the F-SiO₂ peeling off. The robustness of the surface makes it suitable for practical applications such as water-pool covers for complex/curved surfaces or self-cleaning coatings. Similarly, Peng et al. developed a superhydrophobic fabric strain sensor with a multilayer coating approach [61]. Multi-walled carbon nanotubes (MWCNTs) and silver nanoparticles (AgNPs) were constructed on polydopamine (PDA)-coated fibers and subsequently modified with polydimethylsiloxane (PDMS). The fibers provided the elasticity, while the MWCNTs and AgNPs dominated the necessary physical structures, and the PDMS contributed to the low surface energy for the substrate. The synergism of the components endowed the complex surface with stretchability, superhydrophobicity, and conductivity. Water droplets deposited on the surface demonstrated a spherical morphology with a contact angle of about 156°, and the surface liquid repellency was maintained when stretched from 0 to 100%. Taking advantage of the PDA's strong adhesion and the PDMS's elasticity, the MWCNTs and AgNPs on the surface can easily rearrange their organization to maintain surface roughness during stretching–releasing cycles. The composite surface is durable, and the structure and superhydrophobicity are maintained after 4000 rounds of stretching–releasing. Moreover, the as-prepared superhydrophobic surface possesses long-term stability. After being placed in a normal environment for

5 months, the contact angle of the surface was maintained not only for pure water, but also for acid, alkaline, and salt solutions, demonstrating excellent durability. With the synergistic effect of conductive MWCNT-AgNP networks, the strain sensor prepared by the superhydrophobic surface exhibited a wide sensing range of 120% strain, a high GF up to 527.1, a minimum detection range of 0.1% and a fast response time of 50 ms, indicating that the reported stretchable superhydrophobic surface has great potential in waterproof wearable electronics.

In addition to the works mentioned above, researchers have also developed other stretchable superhydrophobic surfaces by covering elastomers with a layer of rough and low surface energy materials [62–71]. The approaches demonstrated above show the flexibility to fabricate a stretchable superhydrophobic surface; however, the application of thin surfaces is limited due to the need for a bulk elastomer layer to support the superhydrophobic surface, leading to increased thickness and processing complexity.

2.2. Hybridizing Functional Materials in Elastomers

Stretchable superhydrophobic surfaces have shown great promise in various applications, from wearable sensors to smart windows. However, the challenges in integrating elastomers have hindered the widespread utilization of elastomers covered with a layer of rough and low surface energy materials to obtain superhydrophobicity. Thus, the fabrication of stretchable superhydrophobic surfaces was proposed by hybridizing functional materials in elastomers to coat target materials directly, as other materials, mainly inorganic particles, are embedded in the elastomers to form the essential physical protrusions for superhydrophobicity, and the stretchability of the composite superhydrophobic surface is derived from the chosen elastomer. This hybridization presents an alternative pathway to expand the application fields of stretchable superhydrophobic surfaces, breaking through the restrictions of specific application requirements and enhancing the feasibility of practical utilizations.

By employing the phase separation of thermoplastic elastomer (TPE) and carbon nanotubes (CNTs) at the air/water interface to create this innovative material. Ding et al. developed a stretchable superhydrophobic composite TPE/CNTs film that finds applications in wearable sensors [72]. A mixture suspension containing TPE and CNTs was introduced into the water and allowed to settle, forming a TPE/CNTs sheet at the water surface due to the differing surface tensions and solvent evaporation on either side of the film. Subsequently, n-hexane was sprayed onto the sheet to dissolve the TPE segment and effectively coat the CNTs with TPE molecules, resulting in a stable TPE/CNTs film. Finally, the assembled film was transferred from the air/water interface and dried to yield a free-standing TPE/CNTs film (Figure 5a). The air-contacting side produced a TPE layer on the back of the film, enhancing its flexibility. Meanwhile, the water-contacting side featured a rough layer of TPE-backed CNTs with a thin polymer coating, rendering the film superhydrophobic. The microstructural morphology of the TPE/CNTs film at the water side indicates the beneficial effect of the TPE coating on the CNTs. The interpenetrating networks of CNTs provides a rough surface structure, while the thin TPE layer effectively prevents water from wetting and minimizes the capillary effect of CNTs. The TPE in the TPE/CNTs film clusters primarily on the air side due to the tendency of TPE to aggregate in n-hexane solvent. The cross-section of the TPE/CNTs film demonstrated a conductive network of CNTs encapsulated by TPE, spanning the entire film. Micropores in the TPE/CNTs film primarily resulted from the rapid evaporation of n-hexane. The composite film exhibited superhydrophobicity, supporting numerous water droplets with a contact angle (CA) of 160° . Leveraging the flexibility of the elastomer and the integrated rough TPE/CNTs structure, the surface maintained durable liquid repellency even under stretching. As depicted in Figure 5b, the CA of the TPE/CNTs film remained above 150° until the strain reached 100%, at which point the film began to exhibit cracks. Figure 5c displays the CA variation of the TPE/CNTs film during multiple cyclic stretches of 30% elongation, revealing that, even after 500 stretching cycles, the CA only decreased from

160° to 154°, demonstrating stable superhydrophobicity during repeated stretching cycles. Thanks to the TPE coating's protective nature, which prevents solutions from penetrating the CNT network, the composite film effectively repelled various liquids, including acids, bases, salt solutions, milk, coffee, and tea droplets, all with contact angles exceeding 150° and sliding angles lower than 10° (Figure 5d). Furthermore, the prepared surface exhibited electrical conductivity, with a resistance of 15 K Ω due to the inclusion of CNTs. When applied as a sensor, it demonstrated exceptional performance, featuring superior sensitivity (a gauge factor of approximately 1), rapid response times (100–150 ms), stable responses over 1000 stretching–relaxing cycles, and a wide sensing range for stretching (over 76%). Crucially, it remained functional even in wet conditions, making it an ideal candidate for wearable electronic devices for fast responses, long-term use, and reliable human behavior monitoring.

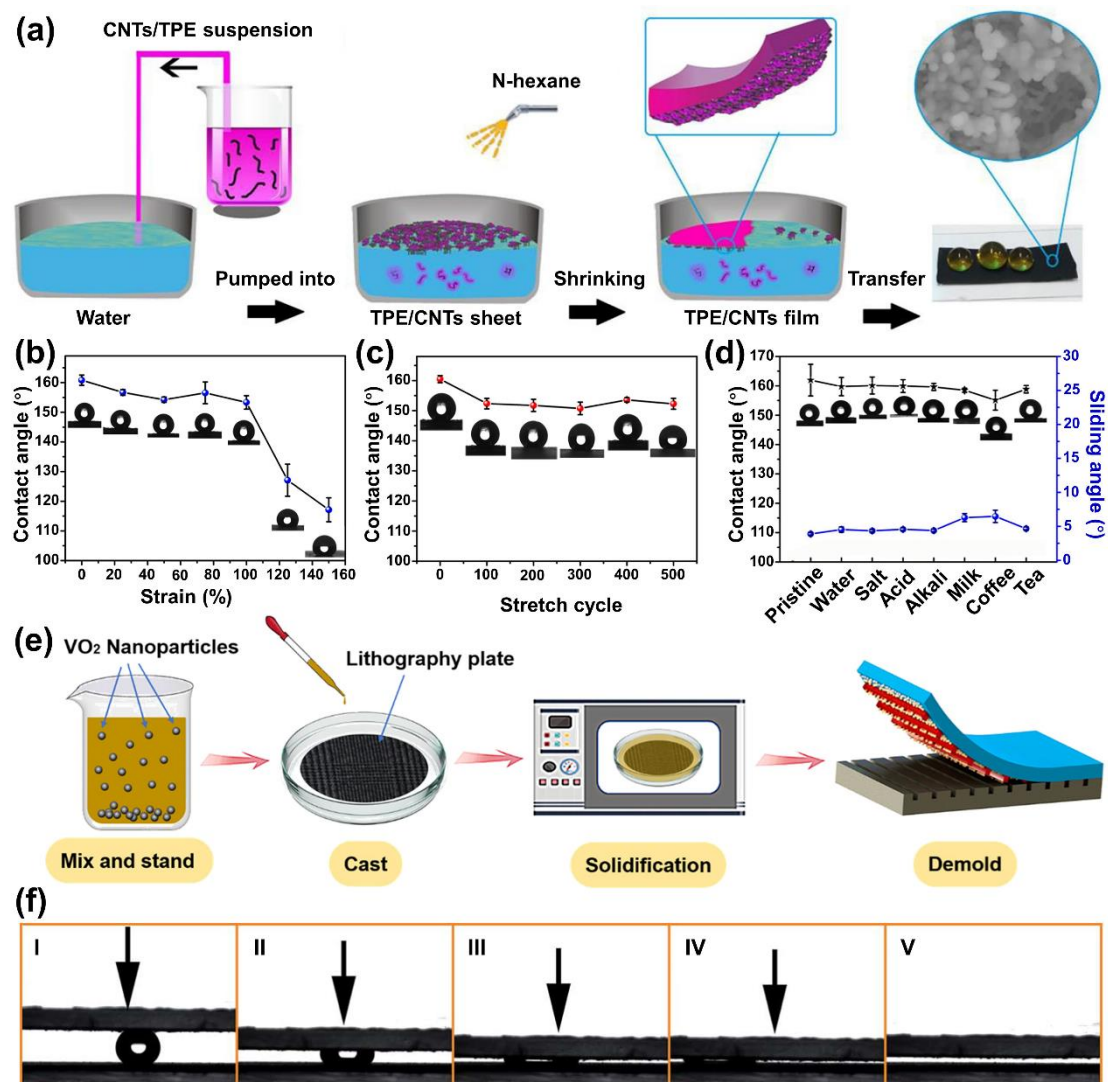


Figure 5. (a) Schematic illustration of the fabrication process of the TPE/CNTs film; (b,c) variation of CAs for the TPE/CNTs film with (b) increased strain; and (c) stretch-cycles times. (d) The CAs and SAs of different liquid droplets on the surface [72]; and (e) synthesis process of the VO₂ NP/PDMS composite films [73]. (f) Stability of Cassie–Baxter state: (I–V) behavior of a 5 mL water droplet squeezed between two superhydrophobic silicones [74].

Employing a one-step casting approach, Yao and colleagues created three-tiered films composed of vanadium dioxide and polydimethylsiloxane (VO₂/PDMS) with structured arrays (Figure 5e) [73]. Intricately designed surface patterns, encompassing stripes, lattices,

and trapezoids, were artfully fashioned to replicate the distinctive characteristics of the 'lotus effect' for macro-scale roughness. In contrast, nanoscale roughness was attributed to the presence of VO₂ nanoparticles. Liquid droplets, such as vinegar, milk, and soy sauce, deposited on the as-prepared surfaces maintained their spherical morphology without spreading, underscoring its remarkable liquid-repellent properties. The film demonstrated exceptional oleophobic capabilities, exemplified by water- and oil-contact angles of 165° and 158° for the lattice structure. These results indicated a truly remarkable self-cleaning and anti-icing performance. Even at a chilling −15 °C, droplets on the stripe-VO₂/PDMS film defied freezing for over 5 min, a noteworthy eightfold extension compared to ordinary glass. This resilience against freezing is due to several factors: the notable surface roughness, the disparate elastic moduli between VO₂ and PDMS, and the inherently low surface energy of PDMS. The stripe-VO₂/PDMS surface exhibited a comparatively low ice-adhesion value of 24.7 kPa, contrasting sharply with 627.0 kPa (for glass) and 118.7 kPa (for PDMS). Beyond its anti-icing prowess, the stripe-VO₂/PDMS film delivered an average integrated transmittance (T_{lum}) of 31.21%, coupled with solar energy modulation values (ΔT_{IR} and ΔT_{sol}) of 17.80% and 6.60%, respectively. This impressive thermochromic performance is rooted in the remarkable self-regulating attributes of VO₂ nanoparticles, which adeptly modulate optical transmission/reflection characteristics in response to temperature shifts. Remarkably, the stripe-VO₂/PDMS film consistently maintained its excellent wettability and optical properties despite being subjected to various physical stresses, such as tape peeling, sand abrasion, sponge washing, and even chemical treatments involving prolonged immersion in strong acid or alkali solutions for over 30 h. This groundbreaking work convincingly demonstrates the immense potential of such multifunctional intelligent surfaces, particularly in pivotal practical applications such as advanced smart windows.

Lv et al. introduced a mechanically robust superhydrophobic porous membrane achieved through 3D printing using a viscoelastic ink composed of hydrophobic nanosilica-filled polydimethylsiloxane (PDMS) [75]. Incorporating nanosilica enhanced the ink's mechanical strength, ensuring that the desired topographical structures were formed without collapsing during 3D printing. Simultaneously, PDMS conferred a low surface energy to the resulting membrane. The prepared porous membrane exhibited remarkable superhydrophobic properties, with water droplets forming spherical shapes and a static contact angle of approximately 160°. The presence of hydrophobic nanosilica embedded in the PDMS matrix endowed the composite membrane with sturdy physical structures complemented by the elasticity characteristic of the PDMS elastomer. The membrane maintained excellent stability even when subjected to mechanical stretching, with no significant decrease in surface superhydrophobicity observed when stretched from 0% to 60%. After 1000 stretching–releasing cycles with a 60% strain, the water-contact angle remained around 160°. Notably, the membrane demonstrated resilience against bending and endured water scouring during ultrasonication. This superhydrophobic PDMS membrane proved highly effective in oil–water (hexane–water) separation, achieving a maximum separation efficiency of 99.6% while maintaining a high liquid flux of 23,700 L m^{−2}h^{−1}. Thanks to its stable mechanical and chemical properties, this printed superhydrophobic PDMS membrane retained its original superhydrophobicity even after long-term exposure (one month) to acidic (pH = 4) or alkaline (pH = 12) aqueous solutions. The superhydrophobic membrane demonstrates potential in applications separating oil and corrosive aqueous solutions, as it maintained a separation efficiency of over 96% for mixtures of hexane and non-neutral aqueous solutions with varying pH levels. Moreover, the membrane exhibited high separation efficiency (over 90%) when dealing with mixtures of water and high-viscosity oils, including kerosene, bean oil, corn oil, and silicone oil. This performance underscores its practical suitability for oil–water separation applications.

Davis et al. developed a durable, stretchable superhydrophobic surface using an environmentally friendly emulsion templating technique [76]. Their approach introduced a scalable and eco-conscious method to create stable water-in-PDMS (polydimethylsiloxane) emulsions by mechanically mixing PDMS and water. As shown in Figure 6a, the emulsions

formed without surfactants. The base and curing agent of Sylgard 182 were mixed in a 10:1 ratio (*w:w*) and diluted with polypropylene. Then, a water dispersion of hydrophilic fumed silica (Aerosil 300, Evonik, Pandino, Italy) with a 10 nm primary particle size was added drop by drop to the uncured PDMS while stirring to form the emulsions (Figure 6b). These emulsions were cast onto a substrate and degassed under vacuum. Subsequent heating cured the surface. During degassing and heating, the water droplets within the PDMS matrix evaporated, leaving pores behind. Simultaneously, the silica nanoparticles assembled to create nanostructures on the pore walls, resulting in hierarchical structures (Figure 6c). The pore size, density, and nanostructure on the pore walls could be easily controlled by adjusting the concentration and amount of the silica nanoparticle dispersion, optimizing the structure and properties of the resulting surface. Combining the low surface energy of PDMS with the rough hierarchical structures, the prepared surface (containing 60 wt% water and 10 wt% water) exhibited exceptional superhydrophobic behavior, with a contact angle of 159° and a roll-off angle of 5° (Figure 6e). The synergy between PDMS's flexibility and the rigidity of the silica nanoparticles provided the surface with robust mechanical stability, allowing it to withstand strains of up to $95 \pm 10\%$ without breaking. The superhydrophobicity was retained even under mechanical deformation, with no adverse effects observed when the surface was stretched uniaxially at 100%. This resilience was attributed to the deformation of the porous hierarchical structure during stretching. As depicted in Figure 6f, the micropores stretched along the tensile axis, preserving the essential surface roughness and superhydrophobicity due to the elastomeric nature of the silicone monoliths.

Furthermore, the contact angle of the stretchable superhydrophobic surface remained constant when subjected to a 50% strain in both lateral directions, demonstrating the surface's robustness against various forms of deformation. The prepared superhydrophobic surface maintained its liquid repellency when exposed to harsh environmental conditions, including corrosive solutions, UV light, extreme temperatures, and high-energy droplet impacts. These properties make it suitable for practical applications such as self-cleaning, stain resistance, and repelling blood, offering valuable benefits in real-world scenarios.

Through an electrospinning process, Lim et al. achieved a remarkably stretchable superhydrophobic elastic fibrous mat [77]. In their approach, poly(styrene-*b*-butadiene-*b*-styrene) (SBS) served as the organic matrix, bestowing the fibrous mat with expansive stretchability and an impressive surface area. Inorganic silica nanoparticles (SiNP) were seamlessly integrated to augment surface roughness. The pristine mat underwent further enhancement through the introduction of a fluorinated material, specifically 1H,1H,2H,2H-perfluorodecyltriethoxysilane (PFOTS), effectively lowering the surface energy. The resultant SBS/SiNP fibrous mat showcased resilient stretchability, enduring strains exceeding 1000%, while maintaining the superhydrophobic feature with a water-contact angle of 156° and a sliding angle of 7.8° . The superhydrophobic performance persisted even under stretching up to 1000% strain. This robust behavior is primarily attributed to the incorporated silica nanoparticles, which, when subjected to high strain, could extend and create fresh surface bumps, reinforcing the surface roughness. Remarkably, the sliding angles remained consistently below 10° across different longitudinal strains, which is attributed to the wetting property of the SBS/SiNP/PFOTS fibrous mat, promoting a *Cassie-Baxter* state where air pockets beneath the water droplets lead to reduced sliding angles in the longitudinal direction. After undergoing 1000 cycles of stretching and releasing, the obtained superhydrophobic elastic fibrous mat maintained a contact angle of 156° and a sliding angle of 6° . Furthermore, the mat's molecular structure exhibited remarkable stability when exposed to demanding chemical conditions, including corrosive liquids and seawater. This unparalleled durability endows the superhydrophobic and stretchable fibrous mat with significant potential in various practical applications. Notably, the mat's versatility positions it as an ideal candidate for utilization in wearable devices, stretchable electronics, and implantable biosensors, marking a substantial leap forward in the realm of advanced functional materials.

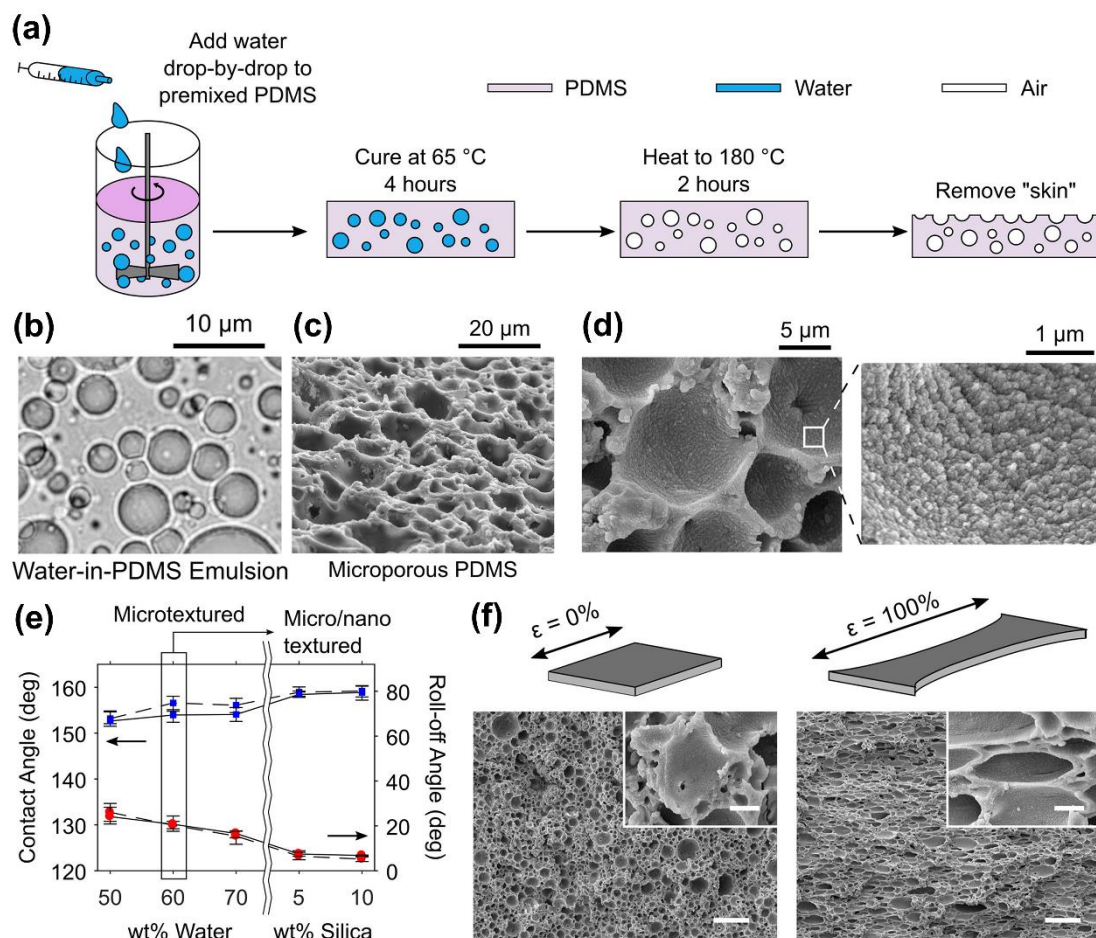


Figure 6. (a) Scheme of the emulsion templating process used to produce microtextured PDMS monoliths; (b) optical micrograph of the emulsion reveals well-dispersed water microdroplets; (c) SEM image of a cured monolith; (d) SEM images of a micro/nanotextured monolith, with nanotextured pore walls visible at high magnification; (e) wettability of textured monoliths while nonstretched (dashed lines) and stretched 100% (solid lines); and (f) SEM images of a micro/nanotextured while nonstretched and stretched 100%. Main scale bar = 50 μm . Inset scale bar = 5 μm [76].

Incorporating carbon nanotubes (CNTs) into a PDMS matrix with exceptional uniformity, Hu and collaborators achieved a remarkable, stretchable, superhydrophobic, and wearable strain sensor via a rapid and cost-effective laser-texturing with a CO₂ laser engraver [78]. PDMS was strategically chosen as the foundation, endowing the composite film with impressive stretchability and hydrophobic attributes, while dispersed CNTs seamlessly established a conductive network. The CNTs were uniformly dispersed in toluene with the help of ultrasonication, followed by the addition of PDMS and silicon oil. The concentration of CNT was optimized to 10 wt% to meet the high-conductivity and stretchability requirements. The advantageous swelling effect of the silicon oil reduced intermolecular interactions within the PDMS chains, consequently enhancing their mobility. Upon pouring the composite into a poly(methyl methacrylate) (PMMA) template and curing it at 80 °C for 2 h, a CO₂ laser machine was employed to ablate the PDMS/CNT composite, resulting in superhydrophobic properties with contact and sliding angles of approximately 155° and 4.5°, respectively. Due to the laser irradiation-induced superhydrophobicity, the engineered surface exhibited exemplary resistance against different liquid droplets, encompassing water, acid, base, and mineral solutions. The PDMS/CNT composite retained its superhydrophobic characteristics throughout repeated stretching–releasing cycles. The surfaces' performance remained resolute across various cyclic tension strains and frequencies, signifying its remarkable frequency-independent capability. This facet

holds significant promise for its application as a strain sensor to monitor human bodily movements at various frequencies, including wrist pulses, elbow motions, knee bends, etc. These strain sensors demonstrated impressive sensitivity, boasting a gauge factor of 3.1, a broad sensing range of up to 100%, and a prolonged stability over 5000 tension cycles. These exceptional attributes position the PDMS/CNT composite as a potential contender for serving as a human motion and physiological signal sensor in real-world or even demanding environments. The integration of these unique properties and versatile capabilities opens avenues for developing practical applications with profound implications.

Zhang et al. fabricated a flexible and remarkably durable superhydrophobic silicone monolith in a stable *Cassie–Baxter* state [74]. In their work, hydrophobic SiO₂ particles and PDMS were blended and subsequently cured under varying temperatures to achieve elastic silicone monoliths, which are efficient for large-scale production. The resultant monolithic silicone surface exhibited a static water-contact angle of 156° with a sliding angle of 4°. It showcased exceptional repellency against diverse liquids such as juice, coffee, milk, and blood. The *Cassie–Baxter* state's stability in the silicone monolith's hydrophobic surface was evaluated by squeezing water droplets between two surfaces (Figure 5f). Under external pressure, the water droplet assumed a flattened shape, but crucially, it did not wet the surface; instead, it effortlessly slid away from the silicone surfaces. This phenomenon underscored the robust stability of the *Cassie–Baxter* state, a result attributed to the silicone surface's elastic deformation, which bolstered the stability of the air cushion. This elastic deformation also contributed significantly to the monolith's outstanding durability. Elastic micro-protuberances within the silicone could compress and collapse under pressure, rebounding to their original state upon removal of the external force. This dynamic behavior ensured the maintenance of superhydrophobicity. The silicone monoliths exhibited robust superhydrophobicity even under rigorous conditions, such as tape-peel tests, finger wipes, and knife scratches. In addition, the as-prepared silicone displayed commendable self-cleaning behavior not only in air but also in oil. Notably, its efficacy in removing dirt in oil proved comparable to its performance in the air. The capability for large-scale production of such non-fluorinated superhydrophobic silicone while maintaining a stable *Cassie–Baxter* wetting state has various promising practical applications.

Utilizing a simple immersion technique, Hong et al. unveiled a superhydrophobic/superoleophilic surface with exceptional flexibility and mechanical durability [79]. The surface was fabricated by solvent evaporation in tandem with the polymerization of ethyl cyanoacrylate (ECA), which robustly affixed superhydrophobic/superoleophilic fluorine-coated silica nanoparticles (F-SiO₂ NPs) to the substrate surface, imparting remarkable wetting properties. Concurrently, incorporating highly stretchable polycaprolactone (PCL) introduced suppleness to the otherwise rigid polymerized ECA, further enhancing flexibility. The surface was harnessed to optimize a modified polyurethane (PU) sponge, showcasing superior efficacy in oil-spill cleanup, excellent mechanical endurance with over 99% oil separation efficiency sustained through 120 tape-test cycles and 50 rubbing test cycles, and outstanding reusability (maintaining separation efficiency even after 100 sorption/squeezing cycles). Drawing inspiration from the structures of fish scales and lotus leaves, Manna et al. obtained stretchable and durable multilayers through a covalent integration of graphene oxide nanosheets and polymeric nanocomplexes featuring residual acrylate groups, facilitated by a 1,4-conjugate addition reaction [80]. These bio-mimicking interfaces expertly replicated the constituent nanomaterial's appropriate topography and essential chemical functionality, resulting in durable superhydrophobicity and underwater superoleophobicity. Impressively, these durable multilayers retained their water/oil-repellent property even when subjected to physical damage or stretching, demonstrating their robust nature. Moreover, these versatile multilayers could be applied to diverse substrates, suggesting their potential in practical and challenging environments. Wang et al. introduced an efficient approach for producing durable superhydrophobic films by utilizing CNTs and main-chain type polybenzoxazine (P(B-oda)) precursors [81]. By capitalizing on a probe ultrasonicator, the preparation time for the CNT/P(B-oda) suspension

solution was dramatically reduced to just 5 min, a significant improvement compared to the several hours required by alternative methods. The achieved CNT/P(B-oda) film exhibited a contact angle of 167° , attributed to the surface roughness induced by the branch-like CNT nanostructures integrated into the P(B-oda) film. The enhanced dispersion of CNTs within the CNT/P(B-oda) film, facilitated by the probe ultrasonicator, correspondingly elevated hardness, withstanding the pencil-scratch test with a rating of 3H. Furthermore, the CNT/P(B-oda) film demonstrated outstanding mechanical stability across various durability assessments, including thermal treatment, sandpaper abrasion, and tape-testing. Meanwhile, the as-prepared surfaces retained their superhydrophobic performance under extreme environmental conditions, including exposure to corrosive solutions (acidic/basic) and long-term UV irradiation (up to 100 h). The robust superhydrophobicity exhibited by these surfaces demonstrates their profound significance across academic and practical domains, encompassing applications like anti-corrosion, self-cleaning, drag reduction, etc.

In conclusion, the hybridization of functional materials in elastomers has opened new frontiers in the development of stretchable superhydrophobic surfaces. Researchers have achieved remarkable properties by combining elastomers with various functional materials, such as high flexibility, stability, and self-cleaning capabilities. These advanced surfaces have potential applications in wearable devices, stretchable electronics, implantable biosensors, oil spill cleaning, and smart windows. The continuous exploration of innovative materials and fabrication techniques will undoubtedly lead to further breakthroughs, unlocking the full potential of stretchable superhydrophobic surfaces in diverse real-world scenarios.

2.3. Directly Manufacturing Rough Surfaces Utilizing Bulk Elastomers

In addition to the strategies mentioned earlier, researchers have also explored using bulk elastomers directly to achieve stretchable superhydrophobic surfaces. This approach aims to simplify the fabrication process, improve surface integrity, and reduce material consumption. Notably, the superhydrophobic surface retains the properties of the elastomer to a great extent and thus exhibits better stretchability than the above methods.

Oh et al. orchestrated the creation of an ultrathin nanoscale stretchable superhydrophobic polymer film, exhibiting coverage conformity and optical transparency [82]. The researchers employed an initiated chemical vapor deposition (iCVD) technique to co-polymerize 1H,1H,2H,2H-perfluorooctyl acrylate (PFOA) and 1,3,5-trivinyl-1,3,5-trimethylcyclotrisiloxane (V3D3). The selection of PFOA stemmed from its considerable extra free volume, the low glass transition temperature (T_g) of the resulting fluoropolymer, and the elongated fluoroalkyl chains, which provide low surface tension and impart the polymer surface with superhydrophobicity. V3D3 was seamlessly integrated into the copolymerization process, functioning as a pivotal cross-linker. This component played a crucial role in instilling a restorative force within the pPFOA (PFOA homopolymer) chain, thus transforming it into an elastomeric film, counteracting the liquid-like behavior exhibited by pPFOA at room temperature.

Through a regulation of the iCVD conditions and the PFOA-to-V3D3 ratio, the researchers achieved a cross-linked fluoropolymer network (pF2V1, wherein 2 and 1 symbolize the input flow rate ratio of PFOA and V3D3) with low crystallinity and remarkable elasticity (Figure 7a–c). Upon coating a rubber band with an 800 nm thick pF2V1 film, the resulting water-contact angle exceeded 150° , and its superhydrophobic performance was maintained even after 2000 cycles of extensive stretch-testing, reaching up to a 200% elongation (Figure 7d). Additionally, the as-prepared surface demonstrated exceptional transparency, surpassing 90% throughout the visible range while upholding uniformity and coverage conformity across large areas. Notably, the iCVD process exhibited precise control over nanoscale polymer film thickness and outstanding conformal coverage characteristics. These characteristics ensure facile and uniform deposition of the stretchable superhydrophobic surface onto various substrate materials, spanning micro- to nanotopographies, thereby emphasizing its versatility and broad applicability.

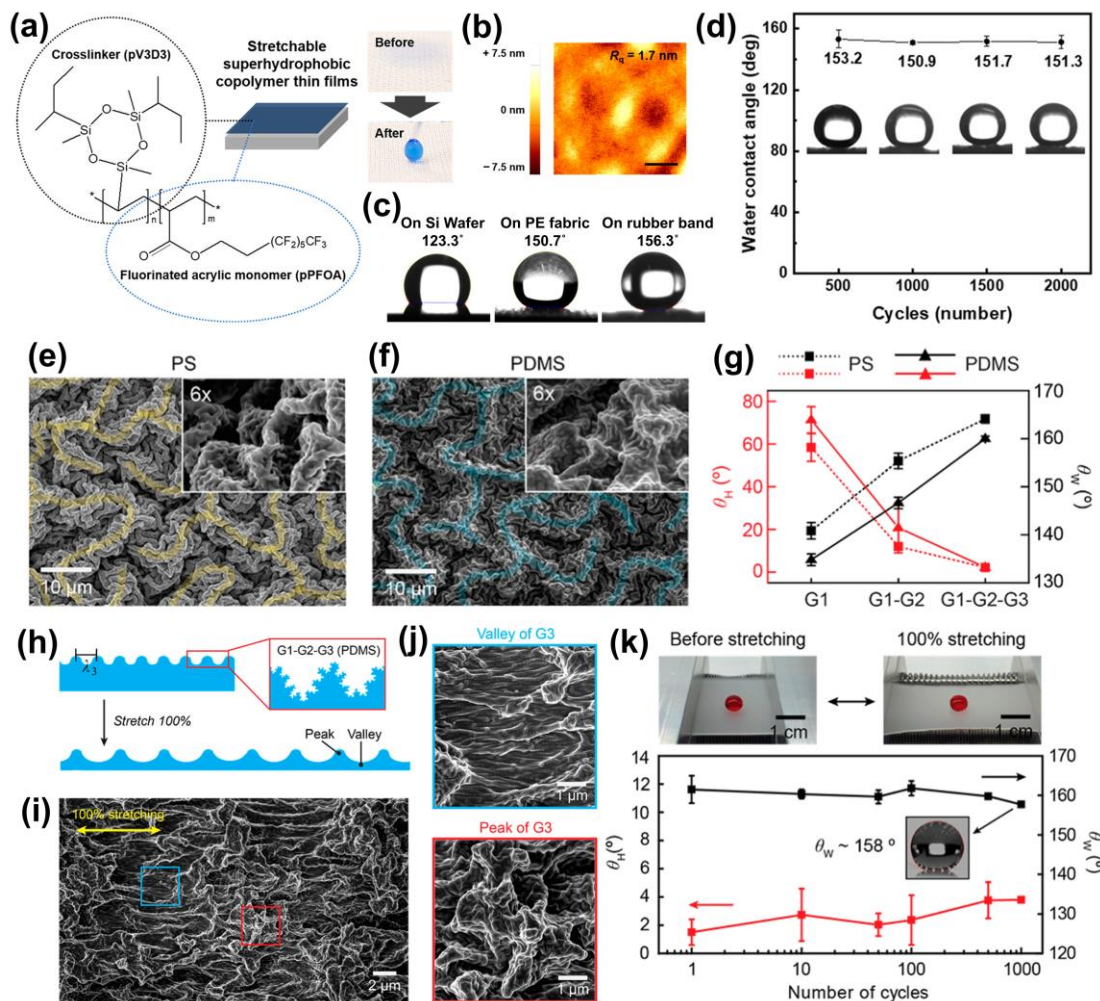


Figure 7. (a) schematic of p(PFOA-co-V3D3) copolymer thin film with mechanical stretchability and superhydrophobicity, * represent the end groups of the polymer chain. The digital camera image on the right illustrates the polyester (PE) fabric before (top) and after (bottom) the pF2V1 deposition; (b) AFM image of pF2V1 coated on a Si wafer. The scale bar is 1 μm; (c) water-contact angle images of various substrates deposited with pF2V1; (d) variation of water-contact angle of the pF2V1-coated rubber band surface along with the 200% stretching cycles [82]. (e–g) Monolithic formation of 3D hierarchical wrinkles in PDMS. SEM images of G1-G2-G3 hierarchical wrinkles on: (e) PS mold (f) inverted structures on PDMS; and (g) measured contact angle (θ_W) and contact angle hysteresis (θ_H) on the surfaces of PS and PDMS wrinkles. (h–j) Partial preservation of monolithic G1-G2-G3 wrinkles (PDMS) under stretching; (h) simplified schematics of inhomogeneous structural deformation of G1-G2-G3 wrinkles under 100% tensile strain; SEM images of (i) zoomed-out G1-G2-G3 features, blue and red frames demonstrated the valley and peak structures of G3; (j) zoomed-in valley and peak of G3. (k) Superhydrophobicity satisfying both $\theta_W > 160^\circ$ and $\theta_H < 3^\circ$ was maintained on 2D-2D-2D PDMS surface even after 1000× stretching and releasing cycles [83].

Utilizing bulk elastomers integrated with structured surfaces is another highly effective strategy for fabricating stretchable superhydrophobic surfaces. Lee et al. achieved a stretchable superhydrophobic PDMS surface featuring intricate 3D hierarchical wrinkles [83]. In their work, 3D wrinkle templates were first fabricated on thermoplastic polystyrene (PS) by employing a memory-based, sequential wrinkling of a soft CF_x skin layer deposited through reactive ion etching (RIE). This process yielded three distinct wrinkle generations (G1, G2, and G3), with each possessing a fixed wrinkle wavelength (λ) of 150 nm, 900 nm, and 10 μm, respectively (Figure 7e). These multiscale wrinkles were further treated with SF₆ via RIE to modulate the sharpness of out-of-plane features and

enhance hydrophobicity. Ultimately, PDMS was cured against the PS template, resulting in a PDMS surface adorned with intricate 3D hierarchical wrinkles (Figure 7f). The synergistic effects of hierarchical roughness and PDMS's low surface energy contributed to the surface's superhydrophobicity. Water droplets deposited on the G1-G2-G3 wrinkles exhibited a substantial contact angle of 160° and contact-angle hysteresis below 3° , indicating that the droplet was in a *Cassie–Baxter* wetting state (Figure 7g). The inherent elasticity of PDMS endowed the superhydrophobic surface with stretchability. Under mechanical stretching, λ_3 of G3 features expanded to approximately $18\text{ }\mu\text{m}$. Simultaneously, smaller G1 and G2 wrinkle rearrangements transpired solely within the valleys of G3 features. The alignment of G1 and G2 features transformed from a random distribution to a well-organized alignment parallel to the stretching direction. However, the disordered G1 and G2 features on the peaks of G3 remained intact post-stretching, with the tensile strain being evenly distributed (Figure 7h–j). This non-uniform strain distribution partially preserved the hierarchical G1-G2-G3 structure, sustaining the *Cassie–Baxter* wetting state and preserving superhydrophobicity throughout stretching. The superhydrophobicity, characterized by water-contact angles exceeding 150° and contact-angle hysteresis below 5° , endured even after subjecting the G1-G2-G3 PDMS wrinkles to 1000 cycles of uniaxial 100% stretching and subsequent release (Figure 7k). Intricate 3D surface topologies within a single material system eliminated interfacial instabilities, rendering lasting structural defects absent on the G1, G2, and G3 wrinkles. This exceptional stability positions it as a superior choice over conventional superhydrophobic surfaces for applications necessitating long-term stability, such as waterproof and antifouling treatments for stretchable devices, including wearable electronics and functional textiles.

Cha et al. presented a method for creating a stretchable microporous superhydrophobic surface using polymer tubes synthesized through the Sonogashira coupling reaction [84]. In their research, they conducted the Sonogashira coupling reaction between 1,4-diiodotetrafluorobenzene and 1,3,5-triethynylbenzene under dilute conditions, utilizing a solvent mixture of toluene and triethylamine with CuI and $\text{PdCl}_2(\text{PPh}_3)_2$ as catalysts without stirring (Figure 8a). After a specific reaction time, the mixture transformed into gel-like polymers. These polymers were filtered, washed sequentially with methanol, tetrahydrofuran, and acetone, and dried to produce a polymer sheet. The resulting sheet consisted of polymer fibers with diameters ranging from 100 to 200 nm (Figure 8b,c), and these polymer fibers featured tubular structures with smooth inner surfaces. The stacking and tangling of these fibers created large pores among them. Simultaneously, micro- and mesopores formed in the tube walls, imparting a hierarchical pore structure to the polymer surface, making it adaptable to external mechanical deformations. Because the system incorporated 1,4-diiodotetrafluorobenzene, the polymer fibers exhibited a uniform distribution of fluorine atoms (Figure 8d), rendering the polymer sheet with low surface energy, leading to superhydrophobicity with a water-contact angle of 162° (Figure 8e). The obtained superhydrophobic polymer surface also displayed mechanical stability. The tetrafluorobenzene and triethynylbenzene units in the polymer acted as electron-poor and electron-rich moieties, respectively. The incorporation allowed for electrostatic interactions between these groups, contributing to the mechanical resilience of the polymer sheet, which could elongate with up to a 15% strain (Figure 8h) while maintaining its liquid repellency. Significantly, this straightforward fabrication process facilitated the production of large-scale surfaces, offering a novel approach to creating functional superhydrophobic surfaces suitable for practical applications.

Wang et al. introduced a method for creating stretchable superhydrophobic silicone rubber surfaces using a compression molding process combined with a template approach [85]. In their technique, a stainless-steel mesh template was utilized and placed flat on the surface of a rubber sheet. The template was carefully removed after a vulcanization step, leaving a distinctive structure on the silicone rubber surface (Figure 8g). This structure consisted of numerous boat-shaped pits, each measuring $137\text{ }\mu\text{m}$ in length and $13\text{ }\mu\text{m}$ in width at the center with S-shaped rises at each end of the pits with a width

of 30 μm . The three-dimensional (3D) topography revealed that the surface exhibited a regular concave-convex structure (Figure 8g, inset). This rough replica structure provided the necessary physical characteristics for the surface to function according to the *Cassie* wetting model. When placing a liquid droplet on the surface, an air layer formed between the droplet and the surface, preventing the droplet from penetrating the depressions on the surface. Combining this rough structure with the inherent low surface energy of the rubber, which was significantly reduced after a heat treatment at 200 $^{\circ}\text{C}$ for 1 h, resulted in the surface achieving superhydrophobicity, with a water-contact angle of approximately 158° and a sliding angle of around 8° . Leveraging the elasticity of the silicone rubber, the created surface exhibited durable superhydrophobic properties during mechanical stretching. When stretched to a strain of 100%, the replica structure remained intact, and the texture remained clear, with no changes in liquid repellency or contact angle. Even after 60 cycles of stretching and releasing (at a 100% strain), the contact and sliding angles remained at 155° and 7° , respectively (Figure 8h). Furthermore, this superhydrophobic surface exhibited a specific self-healing capacity at high temperatures, making it a suitable candidate for applications requiring superhydrophobic surfaces in outdoor environments with elevated temperatures.

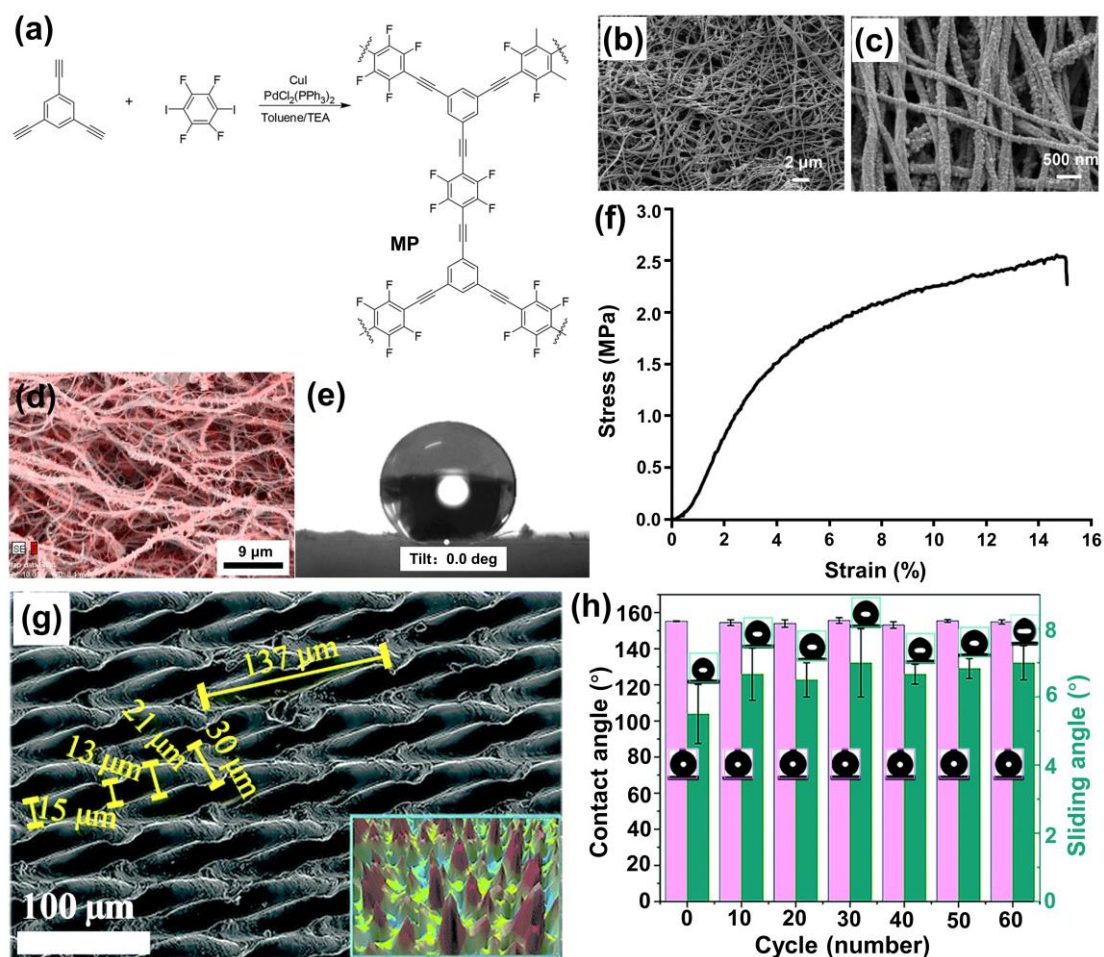


Figure 8. (a) Reaction scheme; (b,c) SEM images of MPP; (d) EDS mapping of fluorine atom for MPP; (e) contact angles with water; (f) stress–strain curve of MPP [84]; (g) SEM diagram of the surface structure of superhydrophobic silicone rubber, the inset shows the 3D topography of the surface structure of superhydrophobic silicone rubber; and (h) contact angle and rolling angle along with the change of tensile cycle, the pink and green columns represent contact angle and sliding angle, respectively [85].

Similarly, Zhang et al. developed a stretchable superhydrophobic surface by combining a replica template structure with PDMS and plasma treatment [86]. The governing factor behind the surface's superhydrophobicity lies in the hierarchical wrinkle structures, which yield a water-contact angle of approximately 172° and a sliding angle of around 5° . The superhydrophobicity durability is attributed to its hierarchical structure within the bulk material. Even after undergoing 500 cycles of stretching and release with the strain, its retained superhydrophobicity remained below 100%. Such superior performance gives the surface potential applications in outdoor electronic displays. By electrospinning, Li et al. created a stretchable superhydrophobic surface composed of fluorinated polycaprolactone (PCL)-block-1H,1H,2H,2H-perfluorooctyl acrylate (TFOA) copolymer (PCL-b-PTFOA) nanofibrous material featuring a hierarchical porous surface [87]. As a result of the combined effects of its hierarchical porous structure and the low surface energy of PTFOA, the PCL-b-PTFOA surface demonstrated a water-contact angle of approximately 150° . Furthermore, the superhydrophobic properties were maintained even as the strain on the surface increases to 600%. This combination of surface wettability and mechanical stability ensures that the surface is viable for applications requiring antifouling and self-cleaning in daily and industrial scenarios.

Wang et al. directly constructed a stretchable superhydrophobic surface with hierarchical micro-convexities in an orderly arrangement and interconnected on fluororubber by combining the strategies of a hot press and the template method [88]. The unique hierarchical micro-convexities kept the droplets in the *Cassie*-impregnating state on the surface, showing excellent superhydrophobicity with a contact angle of $155 \pm 2^\circ$ with excellent potential for droplet transfer in a stretching state. The obtained superhydrophobic fluororubber exhibited a 9.19 MPa of tensile strength and 121.9% of break elongation, reduced by 15.8% and 19.3% compared to the original flat fluororubber, ascribed to the constructed micro-convexities. The contact angle was successfully maintained above 150° when increasing the strain from 0% to 50%, indicating the remarkable stability of the surface structure. Only a slight decrease in the superhydrophobicity of the surface was observed even after 100 rounds of stretch-release cycles, while the contact angle remained above 150° . Moreover, the interconnected micropumps greatly resisted microstructure deformation in the tensile state, significantly improving the surface durability. After 10 cycles of sandpaper abrasion, the contact angle of the coating decreased slightly. In addition, the contact angle showed no obvious change when the obtained superhydrophobic fluororubber was treated at a high temperature of 200°C at different durations. Such superior superhydrophobic surfaces could be used as microfluidic devices under extreme working conditions.

Directly manufacturing rough surfaces utilizing bulk elastomers to create stretchable superhydrophobic surfaces offers a straightforward and cost-efficient approach to developing functional surfaces that align with the demands of real-world applications. These hold significant promise for the future progression of stretchable superhydrophobic surfaces, representing a pivotal direction for advancement. By harnessing the broader potential of bulk elastomers, we can significantly amplify the transition from laboratory-based creations to tangible practical implementations. This, in turn, will drive the proliferation and diversification of superhydrophobic surfaces in various applications.

3. Application of Stretchable Superhydrophobic Surfaces

The development of more durable and stretchable superhydrophobic surfaces has opened up various potential applications. This section provides an overview of some representative applications of stretchable superhydrophobic surfaces.

3.1. Strain Sensing

Strain sensing stands out as a widely embraced application for stretchable superhydrophobic surfaces. Over the last decade, scientists have dedicated significant efforts to creating diverse superhydrophobic surfaces that exhibit stretchability and ingeniously combined them with other functional materials and electronic components to construct

innovative strain sensors suitable for a range of applications, including human activity monitoring, electronics, and robotics, etc. [89–93]. This session will present some illustrative examples to explain how stretchable superhydrophobic surfaces work in strain sensing.

Recently, Wang et al. introduced a wearable strain sensor with an anti-liquid-interference feature, relying on a composite hydrogel that combines superhydrophobicity and conductivity [94]. The sensor showcases a dual-layered design incorporating a conductive composite hydrogel. The arrangement encompasses an exterior layer composed of a composite film of silicone elastomer (Ecoflex) and silica microparticles, as well as an inner layer consisting of a polymer network of P(AAM-co-HEMA)-MXene-Ag hydrogel. The Ecoflex/silica microparticle composite film imparts superhydrophobic functionality to the wearable strain sensor, ensuring liquid-repellency stability during stretching and bending. The contact angle of water droplets on the sensor surface is around 153° , confirming the superhydrophobic feature of the Ecoflex/silica composite surface. The combined sensor demonstrates stretchability, leveraging the elasticity of both elastomer and hydrogel components. Superhydrophobic properties remain intact during stretching, with the water-contact angle consistently exceeding 150° across a strain range (ϵ) of 0–100%. Through monitoring human bodily movements and joint actions, the strain sensors exhibit a notable relative resistance change $\Delta R/R_0$ (%) = $(R - R_0)/(R_0 \times 100\%)$ (R_0 and R are the initial resistance and the real-time electrical, respectively) that escalates from 66% to 396% as strain increases from 20% to 100% (Figure 9a). Different stretching states result in distinct gauge factors (GF): 3.36, 3.72, and 4.08 for strains of 0–60%, 60–100%, and 100–120%, respectively (Figure 9b). The strain sensor's resistance response at a tensile strain of 100% was also evaluated underwater. The outcomes indicate no divergence between resistance changes in water and air due to the sensor's superhydrophobic outer layer that repels water interference. Furthermore, the sensor's liquid repellency effectively shields against the influence of water droplets and flow. This protective feature safeguards the sensor from the impact of water droplets or flows while monitoring subtle human movements (Figure 9c) such as speech, facial expressions, pulse, etc.

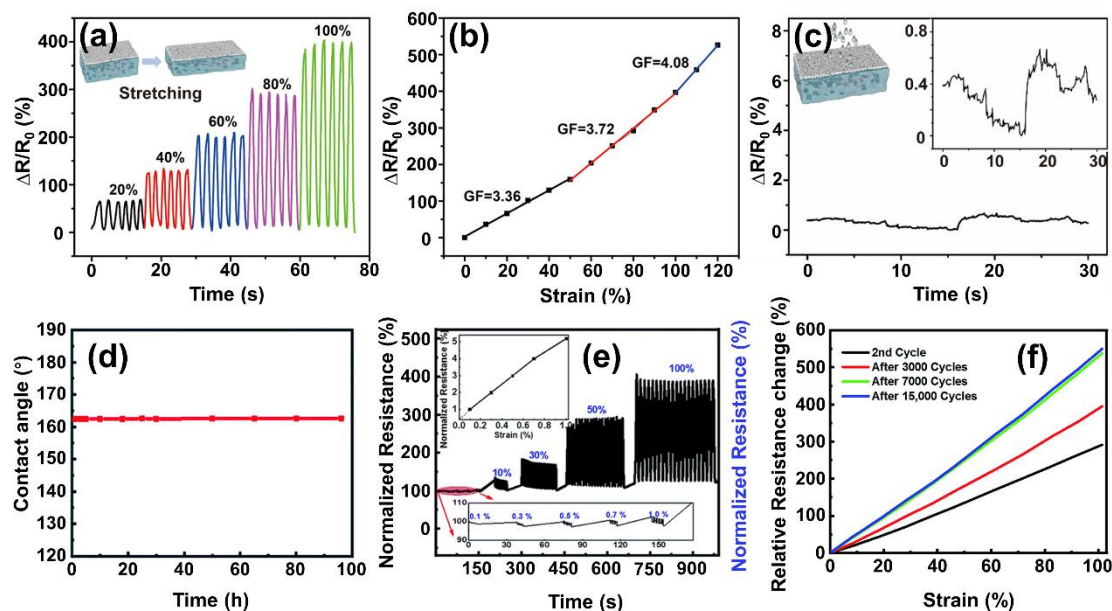


Figure 9. (a) Resistance variation ($\Delta R/R_0$) of the multifunctional wearable strain sensor with strains of 20%, 40%, 60%, 80%, and 100%; (b) gauge factors of the multifunctional wearable strain sensor at different strain regions; (c) change in resistance when the wearable sensor with superhydrophobic film was interfered with by the continuous water droplets, intermittent water droplets, and water flow [94]; (d) time-course evaluation of the contact angle on the water-repellent sensor; (e) normalized resistance changes with increasing strain; and (f) relative resistance changes with strain after particular cycles during cycling stability testing of the sensor [95].

Kaneko et al. developed a superhydrophobic strain sensor capable of monitoring structural integrity by incorporating single-walled carbon nanotubes (SWCNTs) into a non-fluorinated superhydrophobic PDMS coating [95]. The resulting surface, a combination of dual-scale clusters created by silica nanoparticles and the inherent properties of PDMS, exhibited superhydrophobic characteristics with a water-contact angle of 161° . The liquid repellency was impressively maintained even when stretched to a 100% strain for 100 h (Figure 9d). Their group developed a Zn-Al sol-gel dispersant technology for SWCNT bundles, enabling effective anchoring of SWCNTs at a molecular level within the PDMS. This well-dispersed configuration facilitated good electrical contact between SWCNTs. The strain sensor demonstrated a linear increase in resistivity as the strain was applied, with the contact area decreasing. It displayed high sensitivity in detecting low strain levels, as little as 0.1%, up to 100% strain, with a highly linear and rapid response (Figure 9e). Notably, the strain sensor maintained its high linearity and increased response even after stabilization for 7000 cycles (Figure 9f), showcasing its reliability for infrastructure monitoring compared to previously reported sensors. Additionally, the PDMS/SWCNTs/PDMS sensor exhibited exceptional real-time responsiveness, detecting strain changes of less than 1° in aluminum and steel strips. Its low initial resistance allowed it to power an LED using a 3 V battery. Beneficial to its superhydrophobic property, the PDMS/SWCNTs/PDMS strain sensor demonstrated significant potential to function effectively under challenging practical conditions such as humid, acidic, saline, and alkaline environments.

Taking advantage of a post-surface roughening process, Jia et al. engineered a coating-free superhydrophobic material by uniformly embedding MWCNTs in vulcanized silicone rubber (RTV) [96]. The mixture of MWCNTs and RTV was allowed to cure in a paper box at ambient conditions, resulting in a composite surface with rough structures replicated from the paper mold. Subsequently, the surface was abraded with sandpaper to achieve a dual-scale roughness reminiscent of a lotus leaf, featuring continuous large protrusions densely covered with small features. The rough structure and the inherent hydrophobicity of RTV endowed the surface with superhydrophobic properties. Water droplets deposited on this surface maintained a spherical shape, boasting contact angles of approximately 155° and sliding angles of about 6° . Given the high flexibility of RTV and the homogeneous distribution and encapsulation of MWCNTs within the RTV matrix, the resulting superhydrophobic surface displayed impressive mechanical robustness. Water droplets retained their spherical morphology even when stretched within a 0–450% strain range. The water-contact angles (WCAs) and sliding angles (SAs) of droplets at different strain levels remained above 154° and below 8° , respectively (Figure 10a). After subjecting the surface to 5000 cycles of stretching–releasing at a strain of 200%, the WCA still measured above 151° , with the SA remaining below 10° (Figure 10b). The results demonstrated the remarkable stability of the superhydrophobic surface under dynamic, extensive, and long-term strains, ensuring its waterproofing protection throughout its sensing range and after repeated sensing cycles. The prepared composite surface exhibited robust dynamic durability when employed in strain-sensing applications. The signal shape and intensity of relative resistance ($\Delta R/R_0$) remained almost identical over 10,000 stretching cycles at 50% strain (Figure 10c). The average gauge factor (GF) ranged from 2.1 to 214 within a wide range, reaching up to 447%, indicating both high sensitivity and a broad sensing range for the sensor (Figure 10d). Moreover, the stretchable superhydrophobicity ensured the sensing material maintained its sensing performance under harsh conditions such as strong acids, alkalis, artificial sweat, and everyday liquid contaminants (Figure 10e). These exceptional properties resulted in remarkable dynamic durability, rendering the composite material suitable as a flexible and stretchable sensor capable of detecting a wide range of human motions in challenging environments.

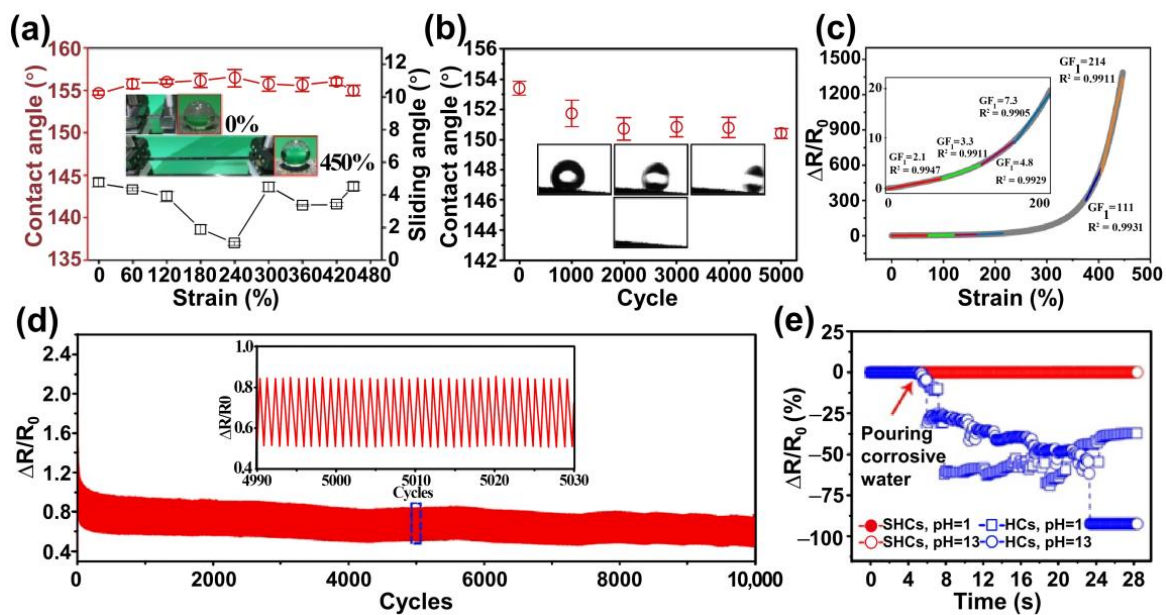


Figure 10. Multifaceted robustness characterization of the superhydrophobic MRS material: (a) water-contact angle and sliding angle variation while stretching the MRS materials stretched from 0 to 450% strain; (b) water-contact angles after 0–5000 stretching cycles at 200% strain; (c) linear fittings of the hierarchically structured MRS material; (d) relative resistance under cyclic stretching from 0 to 50% strain over 10,000 cycles; and (e) relative resistance changes of unabraded and superhydrophobic MRS materials at static states under different vigorous conditions: corrosive water [96].

Moreover, Ding et al. achieved the creation of a flexible, conductive, and superhydrophobic porous film by blending thermoplastic polyurethane (TPU), carbon black (CB), and 1H,1H,2H,2H-perfluorodecyltriethoxysilane (PFDTs) [97]. TPU served as the substrate for electrospinning, CB functioned as the conductive coating, and PFDTs was chosen to impart superhydrophobic properties. The resulting surface exhibited exceptional liquid repellency, boasting a water-contact angle of 179° . This film displayed impressive performance characteristics, including high repeatability and linear sensitivity within a 0–100% strain range. It featured a swift stretch response time of 200 ms and a rapid recovery time of 150 ms. Furthermore, a clear relationship between tensile strength and the peak value of the output current signal was observed over 2000 s, underscoring the strain sensor's outstanding durability and reliability. Thanks to its high sensitivity, rapid response time, stability during stretching and releasing, and superhydrophobic properties, these conductive films are well-suited as wearable devices for monitoring human movements across various conditions.

3.2. Prevention of Corrosion

The Cassie–Baxter wetting status of water droplets on superhydrophobic surfaces significantly reduces the contact between water and the substrate, making it an effective strategy for preventing corrosion. The stretchability ensures that the liquid repellency is maintained when exposed to external deformation or stretching, expanding the superhydrophobic surface's application area to curved and soft substrates. Gao et al. engineered wearable strain sensors with stretchability and anti-corrosive properties using a PDMS/CNT-decorated elastomer nanofiber composite [98]. In their approach, ultrasonication was employed to decorate CNTs onto the surface of conductive thermoplastic PU nanofibers. Subsequently, PDMS was modified to the nanofiber surface to confer low surface energy, imparting superhydrophobic and anti-corrosion properties to the composite. The resulting surface exhibited outstanding water repellency, maintaining its superhydrophobic property even when subjected to various aqueous conditions (water, acid, base, and salt). After a 6 h

immersion in an acidic solution, the contact angles remained stable and hovered around their initial values, demonstrating excellent anti-corrosion characteristics.

Liu et al. introduced a superhydrophobic composite film with exceptional stretchability, recyclability, and anti-acid corrosion by combining thermoplastic elastomers (TPE), inorganic nanoparticles, and fluorinated materials [99]. TPE was chosen for its high stretchability and integrated with fumed silica nanoparticles to enhance film stability during formation and provide necessary surface roughness. Then, the stretchable superhydrophobic surface was achieved after modification with FAS-17 (heptadecafluoro-1,1,2,2-tetradecyltrimethoxysilane). Among a series of screenings, the TPE/17.5% SiO₂ composite film exhibited optimal performance, whose water-contact angle was $151.8^\circ \pm 0.5^\circ$ with a remarkable tensile elongation of up to 750%. The composite films maintained water-contact angles exceeding 151.0° and sliding angles below 10.0° under diverse tensile strains, showcasing remarkable superhydrophobicity. Even after 500 cycles of cyclic stretching, the composite films retained strong hydrophobicity with a contact angle of $148.5^\circ \pm 0.6^\circ$ and a sliding angle of $11.0^\circ \pm 0.2^\circ$. The TPE/17.5% SiO₂ composite film exhibited robust anti-acid corrosion and retained its superhydrophobic state after 15 days of immersion. The inclusion of acid-resistant SiO₂ nanoparticles contributed to the film's superior acid corrosion resistance and the augmentation of micro-nanostructures on the surface. The flexible and easy-to-apply characteristics of the superhydrophobic composite film suggest promising applications in various fields, including electronics, automotive, construction, decoration, and other equipment.

In recent years, controllable wettability has played an essential role in both fundamental and industrial applications, effectively prolonging the lifetime of electronic devices under corrosive and humid environments [100]. However, the hierarchical roughness and low-surface-energy substances that endow the system with super wettability are vulnerable and easily damaged under tensile or flexural strain, significantly limiting the practical application of the functional surfaces. To tackle these challenges, Ye et al. developed a stretchable material composed of carbon nanotubes and polydimethylsiloxane (CNTs/PDMS) using an atmospheric micro-plasma jet (μ PJ) technique [101]. They began by creating CNT membranes through vacuum filtration of a CNT suspension using polyvinylidene fluoride (PVDF) membranes. Next, they spin-coated polydimethylsiloxane precursors onto these CNT membranes and immersed them in deionized water after curing to facilitate the peeling of CNTs, resulting in stretchable CNTs/PDMS membranes. Finally, they employed a custom-made μ PJ to pattern the surface, introducing the necessary roughness. This, combined with the inherent hydrophobicity of CNTs and the low surface energy of PDMS, achieved a stretchable superhydrophobic surface (Figure 11a). Water droplets on this surface exhibited a contact angle of approximately 160° and a sliding angle below 3° . The water repellency of this material proved to be highly robust, with the contact angle experiencing only slight fluctuations within the range of $158^\circ \pm 3^\circ$, even after subjecting it to 1000 cycles of stretching and releasing (at a strain of 50%) (Figure 11b). This exceptional performance was attributed to the synergistic effects of the chemical inertness of CNTs and the hierarchical surface structure. Notably, the superhydrophobic film demonstrated remarkable corrosion resistance, maintaining water-contact angles above 150° after exposure to open air and various corrosive liquids (ranging from pH 1 to 14) for 8 weeks (Figure 11c). The stable *Cassie* wetting state endows the resulting CNTs/PDMS surface with the potential for numerous practical applications in challenging environmental conditions.

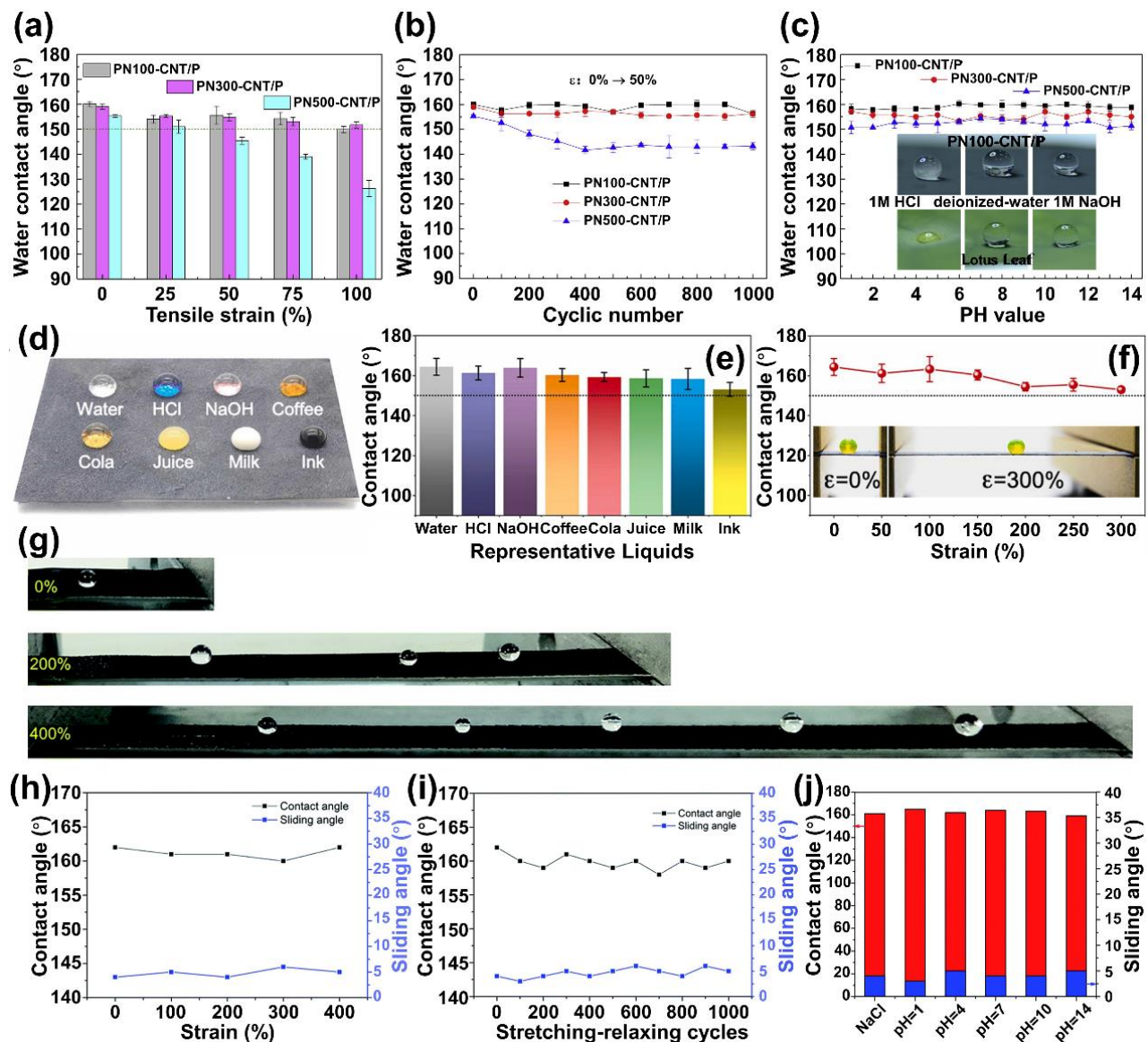


Figure 11. Durability of stretchable and conductive superhydrophobic CNT/PDMS films. WCAs recorded under tensile strain from 0% to 100% (a); and underwent 1000 cyclic stretching from $\varepsilon = 0\%$ to $\varepsilon = 50\%$ (b). (c) WCAs of as-prepared films under corrosive liquids (pH value from 1 to 14). CNT, carbon nanotube; WCAs, water-contact angles [101]; (d) digital photographs of water, HCl (1 M) solution, NaOH (1 M) solution, coffee, cola, juice, milk, and ink droplets on superhydrophobic PTCCS nonwoven textile; and (e) their corresponding WCAs. (f) WCAs of PTCCS under increased strains from 0% to 300% [102]; (g) water droplets on the graphene composite at a strain of 0%, 200%, and 400%. (h–j) CAs and SAs of the graphene composite (h) at various stretching strains; (i) after various stretching–releasing cycles; and (j) after immersing the composite in different corrosive liquids for 24 h, the red and blue colors represent contact angle and sliding angle, respectively [103].

By utilizing a flexible network composed of carbon black nanoparticles and carbon nanotubes (CB/CNT) as well as titanium dioxide nanoparticles modified with perfluorooctyltriethoxysilane (PFOTS-TiO₂ nanoparticles), Dong et al. engineered and successfully fabricated a stretchable superhydrophobic surface with applications in health monitoring and pollution resistance [102]. The process began with electrospinning styrene-ethylene-butylene-styrene (SEBS) to create a nonwoven fabric, followed by the coating of CB and CNT to form composite CCS fabrics. PFOTS and Degussa P25 TiO₂ were then spray-coated onto these CCS fabrics, ultimately realizing a stretchable superhydrophobic surface known

as PTCCS. The flexible SEBS component, integrated with the adaptable CB/CNT network, was designed to accommodate stretching, with CB particles filling the voids between CNTs, effectively acting as bridges. It also ensured that the composite surface exhibited excellent stretchability. PFOTS, known for its high permeability and possessing bifunctional groups (R-SiO₃ and R-F), played a critical role by significantly reducing the surface energy and establishing strong layer adhesion. PFOTS also bridged the TiO₂ nanoparticles and the underlying matrix, enabling the rough structures formed by TiO₂ to adapt to external mechanical deformations. The PTCCS surface demonstrated remarkable liquid repellency, with various droplets such as coffee, cola, juice, yogurt, salt, acid, and alkali solutions, maintaining approximately spherical shapes and contact angles exceeding 150° (Figure 11d,e). The results highlighted the surface's excellent superhydrophobicity. Furthermore, this property remained robust even when subjected to mechanical deformation, as evidenced by a water-contact angle exceeding 150° on the PTCCS surface under high stretching conditions of up to a 300% strain (Figure 11f). In addition to stretching, the PTCCS surface displayed resilience against mechanical wear. After subjecting the PTCCS surface to 1200-grit SiC sandpaper abrasion with a 100 g weight over a 10 cm distance for 50 cycles, the water-contact angle only experienced a slight reduction from 162° to 152°. Moreover, the PTCCS surface exhibited exceptional corrosion resistance. Following immersion in typical corrosive liquids, including HCl solution (pH = 1), 5 wt% NaCl, and NaOH solution (pH = 14), for 24 h, all samples maintained a water-contact angle greater than 150°. Additionally, the surface morphology and structure remained well-preserved, underscoring the outstanding chemical resistance of this superhydrophobic surface, and highlighting its substantial potential for practical applications.

Wang et al. devised a straightforward method to synthesize a superhydrophobic graphene composite through a dissolution and re-solidification process [103]. They accomplished this by partially embedding perfluorosilane-coated graphene into thermoplastic polyurethane (TPU). This approach enhanced the mutual interaction between the components and provided the essential surface roughness. Thanks to the graphene's high surface area and the exceptional tensile strength of TPU, the interface between water and the resulting composite maintained the *Cassie* state. This was evident in the contact angles of water droplets (10 µL), which exceeded 155° and the sliding angles, which measured less than 10°, even when the material was subjected to stretching strains of up to 400% (Figure 11g,h). Moreover, the superhydrophobicity of the surface persisted even after undergoing 1000 stretching–relaxation cycles with a 300% strain, demonstrating remarkable durability in both stretchability and superhydrophobicity (Figure 11i). The micro-nano structure formed on the TPU played a vital role in the surface's robust liquid repellency. This structure effectively traps air, preventing the penetration of water and corrosive substances. Consequently, the composite surface showcased impressive anti-corrosion properties. After immersion in corrosive liquids such as 3.5 wt% NaCl and aqueous solutions with pH values ranging from 1 to 14 for 24 h, followed by rinsing and drying at room temperature, the superhydrophobicity remained intact. Contact angles (CAs) remained above 150° while sliding angles (SAs) stayed below 10° (Figure 11j). This exceptional corrosion resistance opens possibilities for applying the graphene composite in various practical scenarios.

3.3. Oil–Water Separation

Stretchable superhydrophobic surfaces with inherent oleophilic properties have garnered attention for their potential application in environmental protection and resource conservation, particularly in the realm of oil–water separation, where oil possesses a lower surface tension than water, enabling it to permeate the surface while repelling water easily. The flexibility of the substrate effectively resists the impact of liquids, maintains superhydrophobicity under deformation caused by external pressure to maintain the efficiency of oil–water separation, and extends the lifetime of the surfaces. Inspired by the mechanical flexibility observed in nanofibrous biomaterials, Guo et al. fabricated a robust superhydrophobic membrane, PDMS/PVDF@KNFs, through a simple one-step

approach devoid of incorporation with inorganic fillers [104]. The combination of PDMS and PVDF micro/nanoparticles effectively lowered the surface energy and introduced hierarchical surface roughness by incorporating Kevlar nanofibrils (KNFs). The superhydrophobic membrane was realized by employing a single-step vacuum filtration process. When subjected to a mixture of dichloroethane and water ($V_{\text{oil}}:V_{\text{water}} = 10:1$), the resulting PDMS/PVDF@KNFs membrane enabled the oil to permeate without external pressure while water remained constrained at the surface. A remarkable oil purity of up to 99.9% was achieved upon oil collection, and the flow rate remained consistent even after 20 separation cycles, indicating the membrane's high-efficiency separation performance and robust reusability. The static contact angle experienced minimal alteration during each cycle, fluctuating within a $3\text{--}6^\circ$ range, affirming the membrane's durability and superhydrophobic properties throughout the oil–water separation. Similarly, Gao et al. engineered a stretchable, superhydrophobic, and anti-ultraviolet nanofiber composite membrane [105]. TiO_2 nanoparticles were anchored onto PU nanofiber surfaces via ultrasonication, followed by PDMS modification, lowered surface energy, and bolstered interfacial adhesion between TiO_2 nanoparticles and PU nanofibers. Due to its superior corrosion resistance, this composite membrane displayed remarkable potential in oil–water separation and oil–corrosive-solution separation. Dichloromethane–water mixture separation showcased the rapid penetration of dichloromethane and containment of the corrosive aqueous solution on the nanofiber membrane's top surface due to its superhydrophobic and superoleophilic characteristics. The nanofibrous composite membrane demonstrated a substantial oil permeate flux and separation efficiency of $1964.7 \text{ L m}^{-2} \text{ h}$ and 90.3%, respectively, during the initial separation and $1972.0 \text{ L m}^{-2} \text{ h}$ with a sustained separation efficiency of about 92% during cyclic testing, underscoring its impressive recyclability. A meticulous study of the oil–water separation mechanism revealed that oil exhibited the *Wenzel* state upon contact with the nanofiber composite membrane. It was augmented by a Laplace pressure gradient (produced by superoleophilicity) that facilitated its continuous penetration. Simultaneously, the superhydrophobic *Cassie–Baxter* state retained water on the nanofiber surface through repulsive forces, reinforcing the separation efficiency via Laplace pressure and gravity interplay.

Using a straightforward dip-coating technique, Li et al. constructed hierarchical superhydrophobic architectures on the surface of a three-dimensional copper foam (CF) [106]. Surface modifications involved mussel-inspired polydopamine (PDA) and Ag nanoparticles onto the CF substrate, sequentially followed by n-dodecyl mercaptan (NDM) coupling. The incorporation of NDM coupling effectively reduced the surface energy, while the resulting CF-PDA-Ag-NDM exhibited heightened surface roughness through its hierarchical structures, thereby establishing a superhydrophobic property. To evaluate its oil–water separation capabilities, a hexane–water mixture ($m_{\text{oil}}/m_{\text{water}} = 1$) was employed. Gravity-driven, the hexane permeated the mesh while the water was blocked, remaining confined within the upper PMMA tube. Moreover, the superhydrophobic CF demonstrated a separation efficiency exceeding 95% for a range of oil–water mixtures (hexane–water, heptane–water, octane–water, dodecane–water, and sesame oil–water), notably reaching 98.3% for the dodecane–water mixture. Quantitatively, the maximum height and intrusion pressure (p) for water were $14.4 \pm 0.9 \text{ cm}$ and $1.4 \pm 0.1 \text{ kPa}$, respectively, indicating that water could not traverse the foam's structure under specific intrusion pressures.

Huang et al. developed a flexible and stretchable superhydrophobic surface using a process involving ultrasonication-induced decoration of carbon nanotubes (CNTs) onto thermoplastic polyurethane (TPU) nanofibers, followed by the hydrolysis of methyltrichlorosilane (MTS) on the surface of the CNTs [107]. Utilizing CNTs and polysiloxane derived from MTS, this approach conferred multi-scale physical structures onto the polymer nanofiber. It also imparted low surface energy, resulting in a *Cassie–Baxter* wetting state for water droplets deposited on the surface. Consequently, the material exhibited superhydrophobic properties, with a water-contact angle reaching 155° .

Due to the anchoring or embedding of polysiloxane-modified CNTs onto the TPU fiber, the resulting superhydrophobic surface retained the flexibility of the TPU nanofibers, enabling it to adapt to mechanical deformation. Tensile testing revealed that the TPU nanofibers and the polysiloxane-coated CNTs tended to reorient themselves at different strain levels. Nanofiber orientation became evident at a strain of 20% (Figure 12a), and this effect intensified as the strain increased to 80%. Simultaneously, the polysiloxane-coated CNTs aligned along the nanofiber axis during stretching and winding, maintaining the hierarchical structure on the nanofiber surface. It increased interfacial contact area and contributed to enhanced tensile strength. This adaptability allowed the prepared surface to stretch up to 370% at the break, with Young's modulus of 2.35 MPa and tensile strength of 9.11 MPa. Remarkably, the surface's superhydrophobicity was maintained throughout this process. Water droplets retained their spherical shape on the surface even when stretched to 20%, 50%, and 80% strains. The contact angles varied from 150° to 153° , while the contact angle fluctuated around 151° during stretching–releasing cycles (stretching at 50%) (Figure 12b,c).

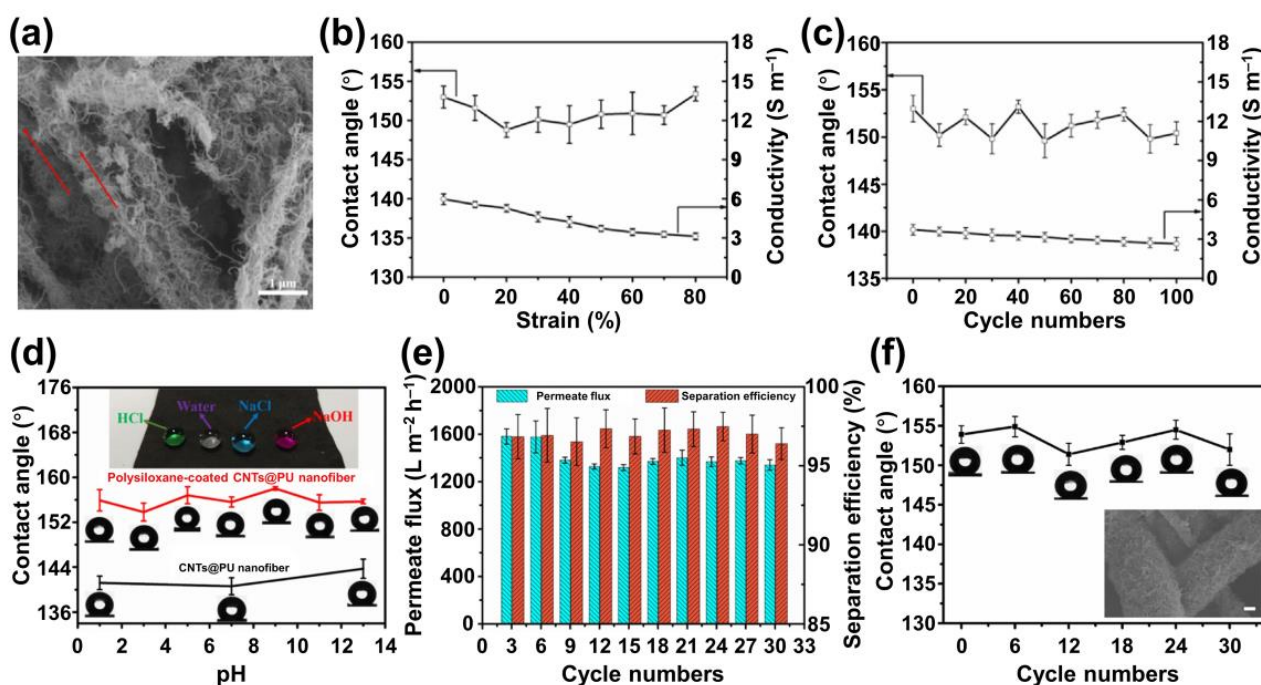


Figure 12. (a) SEM images of the polysiloxane-coated CNTs@PU nanofiber mat under different strain 20%, the arrows demonstrated the stretching direction; (b,c) variation of the CAs and conductivity of the superhydrophobic mat (b) under different strains; and (c) during 100 uniaxial stretching cycles. (d) Variation of the CAs of the CNTs@PU nanofiber mat and the polysiloxane-coated CNTs@PU membrane with the pH values of water droplets; (e) permeate flux and separation efficiency of the oil–water separation using polysiloxane-coated CNTs@PU membrane during different cycles. (f) Variation of CAs of polysiloxane-coated CNTs@PU membrane during different oil–water separation cycles [107].

Thanks to the water-resistant and corrosion-resistant nature of the polysiloxane-coated CNTs, which form a protective shell layer, the stretchable superhydrophobic surface demonstrates excellent durability for use in harsh environments. When exposed to solution droplets with pH values of 1, 7, and 13, the contact angles remained consistent, ranging from 153° to 158° , regardless of the droplet's pH level. Even after immersing the surface in acidic and alkaline solutions with pH values of 1 and 3 for 5 days, the contact angles still exceeded 150° , showcasing remarkable corrosion resistance (Figure 12d).

When the stretchable superhydrophobic surface was exposed to oil–water mixtures (chloroform and water, each phase was dyed for better visualization), separation could be easily achieved under gravity with high flux and efficiency. The oil rapidly permeated through the membrane and ultimately dripped into the beaker due to its superoleophilic properties. In contrast, water remained on the top surface of the membrane due to its superhydrophobic nature. Following separation, almost no residual chloroform was detected in the separated water. The surface could be reused after each oil–water separation. As depicted in Figure 12e, the oil permeation flux through the surface and the separation efficiency were monitored over multiple cycles. It was observed that the superhydrophobic surface exhibited a high oil permeation flux of approximately $1500 \text{ L m}^{-2} \text{ s}^{-1}$ in the first three cycles. Then, the flux stabilized around $1350 \text{ L m}^{-2} \text{ s}^{-1}$ over the subsequent 27 cycles, indicating good reusability. Furthermore, oil–water separation efficiency remained above 96% during all 30 cycles, demonstrating high cyclic separation performance. In addition to its recyclability in oil–water separation, the superhydrophobicity persisted throughout the separation cycles, with contact angles remaining nearly unchanged and staying around their initial value of 154° (Figure 12f). It affirms the durability of superhydrophobicity and its potential for practical applications in separating oil from various corrosive solutions.

Leveraging the flexibility of polymers, Chen et al. engineered a robust and stretchable superhydrophobic surface comprised of elastic polyurethane (PU) and chromatic polydiacetylenes (PDA) for highly efficient oil–water separation [108]. In their method, PU and 10, 12-pentacosadiynoic acid (PCDA) were initially blended and electrospun to create a smooth, interconnected fibrous membrane (Figure 13a). Subsequently, a brief UV irradiation was applied to initiate PCDA polymerization, forming PDA clusters on the electrospun fibers (Figure 13b). These clusters resulted from the phase separation between PU and PDA and could be further enhanced by a heat treatment to increase surface roughness (Figure 13c,d). The combination of the polymers' low surface energy and the resulting hierarchical structures conferred superhydrophobicity on the surface, boasting a water-contact angle of 157° and superoleophilicity with a tiny oil-contact angle of 0° . The obtained superhydrophobic surface was also stretchable thanks to the in situ formed structure and the polymers' elasticity. When subjected to biaxial mechanical strains within the 0–300% range, the water-contact angle barely changed (Figure 13e). Furthermore, liquid repellency was preserved at around $\sim 155^\circ$ even after 1000 cycles of stretching and retracting (Figure 13f). During the separation of a dichloromethane and seawater mixture, the oil swiftly permeated through the membrane under the influence of gravity while the water remained above. This remarkable permeation flux reached $6369.4 \pm 37.7 \text{ L m}^{-2} \text{ h}^{-1}$, signifying an easily operable, low-energy-consuming process. Additionally, other oils with surface tensions below 30 mN m^{-1} , such as n-hexane, petroleum ether, ethyl ether, and toluene, could also be effectively separated from water mixtures, exhibiting separation efficiencies of 99.3%, 99.1%, 98.7%, 99.5%, and 98.4%, respectively (Figure 13g). Moreover, after 12 separation cycles, the water-contact angle remained above 150° , underscoring the robust reusability of the superhydrophobic surface due to the advantages of the in situ growth approach. It ensured that the surface maintained a *Cassie–Baxter* wetting state for long-term applications.

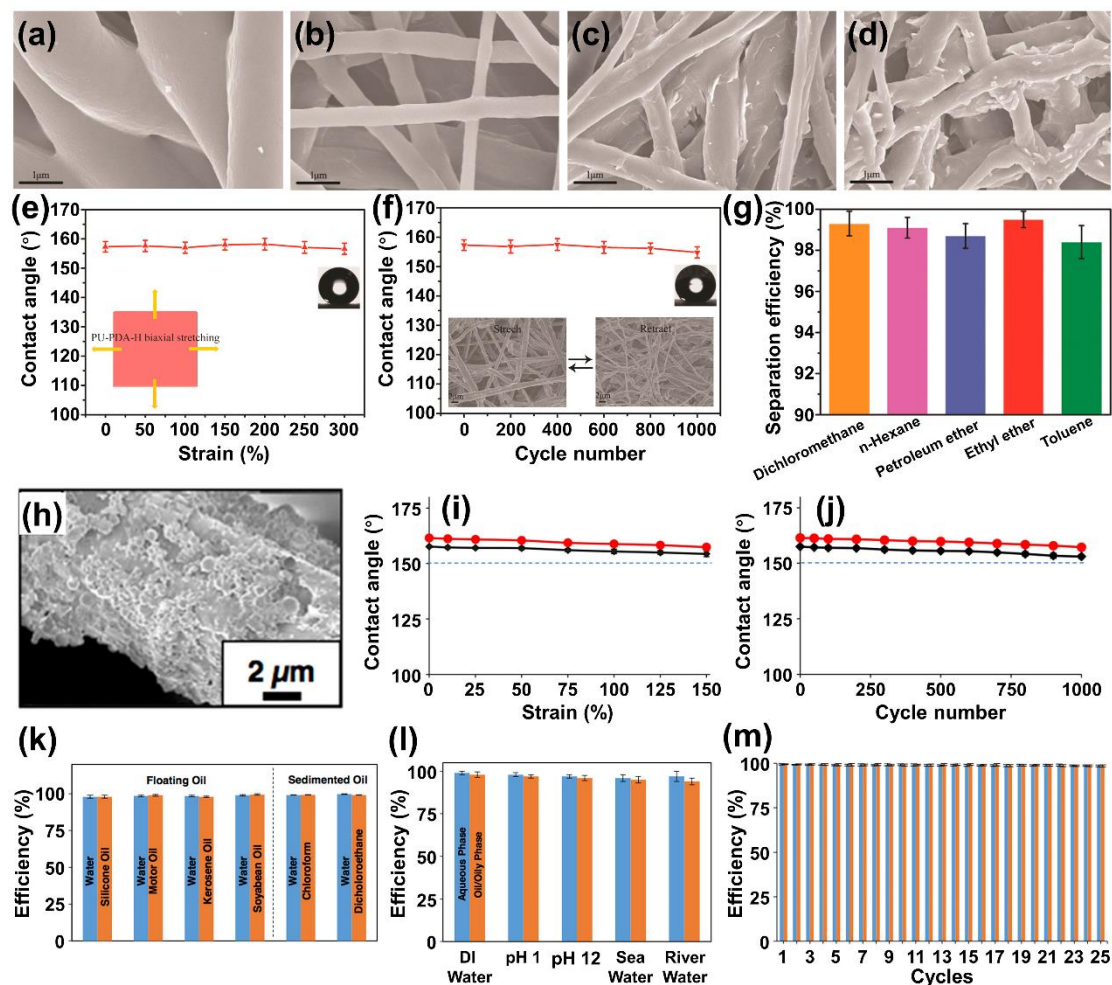


Figure 13. SEM images of (a) pure PU; (b) PU-PCDA; (c) PU-PDA; and (d) PU-PDA-H FMs. (e) WCA of PU-PDA-H FM under various strains; (f) WCA of PU-PDA-H FM after 1000 stretching cycles; (g) separation efficiency of PU-PDA-H FM for several oils [108]; (h) FESEM images of the fibrous substrate after deposition of the multilayer (10 bilayers) coating; (i) change in static contact angle of beaded water (black) and oil (red) droplets on the SHM and UWSOM during gradual increment of the tensile strain from 0% to 150%; (j) changes in water (in the air, black) and oil (underwater, red) wettability during successive (1000 times) tensile deformations of SHM and UWSOM, respectively; (k) simultaneous oil (orange) and aqueous (blue) phase separation efficiency; (l) separation efficiency of both aqueous phase (blue) and oil phase (orange) under various severe settings; and (m) ability of repetitive (minimum 25 times) oil (orange) and aqueous (blue) phase separation using the same lab-made prototype [109].

Utilizing a layer-by-layer approach, Das et al. presented the creation of amine-reactive and covalently cross-linked multilayers composed of chemically reactive polymeric nanocomplex (CRPNC) and aminographene oxide (AGO) nanosheets. These multilayers were modified with octadecylamine to yield a stretchable superhydrophobic surface for oil–water separation [109]. Starting with a fibrous polyurethane (PU) substrate, they alternately deposited CRPNC and AGO layers to generate a multi-layered structure impeding essential surface roughness (Figure 13h). Subsequent covalent chemical modification with hydrophobic octadecylamine endowed the surface with low surface energy. The resulting surface displayed remarkable superhydrophobicity, boasting a water-contact angle of 157° and a sliding angle of 5° . Due to active amine groups within the multilayer structure, the surface could be modified with glucamine to achieve an underwater superoleophobic state, featuring an advancing oil-contact angle of 161° and a sliding angle of 4° . Even

when mechanically stretched to a strain of 150%, the prepared surface maintained its liquid repellency, with both water and oil droplets assuming a spherical morphology and contact angles exceeding 150° (Figure 13i). Impressively, the super liquid repellency remained unchanged even after undergoing 1000 cycles of stretching–releasing at a tensile strain of 150% (Figure 13j). Combining the superhydrophobic and underwater superoleophobic surfaces in a prototype oil–water separation device made simultaneous separation of water and oil phases possible. In the case of a water and kerosene (light oil) mixture, kerosene selectively permeated through the superhydrophobic surface. In contrast, the water phase adhered to the underwater superoleophobic surface and penetrated it, ultimately collecting in a separate container. This process achieved the parallel separation and collection of oil and aqueous phases. Notably, no accumulation of any liquid phase was observed on the top of the utilized surfaces, confirming the high separation efficiency, consistently exceeding 98%. Furthermore, the efficiency of separation extended to various oil phases, including dichloromethane (heavy oil), vegetable oil, silicone oil, motor oil, and chloroform, when mixed with an aqueous phase. In all cases, the separation efficiency remained consistently high, exceeding 98%. The surface prepared in this manner was also suitable for separating oil and aqueous phases from three-phase oil–water mixtures comprising light oil, an aqueous phase, and heavy oil, as shown in Figure 13k. In such mixtures, where the top layer consisted of kerosene, the middle layer contained deionized water, and the bottom layer was dichloromethane, the heavy and light oil phases selectively traversed the superhydrophobic surface. In contrast, the aqueous phase was effectively filtered through the underwater superoleophobic surface. The separated oils and deionized water collection efficiency consistently exceeded 98% (Figure 13l). Moreover, the surface’s stretchability allowed for maintaining high-efficiency oil–water separation even after undergoing 1000 stretching cycles with a tensile strain of 150%. Furthermore, the separation process could be successfully repeated for a minimum of 25 cycles (Figure 13m), endowing the surface with the potential for parallel and selective separation of various oil–water mixtures repetitively, regardless of variations in surface tension, density, viscosity of the oil phase, or chemical complexity in the aqueous phase.

3.4. Anti-Icing

Another potential application for stretchable superhydrophobic surfaces lies in anti-icing technology, which stems from the advantageous combination of low adhesion and minimal contact area between water droplets and superhydrophobic surfaces. A superhydrophobic surface hampers heat transfer and significantly delays the nucleation of droplets deposited on the surface at low temperatures. When tilting the surface at an angle more significant than the water droplet’s rolling-off angle, the droplets release from the surface without nucleation, exhibiting anti-icing properties. However, conventional superhydrophobic surfaces are often delicate and prone to destruction from external forces. Thus, stretchable superhydrophobic surfaces with robust mechanical stability and adaptable surface wettability emerge as viable alternatives for durable anti-icing applications to resist the influence of external pressure, stretching, twisting, etc., to maintain the efficiency of anti-icing in harsh environments. Wang et al. devised an anti-icing stretchable superhydrophobic surface by sequentially applying 2,2,6,6-tetramethylpiperidiny-1-oxyl (TEMPO)-oxidized cellulose-silica (TOC-SiO₂) and PDMS onto cotton fabric [110]. Water droplets on the surface exhibited a static contact angle of 158° , which can be retained even after 150 bending cycles. To evaluate anti-icing behavior, they deposited 40 μ L water droplets on the superhydrophobic surface and untreated cotton fabric at -10°C . On untreated cotton fabric, droplets froze in 6 min, whereas on the superhydrophobic surface, freezing was delayed to 11 min, a 5 min extension, indicating an outstanding anti-icing performance. Additionally, the anti-icing effect persisted after 8 freeze-thaw cycles, suggesting the potential for repetitive anti-icing applications. In another work, Liu et al. achieved anti-icing stretchable superhydrophobic surfaces by using direct laser writing on the top silicone rubber layer of a silicone rubber (SR)/MWCNTs/laser-induced graphene (LIG)/SR

composite strain sensor [111]. The composite surface acquired micro-nano convex structures through laser engraving, yielding outstanding superhydrophobicity. Deposited water droplets exhibited a static contact angle of 155° and a sliding angle of 5° . The surface wettability was proven to be durable, maintaining a contact angle of around 152° and a sliding angle of about 8° even after 2500 stretching–releasing cycles performed at a 200% strain. To address the vulnerability of polymer-based conductive composite strain sensors to ice accumulation, the anti-icing performance of the SR/MWCNTs/LIG/SR composite strain sensor was evaluated by measuring icing delay times at various low temperatures. Results revealed that the icing time for 6 μL water droplets deposited on the laser-induced superhydrophobic surface could be extended to 36, 17, 8, and 4 min at temperatures of -5° , -10° , -15° , and -20°C , respectively. This underscores the excellent deicing capability, effectively enhancing sensor applicability in low-temperature environments.

Recently, Yu et al. introduced a robust anti-icing composite surface based on modified PU elastomer and silica nanoparticles (SiO_2) [112]. Initially, fluorinated silica nanoparticles ($\text{SiO}_2\text{-F}$) were blended with modified PU elastomer (PUE) at a $\text{SiO}_2\text{-F}$ concentration of 8 wt%. Using a spray gun, the resultant mixture was sprayed onto an aluminum alloy substrate. After allowing the sprayed surface to cure at room temperature for 2 h to evaporate the organic solvent, followed by an 8 h cross-linking process at 80°C , a stretchable, superhydrophobic, and anti-icing surface is achieved. Modification of PUE with dihydroxydodecyl-terminated PDMS endowed the surface with low surface energy, while the $\text{SiO}_2\text{-F}$ nanoparticles were densely clustered to create micro-nanostructures. The synergy between the low surface energy and micro/nanostructure formation contributed to the composite surface's superhydrophobicity. A 4 μL water droplet deposited on the surface exhibited a static contact angle of 162° and a sliding angle of 2° , indicating the excellent liquid repellency of the as-prepared surface. Capitalizing on the elasticity of PUE, the composite surface demonstrated stretchability up to a strain of 385% while maintaining the superhydrophobic characteristics. The anti-icing property was evaluated through an ice shear adhesion experiment, mimicking the real-world behavior of moving ice blocks. Low ice adhesion is indicative of superior anti-icing performance. The unmodified aluminum panel exhibited the highest ice adhesion strength at 235.36 kPa. Upon application of the PUE coating, the ice adhesion strength decreased to 68.04 kPa. Remarkably, the superhydrophobic $\text{SiO}_2\text{-PUE}$ surface exhibited an ultra-weak ice adhesion strength of 14.33 kPa, over an order of magnitude lower than the bare aluminum. Accumulated ice on the superhydrophobic surface readily detached under its weight or natural wind forces [113]. The as-prepared superhydrophobic surface showcased extraordinary anti-icing capabilities, positioning it as a promising candidate for widespread anti-icing surface applications in the aerospace and automotive industries.

Emelyanenko et al. introduced a straightforward approach for creating a robust superhydrophobic coating tailored for outdoor applications, even in harsh conditions [114]. Initially, they used laser technology to texture commercial composite silicone rubber, followed by a UV-ozone treatment to instill hydrophilicity on the surface. Subsequently, they covalently grafted methoxy- $\{3-[(2,2,3,3,4,4,5,5,6,6,7,7,8,8,8\text{-pentadecafluorooctyl})\text{-oxy}]\text{-propyl}\}$ -silane onto the treated surface, reducing the surface energy through immersion and heating processes (Figure 14a–c). The resulting surface exhibited exceptional water repellency, as evidenced by static contact angles of up to 170° for 15 μL water droplets, with sliding angles of around 4° for 10 μL droplets. Combining the textured structure and fluorooxysilane treatment significantly enhanced the surface's anti-icing capabilities. Approximately a quarter of the droplets deposited on the surface remained unfrozen for 140 h at -10°C and 20 h at -18°C , prolonging the freezing delay time to approximately 2.5 times that of untreated hydrophobic and solely textured superhydrophobic samples (Figure 14d,e). Additionally, the freezing of an 0.5 M NaCl aqueous solution under the same temperature and humidity conditions was also delayed, with 25% of the test droplets remaining in a liquid state after 40 h of exposure at $T = 18^\circ\text{C}$, further demonstrating the outstanding anti-icing properties of the prepared superhydrophobic surfaces (Figure 14e,

curve 5). Outdoor experiments underscored the effectiveness of the fluorooxysilane coating in improving the mechanical stability of the textured surface structure and reducing surface energy. As a result, the superhydrophobic surface exhibited remarkable resistance to severe outdoor conditions, such as snow and ice accumulation, even at temperatures well below 0 °C. Snow could slide effortlessly along the superhydrophobic surface for 6 h at $T = -1$ °C without adhesion (Figure 14f). In calm or low wind speeds, snowfall led to the formation of a snow cup, which was spontaneously removed from the superhydrophobic surface when the snow layer thickness exceeded a critical value. No snow accumulation occurred during heavy snowfall when the wind velocity exceeded 3–5 m/s. Bouncing droplet experiments also confirmed superior icing resistance at temperatures equal to or below -17 °C. Although the effectiveness of droplet rebound decreased at lower temperatures, the accumulated ice remained significantly less than that on normal hydrophobic and superhydrophobic surfaces. These superhydrophobic silicone rubber surfaces, enriched with enhanced texture, open up significant opportunities for outdoor applications in challenging conditions.

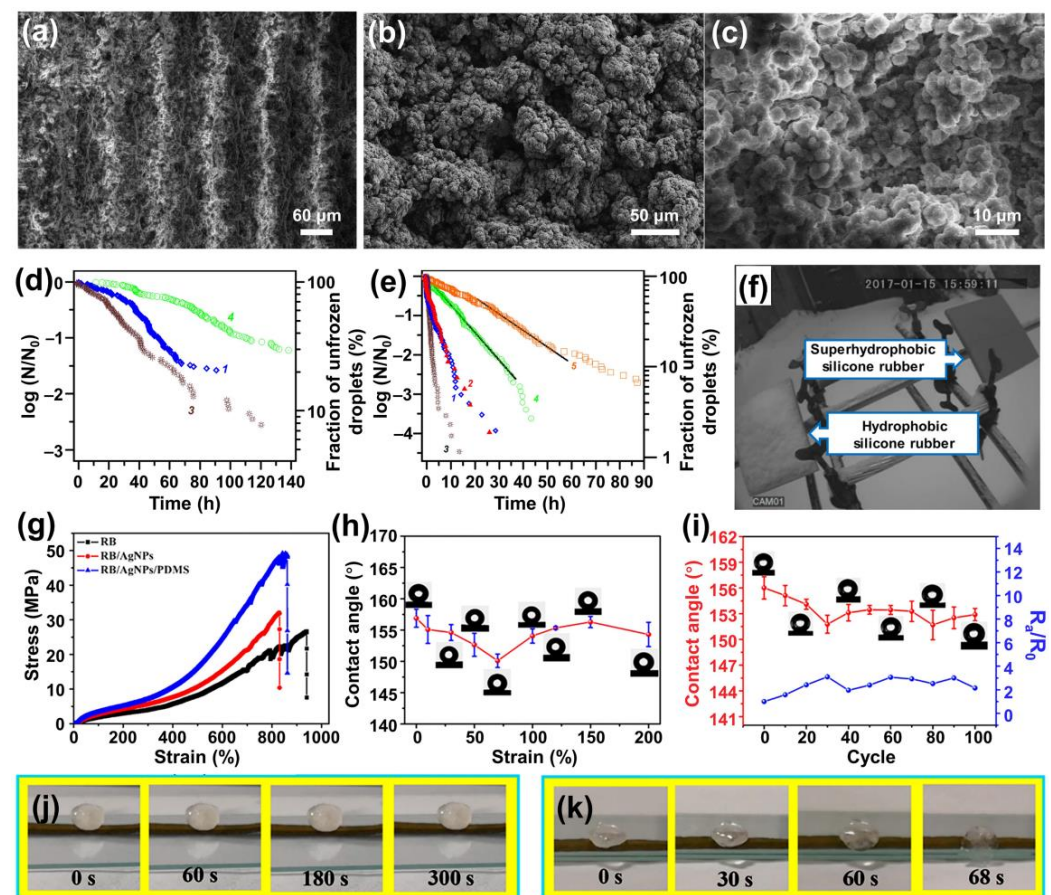


Figure 14. (a–c) SEM images of the laser-textured surface of silicone rubber at different magnifications. The scale bars are 30 (a); 10 (b); and 1 μm (c). (d,e) Time dependences for the fraction of unfrozen droplets at: -10 °C (d); and at -18 °C (e) on different substrates, 1–nontreated silicone rubber, 2–silicone rubber after chemisorption of fluorooxysilane, 3–laser-treated silicone rubber, 4–silicone rubber with texture reinforcement by fluorooxysilane, 5–the corresponding dependence for the ensemble of brine droplets on the surface of sample 4. (f) The behavior of samples 1 (hydrophobic silicone rubber) and 4 (superhydrophobic silicone rubber) during snow. $T = -1$ °C, wind velocity 2 m/s, RH = 90% [114]; (g) stress–strain curves of RB, RB/AgNPs, and RB/AgNPs/PDMS; (h) CAs of the composite under different strains; and (i) the composite’s R_a/R_0 and CAs during cyclic stretching–releasing under a strain of 50%. (j,k) Deicing performance of RB/AgNPs/PDMS: (j) without applied voltage; and (k) with a voltage of 4 V [115].

Moreover, Wang et al. presented a superhydrophobic, fluorine-free rubber composite achieved by encapsulating a rubber band with silver (Ag) nanoparticles, followed by a modification with polydimethylsiloxane (PDMS) [115]. The presence of Ag nanoparticles created surface roughness, while the PDMS binding layer significantly reduced surface energy and greatly enhanced the interfacial adhesion among Ag nanoparticles. This combination resulted in a surface with exceptional superhydrophobicity, self-cleaning capabilities, resistance to corrosion, and excellent electrical conductivity. The static contact angle of 5 μL water droplets deposited on the surface could reach a maximum of 156° . The integration of Ag nanoparticles and PDMS also led to a significant increase in Young's modulus and tensile strength of the composite, measuring 9.0 and 42.8 MPa, respectively, compared to the values for pure rubber band (5.4 and 24.2 MPa, respectively). Additionally, the composite surface exhibited remarkable elongation at break, reaching 901.5% (Figure 14g). Even under a substantial strain of 200%, the superhydrophobicity was maintained, and water droplets on the surface retained their spherical shape (Figure 14h). After undergoing 100 cyclic stretching–releasing tests at a 50% strain, the water-contact angles remained above 150° (Figure 14i), demonstrating the reusability and durability of the surface. The inclusion of Ag nanoparticles endowed the superhydrophobic composites with an effective Joule heating effect, which could achieve a saturation temperature of approximately 21.5°C at an input voltage of 2 V. This temperature increased to 35 and 53°C at 3 and 4 V, respectively, providing the surface with excellent de-icing properties. Figure 14j,k shows that ice placed on the unheated rubber band barely melts and remains on the surface even after 5 min at ambient temperature (Figure 14j). In contrast, when a voltage of 4 V is applied to the composite, the ice begins to melt. It rolls off the material surface within 68 s (Figure 14k), expanding its potential in de-icing and water removal applications.

3.5. Droplet Manipulation

Droplet manipulation in an open environment is another application of stretchable superhydrophobic surfaces. As it is open to the atmosphere, individual droplets can be treated directly without the risk of clogging [116]. Droplet manipulation has attracted great interest, from fundamental biochemical analysis to clinical and diagnostics [117]. General hydrophilic and hydrophobic surfaces usually have large contact-angle hysteresis and contact line pinning, resulting in droplet losses and contamination. In contrast, superhydrophobic surfaces use re-entrant or overhang micro-nanostructures to provide upward Laplace pressure to prevent the droplet wetting downward, presenting large contact-angle and small contact-angle hysteresis, which can efficiently avoid surface contamination and reagent loss. Anisotropic or directional wetting behavior on superhydrophobic surfaces can be realized by fabricating specific surface structures, which means that the surfaces can control the shape and motion of droplets actively, with the help of light, heat, electricity, etc., or in a passive manner, based on the requirements of multiple superhydrophobic surfaces with specific adhesions [118,119]. However, the external fields have difficulties combining the intrinsic structures, while the passive approach based on wetting has a firm application limitation. Based on this, stretchable superhydrophobic surfaces have become an efficient platform for droplet manipulation since they can employ mechanical actuation to regulate the adhesion or transfer of droplets [18,120,121].

By a combination of soft replication and post-1H,1H,2H,2H-perfluorodecyltrichlorosilane modification, Wu et al. achieved an ethylene-vinyl-acetate (EVA)-based stretchable superhydrophobic surface for non-loss droplet transfer [122]. Benefiting from the T-shaped replica surface structure, the as-prepared surface demonstrated a significant liquid repellency with the deposited water and hexadecane droplets presenting contact angles of around 158° and 159° , respectively (Figure 15a). The EVA's intrinsic elasticity endowed the surface with excellent stretchability, which was able to stretch up to more than 400% without destroying the isolated surface structure and liquid repellency (Figure 15b–e). However, the stretching process can effectively regulate the space between the adjacent T-shape pillars, resulting in an apparent change of the solid fraction of the superhydrophobic surface, thus controlling

the adhesion between the droplets and the surface for non-loss droplet manipulation. As shown in Figure 15f,g, water and oil droplets were initially deposited on a PDMS-based liquid-repellent surface. They were easily lifted by the as-prepared surface due to the high surface adhesion derived from the large solid fraction. The adhesion is strong enough to move droplets freely. The adhesion force was significantly reduced when the EVA superhydrophobic surface stretched to ~350%, when the surface could no longer overcome the droplet gravity, resulting in the release of droplets in a non-loss manner.

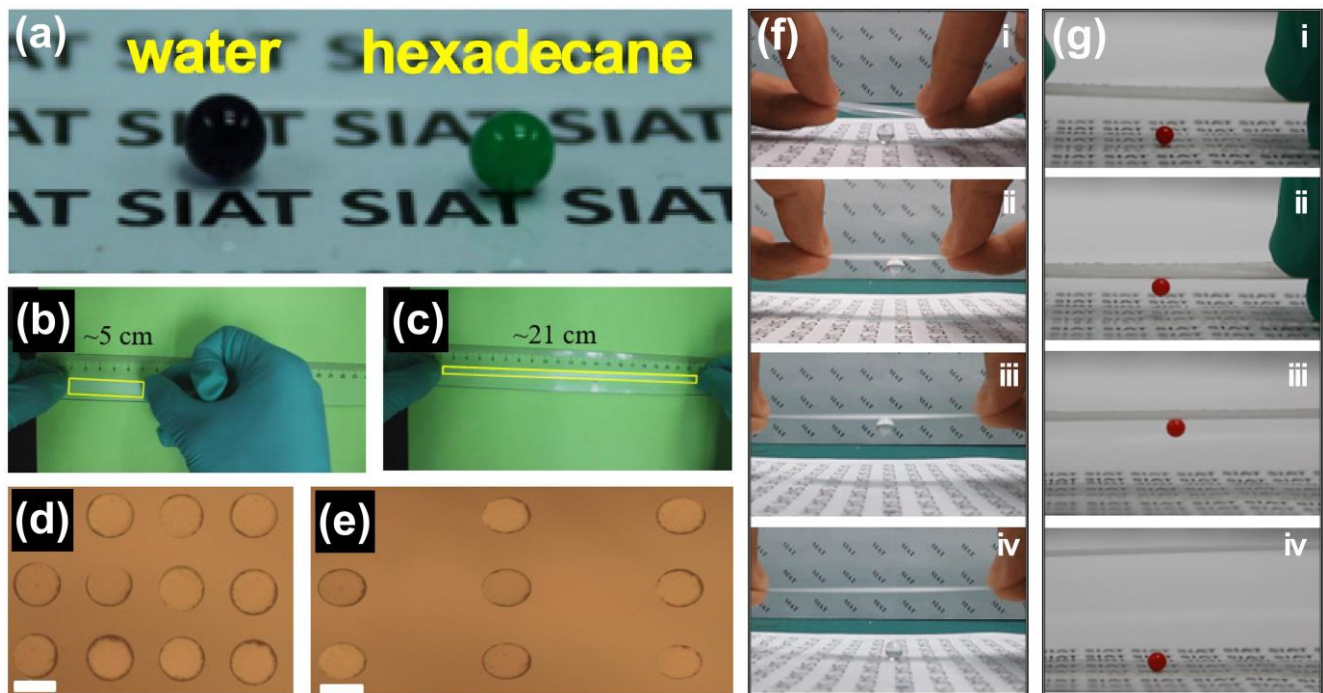


Figure 15. Ethylene-vinyl-acetate-based stretchable superhydrophobic surface: (a) excellent superhydrophobic and transparency performance. (b,c) Stretchability of superhydrophobic surface: (b) before; and (c) after stretching. (d,e) Profiles of microstructures: (d) before; and (e) after stretching for 200%. 10 μm for all scale bars. (f,g) Demonstration of the nearly lossless water (f); and ethylene glycol (g) droplet transfer using the stretchable superhydrophobic surface [122].

Taking advantage of the stretchability of the superamphiphobic surface, Butt et al. realized the programmable coalescence of droplets on the surface [52]. The stretching–releasing process enabled control of the spaces for droplets located on the surface from a separated status to a contact and coalescing status, which made it possible to realize a programmable coalescence of a sequence of droplets. As illustrated in Figure 16a,b, trapezoidal-arranged water droplets and linearly arranged n-hexadecane droplets were deposited on a 100% stretched superamphiphobic surface for controlled coalescence. Once the substrate was gradually released, the distance between droplets changed accordingly. The trapezoidal arrangement enabled the middle droplets to coalesce first, and subsequently coalescence with the left- and right-hand sides, respectively (Figure 16a). While the droplets were linearly arranged along the stretching direction, the releasing resulted in the merge of droplets in a particular order (Figure 16b). The controllable coalescence of droplets was suitable for miscible and immiscible liquids. As presented in Figure 16c, a dumbbell-like merged droplet is formed after a controlled coalescence by depositing one n-hexadecane and two water droplets at appropriate distances. Since the liquids in this case are immiscible, an apparent interface was observed between these two different droplets. The programmable droplet manipulation indicates a possible step-by-step reaction process regulated by liquid-repellent surfaces. Taking sodium alginate aqueous solution and iron chloride (FeCl_3) aqueous solution as a typical system, with the combination of coalescence between sodium alginate aqueous solution droplets and various numbers of FeCl_3 aqueous solution droplets

and the gelation of sodium alginate catalyzed by FeCl_3 , the authors successfully synthesized hydrogels with different morphologies on a superhydrophobic surface. Once the droplets of different solutions were attached, the iron ions rapidly diffused into the alginate drop. They initiated the gelation to convert the alginate droplet quickly to a hydrogel while the FeCl_3 droplets remained liquid. After removing the liquid droplets, alginate hydrogels with hemispherical, cylinder-like, and triangular prism-like morphologies were obtained (Figure 16d), demonstrating the potential of using stretchable superhydrophobic surfaces to study the reactions or interactions of multidroplets.

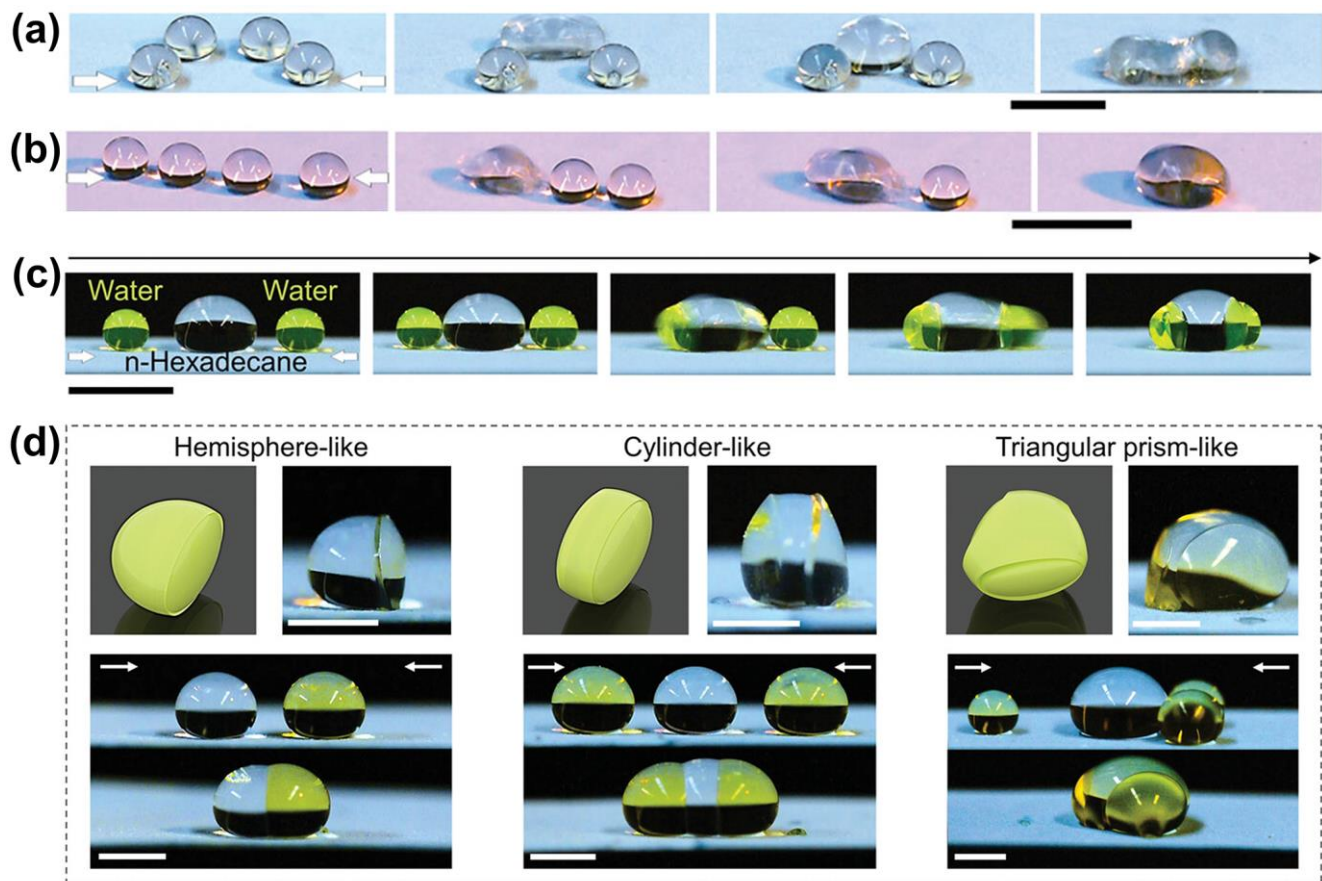


Figure 16. Programmable manipulation of drop coalescences and synthesis of asymmetric hydrogels: (a,b) programmable coalescence of (a) four water drops (15 μL) with a trapezoidal arrangement; and (b) four n-hexadecane drops (10 μL) with a linear arrangement. Scale bars: 5 mm. (c) Coalescence of one n-hexadecane drop (colorless) and two water drops (light green) on the NFSS surface. Scale bar: 5 mm; (d) fabrication of asymmetric hydrogels with specific shapes. One alginate sodium aqueous solution drop (colorless) and different numbers (from left to right: 1, 2, and 3) of FeCl_3 aqueous solution drops (yellow) are used in the hydrogel fabrication process. Scale bars: 2 mm. The arrows represent the releasing of the stretched substrate [52].

Beyond the previously discussed applications, stretchable superhydrophobic surfaces show promise for various other utilizations, including multifunctional sensing [123,124], anti-bioadhesion [125,126], deicing [115,127], droplet manipulation [128,129], and other fields [130–134].

4. Conclusions

Over the past decade, substantial advancements have been achieved in fabricating stretchable superhydrophobic surfaces, resulting in a diverse range of surfaces with outstanding wettability and mechanical durability. Various fabrication approaches were developed to obtain superhydrophobic surfaces with stretchability, including covering

elastomers with a layer of rough and low surface energy materials, hybridizing functional materials in elastomers, and directly manufacturing rough surfaces utilizing bulk elastomers. The development of fabrication techniques promoted the transition from the integration of stretchable properties by a simple elastomer substrate to a fully flexible bulk superhydrophobic material. The maintenance of superhydrophobic surface properties realized a stabilized enhancement from several tens of stretching–releasing cycles to more than 7000 cycles, while the elongation of the obtained superhydrophobic surface achieved a significant strain increase from about 50% up to 1000%. The fusion of superhydrophobic properties and stretchability has opened new avenues for these surfaces, broadening their potential applications and aligning them with the demands of real-world scenarios. This convergence is steering artificial surfaces toward practical utilization in domains such as oil–water separation, anti-icing, anti-corrosion, etc. The significant enhancement in durability empowers superhydrophobic surfaces to withstand rigorous conditions, thus expanding their utility in outdoor and challenging environments (Table 1).

Table 1. Summary of stretchable superhydrophobic surfaces with specific fabrication approaches, materials, and application(s).

Strategies	Materials		Application(s)	Ref.
Covering elastomers with a layer of rough and low surface energy materials	Elastomer substrate	Coating materials		
	Chewing gum	SiO ₂	Self-cleaning	[16]
	Silicone	PS, SiO ₂	Self-cleaning	[17]
	PET	PDMS, SiO ₂	Self-cleaning	[44]
	Cellulose	SiO ₂	Self-cleaning	[46]
	PDMS	F-SiO ₂	Self-cleaning	[63]
	PDMS	Zn	Self-cleaning	[68]
	Elastic tape	SEBS, AgNPs	Strain-sensing	[19]
	Natural rubber	SEBS, M-AgNPs	Strain-sensing	[41]
	PDMS	MWCNTs, FAS	Strain-sensing	[42]
	PDMS	APTES, MWCNTs, Graphene, AgNPs, FAS	Strain-sensing	[53]
	PU	PDA, AgNPs, ACNTs, FCNTs-SiO ₂	Strain-sensing	[54]
	PDMS	CNTs	Strain-sensing	[55]
	Nonwoven fabrics	MWCNT, AgNPs, PDA, PDMS	Strain-sensing	[61]
	PU	CNTs, POSS, FAS	Strain-sensing	[69]
	Elastic band	Carbon black, CNTs, PDMS	Strain-sensing	[71]
	PDMS	rGO	Strain-sensing	[89]
	Rubber band	PDA, AgNPs, PFDTs	Strain-sensing	[91]
	PU	PDA, CNC, Graphene, SiO ₂	Strain-sensing	[92]
	Ecoflex	SiO ₂ , P(AAM-co-HEMA)-MXene-Ag hydrogel	Strain-sensing	[94]
	PDMS	SWCNTs	Strain-sensing	[95]
	Silicon rubber	MWCNTs	Strain-sensing	[96]
	PU	CNTs, PDMS	Anti-corrosion	[98]
	SEBS	Carbon black, CNTs, TiO ₂ , PFOTS	Anti-corrosion	[102]
	PU	Perfluorosilane-coated graphene	Anti-corrosion	[103]
	Polyester	Silicone nanofibers	Oil–water separation	[11]

Table 1. Cont.

Strategies	Materials		Application(s)	Ref.
Covering elastomers with a layer of rough and low surface energy materials	Polyaniline hydrogel	SiO ₂ , OTS	Oil–water separation	[62]
	Kevlar nanofibrils	PDMS, PVDF	Oil–water separation	[104]
	PU	PDMS, TiO ₂	Oil–water separation	[105]
	PU	CNTs, Methyltrichlorosilane	Oil–water separation	[107]
	PU	CRPNC, AGO	Oil–water separation	[109]
	PAI	F-SiO ₂	Anti-icing	[45]
	PDMS	Graphene, FAS	Anti-icing	[48]
	PAI, PU	F-SiO ₂	Anti-icing, Antifouling	[60]
	Silicone rubber	AlN	Anti-icing	[70]
	Cotton	TOC-SiO ₂ , PDMS	Anti-icing	[110]
	PU	F-SiO ₂	Anti-icing	[112]
	Silicone rubber	Methoxy-{3-[(2,2,3,3,4,4,4,5,5,6,6,7,7,8,8,8-pentadecafluorooctyl)-oxy]-propyl}-silane	Anti-icing	[114]
	Rubber band	AgNPs, PDMS	Anti-icing	[115]
	cis-1,4-polyisoprene	PDMS, Silicone nanofilaments	Droplet manipulation	[52]
	EVA	PFDTS	Droplet manipulation	[122]
	Cellulose/polyester	PCL, PGC-C ₁₈	Drug delivery	[22]
	PET	F-SiO ₂	Antifouling, Self-cleaning	[50]
	Rubber	QAS@SiO ₂ , SEBS	Antibiofouling	[64]
	PU	PANI, PTFE	Underwater gas sensing	[57]
	PVA/Carrageenan/MWCNT	MWCNTs, FAS	Supercapacitor	[51]
	Polyester	PDMS, AgNPs	Electrical-heating	[56]
	PDMS	Silicon nanowires	Field effect transistors	[65]
Hybridizing functional materials in elastomers	Ecoflex elastomer	AgNPs	Elastic conductor	[67]
	Silicone	SiO ₂	-	[59]
	Rubber	Carbon black, Polybutadiene	-	[66]
	Elastomer	Functional materials		
	PDMS	-	Self-cleaning	[76]
	CRPNC	Graphene oxide	Self-cleaning	[80]
	TPE	CNTs	Strain-sensing	[72]
	PDMS	CNTs	Strain-sensing	[78]
	PU	Carbon black, PFDTS	Strain-sensing	[97]
	SBS	SiO ₂ , PFDTS	Anti-corrosion	[77]
	P(B-oda)	CNTs	Anti-corrosion	[81]
	TPE	SiO ₂ , FAS-17	Anti-corrosion	[99]
	PDMS	CNTs	Anti-corrosion	[101]
	PDMS	SiO ₂	Oil–water separation	[74,75]
	ECA, PCL	F-SiO ₂	Oil–water separation	[79]
	PU	PDA	Oil–water separation	[108]

Table 1. Cont.

Strategies	Materials	Application(s)	Ref.
Hybridizing functional materials in elastomers	PDMS	VO ₂	Anti-icing [73]
	3M VHB 4910 film	TiO ₂	Droplet manipulation [128]
	Silicone rubber	Graphene	Anti-biofouling [6]
	PDMS	SiO ₂ , STAC, PFDTS	Anti-biofouling [8,18]
	PDMS	TiO ₂	Blood repellent dressing [125]
	PDMS	PPy	Antimicrobial [126]
Directly manufacturing rough surfaces utilizing bulk elastomers	Silicone rubber		Self-cleaning [85]
	PDMS		Droplet manipulation [83,86,129]
	Fluororubber		Droplet manipulation [88]
	PCL-b-PTFOA		Antifouling [87]
	PFOA-co-V3D3		Transparent film [82]
	MPP	-	[84]

Abbreviations in the table: Stearyl trimethyl ammonium chloride (STAC), 1H,1H,2H,2H-perfluorodecyl trichlorosilane (PFDTS), polystyrene-block-poly(ethylene-co-butylene)-block-polystyrene (SEBS), Poly(caprolactone) (PCL), poly(glycerol monostearate carbonate-co-caprolactone) (PGC-C₁₈), 1-octadecanethiol-modified silver nanoparticles (M-AgNPs), 1H,1H,2H,2H-Perfluorooctyltriethoxysilane (FAS), polyethylene terephthalate (PET), poly(amide-imide) (PAI), fluorine functionalized SiO₂ nanoparticles (F-SiO₂), Poly(vinyl alcohol) (PVA), 3-(aminopropyl)triethoxysilane (APTES), polyurethanes (PU), acid-treated carbon nanotube (ACNT), 1H,1H,2H,2H-perfluorodecyltriethoxysilane-modified carbon nanotubes-silica hybrid nanoparticles (FCNTs-SiO₂), polyaniline (PANI), polytetrafluoroethylene (PTFE), trichloro(octadecyl)silane (OTS), dimethyloctadecyl [3-(trimethoxysilyl) propyl] ammonium chloride (QAS), polyhedral oligomeric silsesquioxane (POSS), aluminum nitride (AlN), carbon nanotubes (CNTs), multi-walled carbon nanotubes (MWCNTs), thermoplastic elastomer (TPE), poly(styrene-*b*-butadiene-*b*-styrene) (SBS), ethyl cyanoacrylate (ECA), ‘chemically-reactive’ polymeric nano-complexes (CRPNC), polybenzoxazine (P(B-oda)), co-polymerized 1H,1H,2H,2H-perfluorooctyl acrylate (PFOA) and 1,3,5-trivinyl-1,3,5-trimethylcyclotrisiloxane (V3D3) (PFOA-co-V3D3), microporous polymer by the Sonogashira coupling reaction between 1,4-diiodotetrafluorobenzene and 1,3,5-triethynylbenzene (MPP), polycaprolactone (PCL)-block-1H,1H,2H,2H-perfluorooctyl acrylate (TFOA) copolymer (PCL-b-PTFOA), reduced graphene oxide (rGO), cellulose nanocrystal (CNC), single-walled carbon nanotubes (SWCNTs), heptadecafluoro-1,1,2,2-tetradecyl-trimethoxysilane (FAS-17), perfluorooctyltriethoxysilane (PFOTS), 2,2,6,6-tetramethylpiperidinyl-1-oxyl (TEMPO)-oxidized cellulose-silica (TOC-SiO₂), ethylene-vinyl-acetate (EVA), polypyrrole (PPy).

In future research, despite the noteworthy advancements attained in stretchable superhydrophobic surfaces, there remain pressing limitations and challenges that warrant resolution for effective real-world implementations: (a) the pursuit of streamlined, rapid, energy-efficient, and high-throughput fabrication techniques is of utmost importance, aiming to simplify the complexities associated with conventional methods. Traditional manufacturing processes often involve multiple steps and complex procedures, leading to increased time, energy, and resource consumption. Meanwhile, the quantity of products is relatively low, greatly limiting the transition of stretchable superhydrophobic surfaces from the laboratory to practical applications. To promote the commercial application of stretchable superhydrophobic surfaces, future fabrication techniques are driven by the need for increased efficiency, reduced costs, and improved sustainability in manufacturing. Achieving these goals requires the integration of cutting-edge technologies, innovative materials, and a commitment to continuous improvement in manufacturing processes. It benefits industries by enhancing their competitiveness and contributes to a more sustainable and environmentally friendly approach to production; (b) reproducibility is an essential consideration for the large-scale manufacturing of stretchable superhydrophobic surfaces. Reproducibility refers to the ability to consistently and reliably replicate a manufacturing process to produce identical or highly consistent products. Research techniques may involve intricate manual processes or specialized equipment that is difficult to replicate precisely in different settings. Variability in production can lead to inconsistency and unreliability. However, industries demand reproducibility to ensure product quality,

reliability, and adherence to standards. In electronics and biomedical applications, where precision is paramount, reproducibility is critical to meeting regulatory requirements and ensuring consistent performance of devices. Addressing the challenges associated with reproducibility is fundamental for the practical application of stretchable superhydrophobic surfaces. (c) Developing surfaces that exhibit exceptionally high strain resilience alongside impressive tensile strength is crucial for various practical applications, e.g., anti-corrosion. In various applications, materials experience mechanical stress, deformation, or stretching. High strain resilience ensures that the material can endure mechanical stresses without losing structural integrity. At the same time, tensile strength is crucial in applications where materials need to withstand forces without breaking. High strain resilience and tensile strength are essential for anti-corrosion coatings, as these coatings need to adhere to surfaces and withstand mechanical stresses, such as the expansion and contraction of materials due to temperature variations, especially in harsh conditions. Furthermore, the creation of robust bulk superhydrophobic materials is of significance and is a necessity for their practical viability. Bulk superhydrophobic materials extend the superhydrophobic properties throughout their entire structure, not just on the surface. This ensures that the water-repellent characteristics persist over time and under various environmental conditions, making them more practical and durable for practical applications; (d) fluorinated materials have been a common approach to achieving superhydrophobicity. However, fluorine-containing compounds can have negative environmental impacts and raise concerns about their long-term effects on ecosystems. For example, per- and polyfluoroalkyl substances (PFAS), a class of fluorinated compounds, are known for their environmental persistence and potential toxicity. PFAS contamination has been linked to adverse effects on ecosystems, wildlife, and human health. The long-term environmental persistence of fluorinated compounds raises concerns about their impact on soil, water, and living organisms. The exploration of alternative, non-fluorinated low surface energy materials is preferred for their non-toxic and environmentally friendly attributes. This is essential for applications where materials come into contact with living organisms, such as biomedical devices, food packaging, or agricultural applications; (e) in biomedical applications, the biocompatibility of stretchable superhydrophobic surfaces is of the utmost importance. For applications such as wearable medical devices, implants, or lab-on-a-chip systems, the surface must not cause adverse reactions or harm to living tissues. Ensuring the biocompatibility of the surface materials and optimizing their interactions with biological systems is a critical challenge; and (f) establishing standardized characterization protocols is imperative in order to provide a framework for comparing different productions and ensuring consistency in assessment methodologies. Standardized characterization protocols play a crucial role in quality control. Defining acceptable ranges and testing procedures helps to maintain consistency in quality standards across different productions. Standardized protocols enhance the clarity and transparency of reporting. Researchers and manufacturers can communicate their findings more effectively using a common language and metrics defined by established standards. Establishing standardized characterization protocols is imperative for various reasons, including ensuring consistency, comparability, quality control, regulatory compliance, and fostering innovation. These protocols provide a robust framework for assessing different productions, enabling meaningful comparisons, and contributing to the overall reliability and advancement of materials and products across industries.

5. Future Perspectives

Despite the existing challenges, developing stretchable superhydrophobic surfaces remains an up-and-coming and dynamic research area. Addressing the challenges will require interdisciplinary efforts involving materials science, surface engineering, mechanical engineering, and other relevant fields. As researchers continue to explore novel materials, innovative fabrication techniques, and advanced characterization methods, the capabilities of stretchable superhydrophobic surfaces will continue to expand.

In the future, it is anticipated that stretchable superhydrophobic surfaces will find applications in a wide range of fields, including electronics, aerospace, robotics, wearable devices, and biomedical devices. Their unique stretchability, superhydrophobicity, and other desirable properties make them ideal candidates for various emerging technologies. Here are some potential future perspectives and applications for stretchable superhydrophobic surfaces: (1) one of the most promising applications for stretchable superhydrophobic surfaces is in the field of flexible and wearable electronics. With the rapid growth of wearable devices and flexible electronic components, there is a growing need for surfaces that protect these devices from environmental factors such as moisture, dust, and liquids. Stretchable superhydrophobic surfaces can serve as protective layers for wearable electronics, preventing water and other liquids from damaging sensitive electronic components. Additionally, their ability to maintain superhydrophobicity under mechanical deformation makes them ideal for use in stretchable electronic circuits and sensors; (2) stretchable superhydrophobic surfaces also hold significant potential in biomedical devices and implants. Their biocompatibility and ability to repel liquids can be leveraged to develop biocompatible surfaces for medical implants and devices. For example, implantable medical devices such as pacemakers, defibrillators, and neural implants could benefit from superhydrophobic surfaces that reduce the risk of infections and improve long-term performance. Furthermore, stretchable superhydrophobic surfaces can be used in lab-on-a-chip devices and microfluidics for medical diagnostics and drug delivery systems; (3) stretchable superhydrophobic surfaces have the potential to create antifouling and self-cleaning surfaces. By repelling water and other liquids, these surfaces can prevent the adhesion of dirt, bacteria, and contaminants, reducing the need for frequent cleaning and maintenance. This property is precious in applications that expose surfaces to harsh environments or where cleanliness is critical, such as marine equipment, outdoor infrastructure, and food-processing equipment; (4) stretchable superhydrophobic surfaces with tunable surface roughness and wettability could be used for adaptive camouflage in military and defense applications. By adjusting the surface's properties, such as the contact angle and reflectivity, it could be possible to create surfaces that blend seamlessly with the surrounding environment, making objects and equipment less visible to the naked eye or infrared sensors; (5) stretchable superhydrophobic surfaces with conductive properties could be integrated into energy harvesting and conversion systems. For example, stretchable superhydrophobic surfaces on solar cells could repel water and dust, enhancing the cells' efficiency and longevity. Moreover, such surfaces could be used in energy-harvesting textiles, protecting the energy-harvesting elements while maintaining the fabric's flexibility and comfort; (6) stretchable superhydrophobic surfaces can also be utilized for airflow management in various applications. By controlling the surface roughness and wettability, these surfaces can influence air flow over surfaces, potentially reducing drag and improving aerodynamic performance. It could be precious and valuable in aerospace applications, where fuel efficiency is critical; (7) in arid regions, stretchable superhydrophobic surfaces can be employed for water collection and harvesting. By repelling water, these surfaces could be applied to various surfaces to direct water droplets toward collection points, aiding in water conservation and addressing water scarcity challenges; (8) stretchable superhydrophobic surfaces could be used for thermal management in electronic devices and other heat-sensitive systems. By repelling liquids, these surfaces can protect electronic components from moisture-related damage. At the same time, their stretchability allows them to conform to complex surfaces and maintain good thermal contact; and (9) lastly, stretchable superhydrophobic surfaces have the potential to contribute to environmental protection efforts. By preventing the adhesion of contaminants to surfaces, these surfaces can reduce the need for harsh cleaning agents and minimize the release of harmful chemicals into the environment. Moreover, their ability to repel water and other liquids can protect surfaces and structures from degradation caused by water damage, extending their service life and reducing waste.

In summary, stretchable superhydrophobic surfaces represent a cutting-edge technology with numerous potential applications across various industries. As research and development continue to advance in this field, we can expect to see these surfaces integrated into a wide range of devices and systems, improving their performance, durability, and functionality. As the challenges associated with scalability, durability, and environmental impact are addressed, stretchable superhydrophobic surfaces will undoubtedly play a significant role in shaping the future of materials science and engineering.

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