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Review

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Recent advances and challenges of fluid manipulation on microstructured surfaces

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Abstract

Microstructured surfaces play a pivotal role in fluid manipulation, leveraging their unique chemical and physical properties to exert precise control over fluid behavior. These structures significantly influence fluid wettability, adhesion, mobility, and dynamic behavior, offering broad prospects in microfluidics, biomedicine, energy, materials science, and other fields. Despite existing challenges related to stability, wear resistance and manufacturing processes, the field of microstructured fluid control holds substantial promise for future advancements. This review surveys the latest advancements in microstructured surface fluid control technology, spanning from the design and fabrication of microstructured surfaces to their applications and deployment across various domains. We initially explore the design principles and fabrication methods of microstructured surfaces, and delve into the strategies employed for fluid manipulation by modulating surface chemistry and morphography. Additionally, the applications of microstructured surfaces in microfluidic control, biomedical engineering, energy harvesting, and environmental monitoring are further emphasized and discussed, showcasing the significant contributions to technological innovation. Finally, the current technical challenges and potential applications of liquid manipulation on microstructured surfaces are featured, and their prospects are discussed based on the current development.

Keywords: Micro/nanostructure surface, intelligent surface, wettability, fluid manipulate

INTRODUCTION

The manipulation of fluids on microstructured surfaces is of crucial importance in various fields such as aerospace[1,2], electronic information[3], automotive energy[4-6], and healthcare[7], attracting widespread academic attention. For instance, in microfluidic systems, the controllable manipulation of fluids can significantly enhance operational efficiency, making complex and precise fluid management, which holds promise for applications in biochips, drug delivery systems, and integrated laboratory platforms (commonly known as "lab-on-a-chip" technology)[8-11]. Through the adept regulation of fluid dynamics at micro and nanoscale interfaces, innovative sensors and actuators are emerging, heralding transformative applications in environmental surveillance, energy transmutation, and precision fabrication. Moreover, the control of fluids on microstructured surfaces plays a pivotal role in elucidating and emulating natural fluid phenomena, thereby furnishing a robust theoretical framework and practical underpinning for the field of bionic engineering[12-14].

Against this backdrop, research on microstructured surface fluid manipulation has experienced explosive growth and is poised for further development. For researchers in this field, it is essential to understand the following questions: What are the mechanisms of fluid dynamics on microstructured surfaces? Only with correct theoretical guidance can the accuracy of research outcomes be ensured. Based on these theories, how should microstructured surfaces be designed? Many biological surfaces have evolved to possess special wetting properties, and biomimetic preparation of surfaces is a commonly used method. In 2002, the micro-nano composite structure on the lotus leaf surface was proven to be the critical factor for achieving high apparent contact angles and low adhesion[15]. This work first highlighted the impact of multi-scale microstructures on superhydrophobic properties. With the advancement of nanotechnology, microstructured surfaces with characteristics such as orderliness and periodicity have been fabricated using various physical and chemical methods. By designing microstructures with different shapes and arrangements, they can possess distinct properties and functions. Common fabrication methods include laser ablation[16-21], chemical etching[22,23], template methods[24-26], three-dimensional (3D) printing[27-31], *etc*. Furthermore, how can the various microstructured surfaces designed and fabricated be applied in real-world problems? The ultimate goal of scientific research is to address issues encountered in social development, and utilizing these tools to solve relevant problems is one of the means to promote societal progress. In summary, a review and summary of the design, fabrication, and fluid manipulation on microstructured surfaces will provide better guidance for research in microstructured surface fluid dynamics.

In this review, we first introduce the wetting mechanisms of fluids on various microstructured surfaces. Subsequently, the fabrication of different microstructured surfaces and their fluid manipulation research is focused upon, with their fluid manipulation performances being compared. Furthermore, an overview of the pivotal applications of microstructured surface fluid manipulation across different fields is provided. In conclusion, the future of microstructured surface fabrication and application is projected, with discussions focusing on potential developments and their implications [Figure 1].

FUNDAMENTAL PRINCIPLES OF MANIPULATION ON MICROSTRUCTURED SURFACE

Wettability, also known as wetting property, can be defined as the tendency of a liquid to spread over a solid substrate. It describes the degree of contact between liquid and solid phases. Under equilibrium conditions, governed by thermodynamic laws, it depends on the surface energy and interfacial energies at the solid/liquid interface. When the three phases-solid, liquid, and vapor-are in balance, drawing a tangent line at the triple phase boundary where the gas/liquid interface meets the solid, the angle formed between this tangent and the solid-liquid intersection line is called the contact angle (θ). The concept of contact angles was

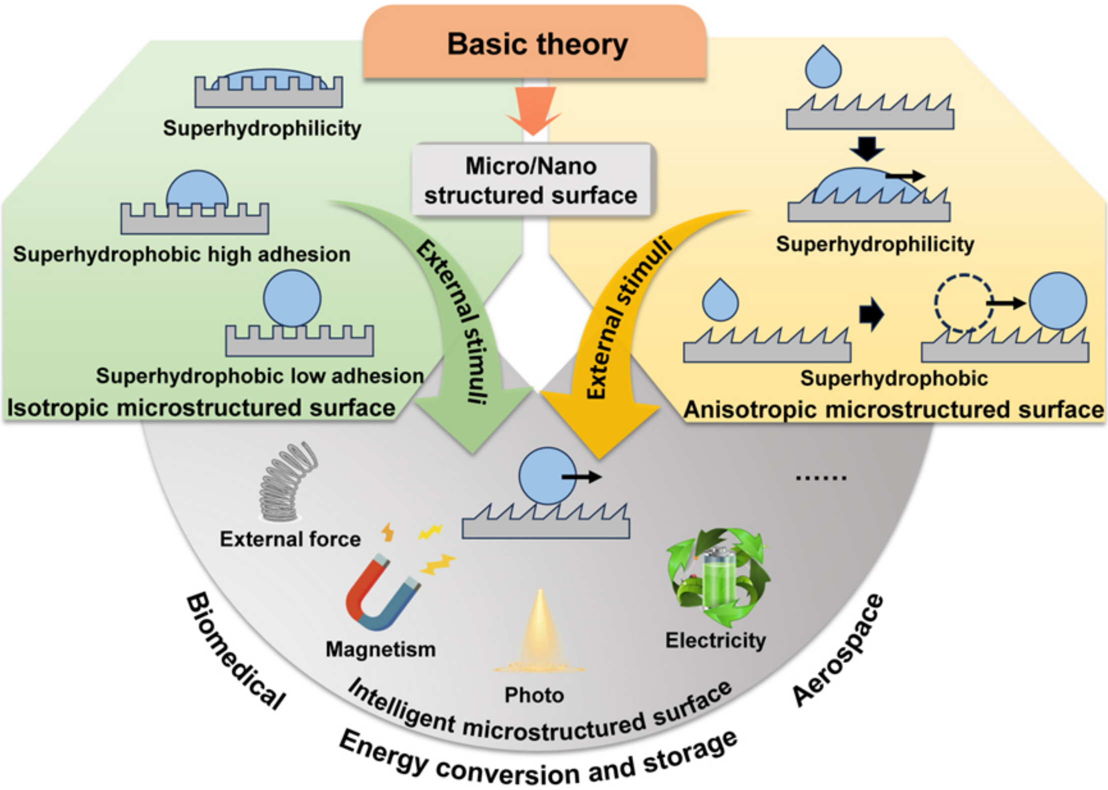

Figure 1. Research strategy of fluid manipulation on micro/nanostructure surface from fabrication to application.

initially proposed by Young in 1805[32]. The angles are widely utilized to characterize interfacial phenomena, wetting/dewetting of solid surfaces, capillary penetration in porous media, coatings, *etc*[33,34]. Generally, the contact angle is used to measure the extent of liquid's wetting ability towards solids: when $\theta > 90°$, the solid surface is considered hydrophobic, and larger values of θ indicate poorer wetting; when $\theta < 90°$, the surface is deemed hydrophilic, with smaller values suggesting enhanced wetting capability. In recent years, Liu *et al.*[35,36] have redefined the wettability of liquid and introduced new boundaries for hydrophilicity and hydrophobicity set at 65°, instead of 90° predicted by Yang's equation, which is called the intrinsic wetting threshold of water (θ^*). Formation of the contact angle is an external manifestation of the balanced surface tensions among solid, liquid, and vapor interfaces.

Assuming ideal conditions where a pure liquid wets and spreads on an inert smooth solid surface, the driving force $F_d(t)$ for wetting is expressed as

$$F_d(t) = \gamma_{sv} - (\gamma_{sl} + \gamma_{lv} \cos\theta\,(t)) \tag{1}$$

Where γ_{ab} denotes the interfacial tension between phases *a* and *b*, with subscripts *s*, *l*, and *v* representing solid, liquid, and vapor phases, respectively. $\theta\,(t)$ signifies the contact angle at time *t*. At equilibrium, liquid spreading ceases. Thus, the droplet at this point experiences no net driving force, $F_d\,(t) = 0$. Under this condition, Young's equation becomes

$$\gamma_{sv} - \gamma_{sl} = \gamma_{lv} \cos\theta \tag{2}$$

Where θ is the equilibrium contact angle, often referred to as the intrinsic contact angle since Young's equation applies ideally to surfaces.

To accurately describe the contact angle of droplets on actual rough surfaces, Wenzel *et al.*[37] built upon Young's framework by introducing a roughness factor, quantifying liquid wettability on roughened surfaces:

$$\cos\theta_r = \frac{r(\gamma_{sv} - \gamma_{sl})}{\gamma_{lv}} \tag{3}$$

Where *r* represents the surface roughness, denoting the ratio of the contact area between the droplet and the rough surface to that of a smooth surface; θ_r denotes the apparent contact angle of the droplet. Physical roughness gradients lead to differing contact angles on either side of the droplet, generating a gradient in surface free energy[38]

$$\Delta E = \int \tau(\cos\alpha_A - \cos\alpha_B)\, dx \tag{4}$$

Here, τ indicates the droplet's surface tension, while α_A and α_B represent the advancing and receding contact angles, respectively. On a rough, water-loving surface, greater roughness boosts hydrophilicity, making droplets naturally migrate to rougher areas[39,40]. On a rough, water-repelling surface, higher roughness increases hydrophobicity, causing droplets to naturally flow toward smoother regions[41,42].

Subsequently, Cassie and Baxter extended Wenzel's work by considering chemically heterogeneous surfaces, proposing a composite contact model[43]:

$$\cos\theta_r = f_1\cos\theta_1 + f_2\cos\theta_2 \tag{5}$$

Where f_1 and f_2 denote ratios of the contact areas of the liquid with substance 1 and substance 2 to the total contact area; θ_1 and θ_2 are the intrinsic contact angles for substances 1 and 2, respectively. Gradients in chemical composition change the contact angle of droplets on the surface, resulting in changes in surface energy:

$$dE = \tau(\cos\alpha_A - \cos\alpha_B)dx \tag{6}$$

For surfaces with chemical component gradients, droplets demonstrate a tendency to move spontaneously toward the hydrophilic end. A larger value of dE indicates a greater surface energy gradient, making the droplet's movement toward the hydrophilic region more pronounced.

FABRICATION AND FLUID MANIPULATION OF MICROSTRUCTURED SURFACES

The distinction among isotropic, anisotropic, and intelligent microstructured surfaces is essential due to their unique properties and applications. The isotropic surface has a uniform microstructure and exhibits uniform wetting behavior in all directions, and the hydrophilicity and adhesion of droplets can be adjusted by changing the surface chemistry or morphology, which is suitable for self-cleaning coating research. Anisotropic surfaces, with their directional microstructures, enable precise control over liquid flow direction and speed, which is crucial for advanced technologies such as microfluidic chips and biosensors. Intelligent microstructured surfaces could respond to external stimuli by dynamically adjusting their wetting behavior, providing real-time control for applications such as adaptive optics and lab-on-a-chip devices. Herein, we will discuss in detail from the following three aspects.

Fabrication method

Many natural materials have excellent physical and chemical properties due to the existence of surface microstructure. The microstructure surface generally has the characteristics of order and periodicity, and it can have different properties and realize different functions by designing the microstructure with various shapes and arrangements. Because microstructure surface has broad application prospects in water collection, microfluidic equipment, energy collection and transfer, heat transfer, aerospace and other fields, it is particularly important to study its preparation methods and properties. Several common methods for preparing microstructure surfaces will be introduced here[44-46].

Etching method

Etching refers to the process technology of uniformly removing the bare film or surface substance on the substrate surface using physical or chemical methods under the protection of the mask, including wet and dry etching. Wet etching is to use the chemical reaction between a specific solution and the film to remove the part of the film that is not covered by the photoresist mask, and achieve the purpose of etching. Dry etching is the use of radio frequency (RF) power to generate ions and electrons with high reactivity of the reaction gas, physical bombardment and chemical reaction on the silicon wafer to selectively remove unwanted areas. The etched material becomes a volatile gas, which is extracted by the extraction system, and finally etched to the required depth according to the design graphic requirements. Traditional laser etching may have the problem of uneven etching depth. In order to improve this process, multi-beam laser etching technology can be used. By precisely controlling the energy, angle and pulse frequency of multiple laser beams, a more uniform etching on the surface of the microstructure can be achieved.

Template method

Template method is based on the spatial limit of template to control the size, morphology and structure of synthetic nanomaterials. In practical application, the microstructure etched on the surface is generally extended to prepare the replica template with resin or artificial rubber and other materials through the replica technology, and then the material surface with a specific structure is prepared under the guidance of the replica template. Template method has the advantages of flexible synthesis of nanomaterials, simple experimental devices, mild operating conditions, accurate control of the size, morphology and structure of nanomaterials, and preventing the occurrence of nanomaterials agglomeration. In the hard template method, the partial filling of raw materials will cause the product to discontinue in the pore, resulting in structural defects. Additionally, removing the formwork may cause partial tunnel structure collapse or affect product properties. Thus, it is essential to design a more reasonable template structure to improve the stability of the template and ease of removal while minimizing the impact on the structure and performance of the product. Additionally, it is important to explore a wider range of formwork materials, especially those with special properties and functions, to meet the needs of different application scenarios.

3D printing method

Three-dimensional printing is an additive manufacturing method, based on digital model files, the use of metals, polymers and other materials, with layer-by-layer printing, stacking, and forming a physical object. This technique is the embodiment of the close combination of digital and manufacturing. Although 3D printing has unique advantages in manufacturing complex microstructure surfaces, there is currently a contradiction between its speed and accuracy. To improve this process, dual-material 3D printing technology can be used. In production applications, 3D printing also can be closely integrated with computer-aided design (CAD) software.

Isotropic microstructured surface

Controlling material surface wettability hinges on micro-nano structuring and chemical alterations[47,48]. Designing precise microstructures enables regulation of superhydrophobic, superhydrophilic, or other specialized wetting characteristics of liquids. Moreover, wettability enhancement techniques are advancing towards crafting and refining multi-scale, multi-layer composite micro-textures and biomimetic functional surfaces[46,49-51].

Han *et al.*[52] combined specific biomimetic morphology and inherent properties of paraffin to prepare a moth-eye nanocolumn structure instead of a porous structure, coated with solid paraffin for waterproofing, and the surface has self-cleaning, anti-icing, anti-reflection and self-healing properties [Figure 2A]. The stability of superhydrophobic surface has always been one of the factors limiting its application. Dai *et al.*[53] prepared polydimethylsiloxane (PDMS) microcilia with magnetic field assistance, and then modified nano-sized particles with excellent hydrophobicity through the expansion process. The substrate has mechanical stability against ultrasonic treatment, sandpaper wear and high-speed water impact [Figure 2B]. Liu *et al.*[28] used two-photon polymerization-based 3D printing technology to prepare triple-entry structures that are super water-repellent to both water and organic solvents. On the basis of the prepared triple entrance structure, micro-open capillaries are constructed to realize liquid directional diffusion, which can be applied to microfluidic platforms and lab-on-a-chip [Figure 2C]. Shi *et al.*[54] propose a thermodynamically based model to predict controllable wetting regions, reveal that the gradual transition of the wetting state is the result of the accumulation of droplets at the nanoscale, and establish a link between the dynamics of the microscale solid-liquid interface and the condensation occurring in the nanostructure. With the deepening of research, Jiang *et al.*[55] achieved the manipulation of liquid immersion behavior at high-temperature surfaces and applied it to heat transfer. They constructed a multi-textured material with different thermal and geometric properties, conductive, protruding columns that act as thermal Bridges to facilitate heat transfer, embedded heat insulation films to absorb and evaporate liquids, and underground U-shaped channels to vent steam. The seamless integration of these heterogeneous elements greatly increases the Leidenfrost effect value without sacrificing high heat transfer capacity [Figure 2D]. Zhang *et al.*[56] proposed a top-constrained self-branching (TCSB) method for preparing biomimetic superhydrophobic four-branched microstructures, and modified the microstructures with hydrophilic microspheres to verify that hydrophilic spires play a key role in air layer recovery during extremely low underpressure recovery [Figure 2E]. Wilhelm *et al.*[57] propose an innovative fabrication method for a biomimetic superhydrophobic egg beater structure with controllable surface topography. It can precisely control the structure size, the number of beater arms, the structure distance, etc., and study its influence on hydrophobicity and water adhesion [Figure 2F]. Wang *et al.*[58] constructed different structures on the substrate surface in two-dimensional (2D) dimensions: a wear-resistant structure on the micron scale; The superhydrophobic structure is constructed on the nanoscale to design materials with both wear resistance and superhydrophobic properties, which solves the problem of superhydrophobic surface stability to a certain extent.

Anisotropic microstructured surface

Some natural surfaces with special structures provide important prototypes for the study of directional liquid transport on 2D materials[59]. The directional infusion capacity of these 2D natural surfaces is closely related to their micro and nanosurface structures. Isotropic microstructures are often used to design and adjust the wetting and adhesion properties of liquids on solid surfaces. The controlled driving of liquids requires asymmetric forces, so the design of anisotropic microstructures becomes necessary[60-63].

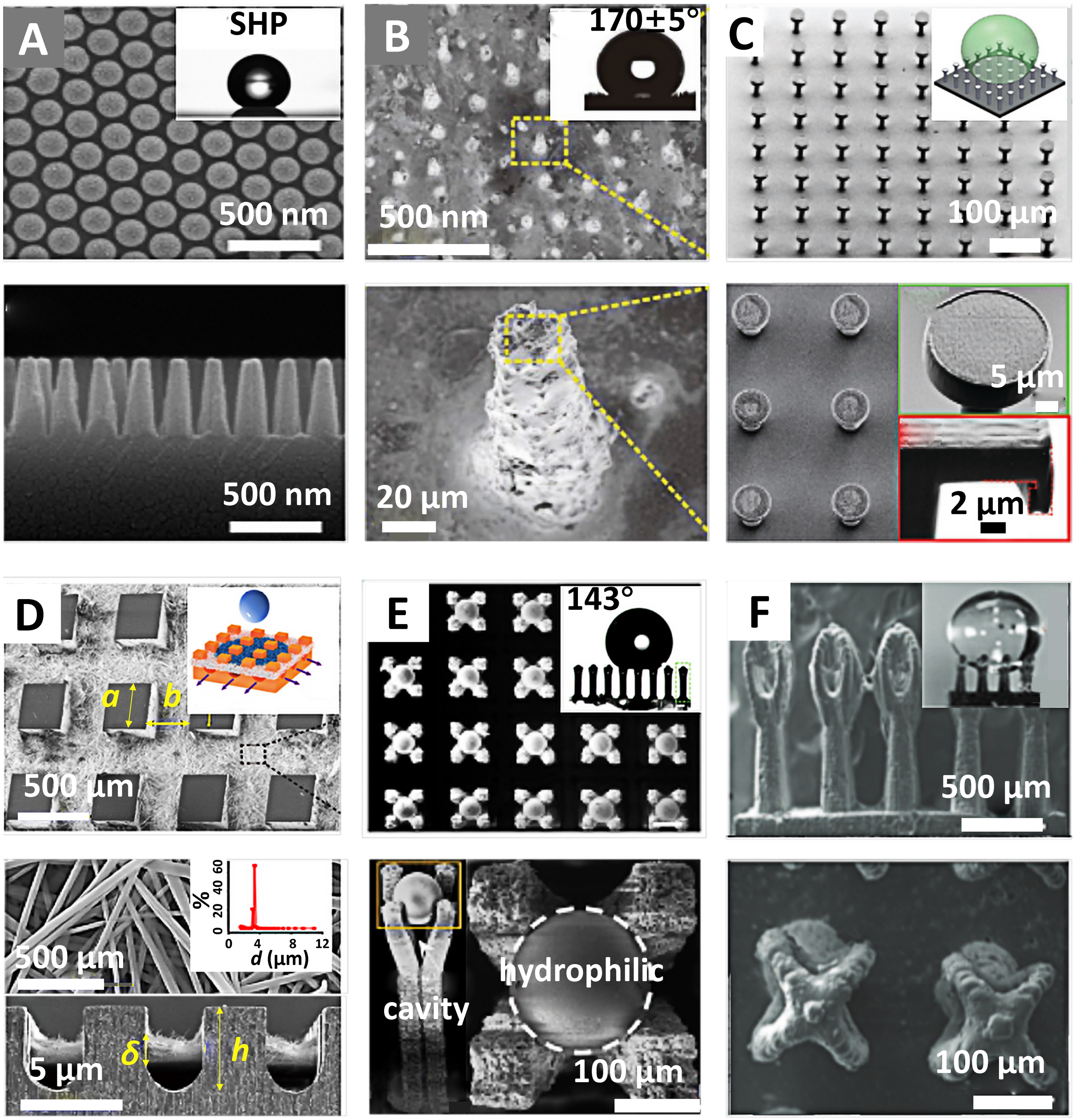

Figure 2. SEM photos of isotropic microstructure surface and contact angle photos of water droplets. (A) Biomimetic nanocolumn array prepared by template method. Copyright 2020, ACS[52]; (B) Microciliary array prepared by self-assembly method under magnetic field. Copyright 2020, Wiley[53]; (C) 3D printing technology based on two-photon polymerization to manufacture reentrant structures. Copyright 2018, Wiley[28]; (D) Multi-structure composite surface prepared by etching and electrospinning. Copyright 2020, Springer Nature[55]; (E) Top-bound Self-branched (TCSB) Bionic superhydrophobic four-branched microstructures. Copyright 2022, ACS[56]; (F) Superhydrophobic egg beater microstructure prepared by Immersed Surface Accumulation 3D printing process. Copyright 2010, Wiley[57]. 3D: three-dimensional.

Zhao *et al.*[64] developed a surface-reconfigurable superamphiphilic organic hydrogel for unidirectional liquid transport, inspired by the functional surfaces of pitcher plants and rice leaves. Due to the surface reconfiguration of heterogeneous networks, organic hydrogels can achieve a highly adaptive wetting transition between superhydrophilic and superlipophilic. Juan *et al.*[65] used a series of probe liquids, including non-volatile ionic liquids, to investigate the source of the microscopic liquid residues by studying the directional self-transport of droplets on an anisotropic completely dispersed surface consisting of radially aligned microstripes [Figure 3A]. Bai *et al.*[66] also prepared a radially structured surface of shell-like superhydrophobic origami (S-SLO) with multiple parallel and double asymmetric channels to improve fluid collection and enhance condensation through directional fluid manipulation and the collaboration of radiative cooling layers, resulting in a 56% improvement in directional drainage efficiency [Figure 3B]. Zhang *et al.*[67] combined shark skin surface and ciliary structure of water strider leg to prepare a superhydrophobic surface with anisotropic structure by phase transformation method, on which droplet can be lossless transported [Figure 3C]. Similarly, inspired by the shark skin surface microstructure, we use the template method to prepare a flexible surface with a V-shaped prism structure, and the direction of liquid transport on the surface is adjusted by changing the curvature of the film[68] [Figure 3D]. Liu *et al.*[69] fabricated a tilted sector array tube (TSAT) that exhibits excellent unidirectional liquid transport over a wide range of liquid surface tension and injection velocity. In addition, it enables anti-gravity climb, circuit isolation and chemical reaction control [Figure 3E]. Feng *et al.*[70] were inspired by the surface structure of the Araucaria leaf and prepared a surface with a 3D ratchet structure, on which liquids with different surface tensions can be transported rapidly and directionally [Figure 3F]. Si *et al.*[29] prepared an open micro and macro dual-scale array through advanced 3D printing technology, and realized one-way transport of liquid without external force or energy through a simple model. The internal Laplace pressure differential driving mechanism is explained by the basic formula. The findings suggest innovative microfluidic applications, such as liquid mode, unidirectional transport without external forces and antigravity, that will contribute to the development of smart laboratory chip devices, microfluidic integrated systems, and advanced biochemical microreactors.

Huang *et al.*[71] coated a liquid perfluoropolyether (PFPE) polymer brush on an anisotropic fully hydrophobic surface to achieve non-destructive, rapid directional self-transport of microscopic liquid residues. Since the surface with micropatterns enables lossless droplet self-transport, can drive droplet directional motion, and precisely locates it in the central region where analysis is required, it can serve as a very ideal intelligent platform for chemical and biological analysis without the loss of analyte quality. The lossless self-transport properties of micropatterned surfaces can greatly advance their application in various fields, for example, in biological and chemical analysis, digital microfluidics, etc. Li *et al.*[72] reported a flexible topological catheter in which liquid can be transported spontaneously, rapidly and in a directional manner. Unlike the capillary-induced liquid transport on the diode film, the liquid transport in the liquid diode is mainly regulated by the interaction of surface effects and volume effects. In addition, the durability and stability of the diodes in long-term bending and twisting operations were tested, a strategy that has broad applications in the transportation of a wide range of liquids, such as low surface tension liquids, medical solutions and lubricants.

Intelligent microstructured surface

Because of the unadjustable structure, the traditional microstructure surface cannot dynamically control the surface fluid behavior, so its practical application in many fields is limited. Therefore, the researchers add the responsiveness factor to the surface of the microstructure, and use the external field to accurately control the surface fluid, so that it has a broader prospect in practical application[73-75]. In contrast to traditional fluid manipulation methods, intelligent response surfaces utilize the material responsive characteristics to external stimuli to manipulate the fluid, without complex mechanical components and large amounts of energy input. Intelligent response surfaces can change their physical and chemical properties, such as surface wettability and roughness, in response to external stimuli (such as temperature, light, electric, or magnetic fields, *etc.*). In terms of fluid manipulation, this adjustability enables precise control of the transport direction, velocity, and shape[76-79].

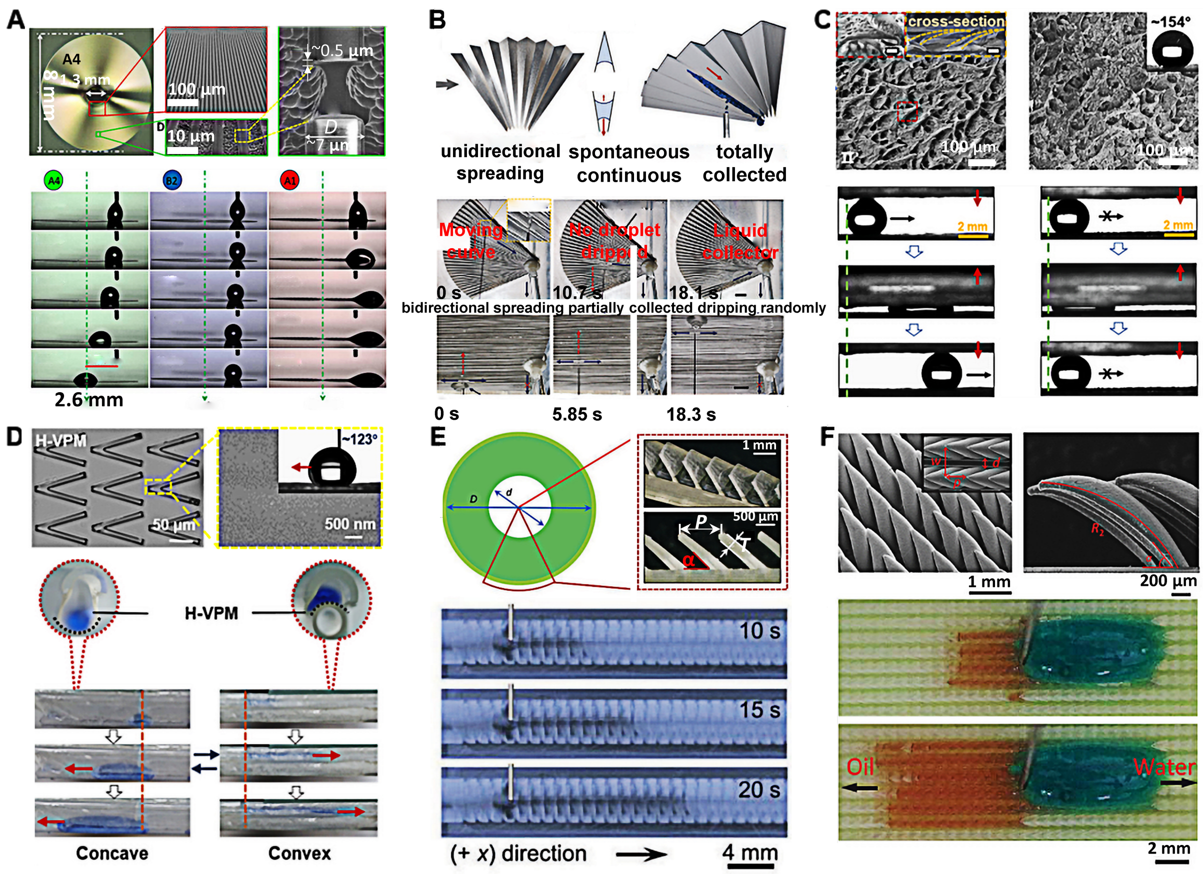

Figure 3. Directional liquid transport on the surface of anisotropic microstructures. (A) Self-transport of oil droplets on a highly oil-phobic radial microtextured surface. Copyright 2016, AAAS[65]; (B) Directional collection of liquid on an asymmetric double-channel hydrophilic surface. Copyright 2023, Wiley[66]; (C) Lossless unidirectional transport of liquid on an ultra-stable superhydrophobic surface with a highly ordered scaly structure. Copyright 2022, ACS[67]; (D) Unidirectional transport of liquid on a V-shaped prism array. Copyright 2023, ACS[68]; (E) Unidirectional transport of liquid in a tilted fan-shaped array tube. Copyright 2016, Wiley[69]; (F) Mimics the micro-junction on the surface of a South American pine leaf Directional transport of liquids with different surface tension. Copyright 2021, AAAS[70].

Material composition, microstructure, and the type and intensity of external stimuli all affect surface properties. The type of intelligent response surface response to external stimuli is determined by its basic material. For instance, surfaces fabricated with thermally responsive polymers such as poly-*N*-isopropylacrylamide (PNIPAM) experience a phase transition upon temperature variation, thereby altering the surface wettability[80]. A composite surface containing magnetic nanoparticles (NPs) will respond to magnetic fields[81]. The surface microstructure (roughness, porosity, and texture direction) significantly influences its performance. A response surface with nanoscale roughness may augment the superhydrophobicity or superhydrophilicity of the surface, thus influencing the contact angle and fluid on surface flow behavior. Different external stimuli (such as temperature, light, electric field, and magnetic field) will initiate different response mechanisms of intelligent response surfaces. For example, temperature stimulation predominantly affects surface properties by modifying the material's molecular conformation or inducing a phase transition, whereas light stimulation may rely on photochemical reactions or photothermal effects[82-84]. Additionally, the intensity of the external stimulus is crucial; insufficient intensity may not elicit a significant response, while excessive intensity may result in material damage or an uncontrollable response. According to this, the researchers designed different intelligent response surfaces to accurately control the surface fluid, so that it has a broader prospect in practical application.

External forces responsive microstructure surface

Mechanical bending, stretching and other deformation is a very simple operation for the solid microstructure surface, but the impact of this series of operations on the surface properties of the microstructure cannot be ignored. The deformation of the material will cause the change of the parameters between the surface microstructure and even the change of the surface chemical composition, resulting in the change of the surface wetting property, wave absorption property and electrical conductivity[85-87].

In 2011, Wu *et al.*[88] found that superhydrophobic surfaces with unidirectional curved microstructures could cause changes in contact Angle adhesion. With the increase of surface curvature, the contact angle of the droplet on the surface increases from 150° to 160°, and the adhesive force also increases gradually. Later, Ma *et al.*[89] studied droplet wettability on the surface of titanium tube with superhydrophobic TiO_2 nanotube array coating, and found that the contact angle of droplet on convex surface was larger than that on flat surface, and that on concave surface was smaller than that on flat surface. On the basis of considering the droplet radius and droplet size, the relation between the intrinsic contact angle of the droplet and the apparent antenna is established. These findings provide a theoretical basis for determining the natural contact angle of opaque or transparent tubular substrates. Hu *et al.*[90] constructed a new structural fiber and realized ultra-fast spreading of liquid on the surface of the fiber. It is believed that the macroscopic conical structure determines the spreading direction of the liquid, and the concave surface and orientation of micro-ridges/valleys affect the capillary rise rate. By reducing the internal angle of the concave curve, the speed of liquid directional spreading can be further accelerated. The results of this study open up a new direction for the fabrication of microfluidic and liquid manipulated fiber systems.

Yang *et al.*[17] introduced a columnar array by utilizing the microstructured template of ethylene vinyl acetate, subsequently modifying it to achieve super hydrophobic properties [Figure 4A]. By stretching and relaxing the film, the adhesion of the liquid on the surface can be changed, and the droplet can be transferred at a fixed point. However, the surface needs to be superhydrophobic modified with fluoride to achieve this property. Lee *et al.*[91] treated polyolefin surfaces with plasma and formed nanoscale ridges during strain release of the substrate [Figure 4B]. By stretching and reshrinking polymer NPs, surface structural characteristics can be controlled without cracking or delamination of the substrate, and transitions to different wetting states can be achieved programmatically, starting from a single surface. This parallel, photolithographic technology enables precise control of the wetting state and is used in a variety of areas such as advanced water collection, self-cleaning systems and directional water delivery.

Photo-responsive microstructure surface

In recent years, the strategy of manipulating droplets using photothermal effect has been developed, and has been widely used because of the advantages of high spatiotemporal resolution, flexible control and fast response of optical response. Light can be easily focused into a tiny beam and used as a local heating source, allowing flexible control of the droplet, which is conducive to controlling its directional movement. In addition, due to its high reconfigurability, the modulator can dynamically adjust the light beam to form an optical array and realize the parallel operation of multiple droplets, ensuring the high throughput of real-time online analysis and biochemical analysis. Therefore, optical strategies based on photothermal effects are expected to be widely used in controlling droplet behavior[92-95].

A light-responsive slippery lubricant-infused porous surface (SLIPS), composed of selective lubricants and a super-hydrophobic Fe_3O_4/PDMS micropillar-arrayed film by Chen *et al.*[96], allows remote actuation of underwater gas bubble in arbitrary horizontal directions via unilateral near infrared (NIR) stimuli loading/discharge [Figure 5A]. Li *et al.*[97] studied the droplet evaporation crystallization process caused by the

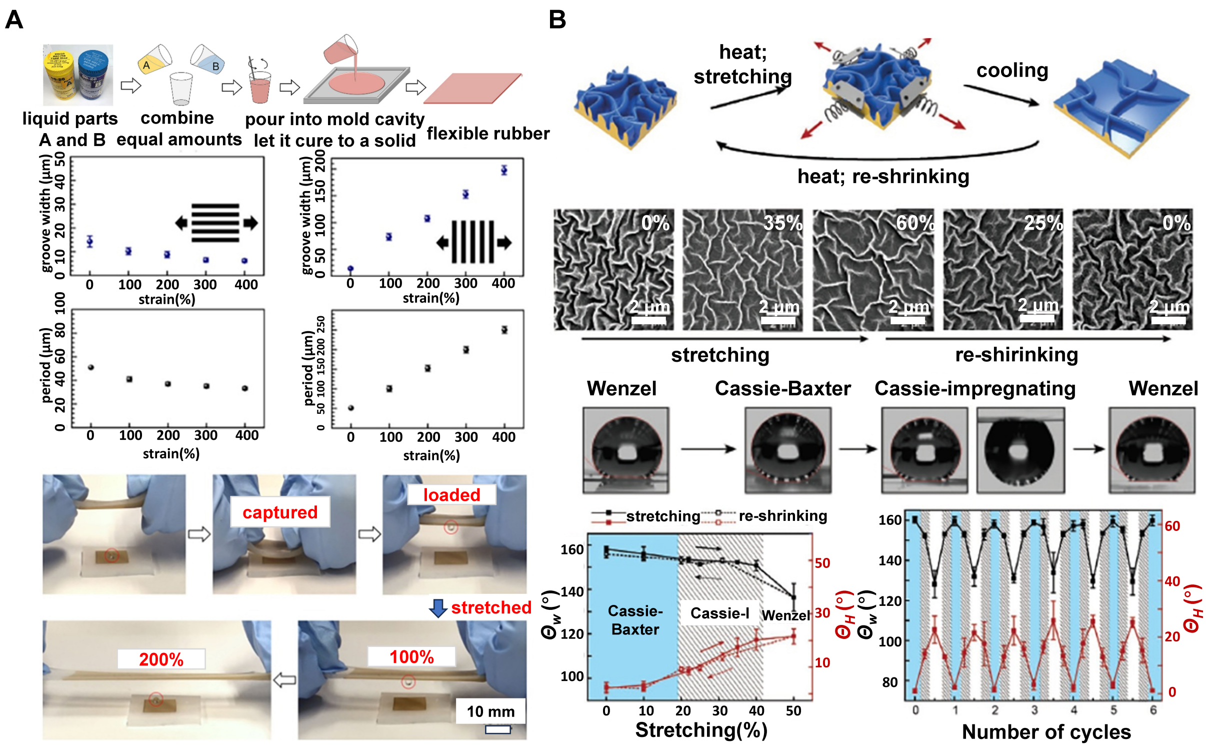

Figure 4. Tensile response of the microstructure surface. (A) A stretchable fluorine-free superhydrophobic surface for droplet transfer. Copyright 2019, Springer[17]; (B) Surfaces with nanoscale ridges can be stretched and released to control the wetting state of droplets on the surface. Copyright 2018, Wiley[91].

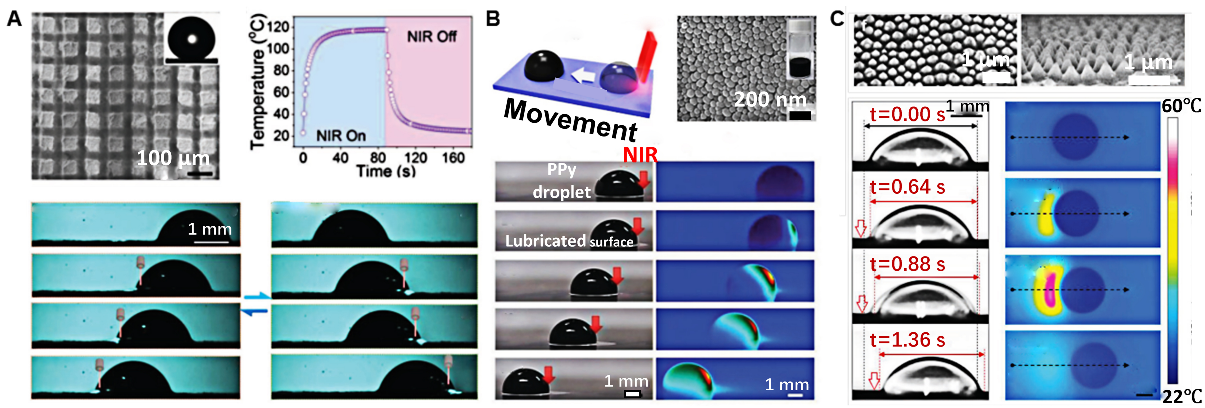

Figure 5. Photoresponse to directional liquid transport on the surface of the microstructure. (A) Remote photothermal drives underwater bubbles in any direction. Copyright 2019, Wiley[96]; (B) The droplet motion is driven by light-driven Marangoni flow propulsion. Copyright 2019, Wiley[98]; (C) Light-induced droplet movement on POS surface. Copyright 2018, Wiley[92].

photothermal effect of an infrared laser with a focusing wavelength of 1550 nm. It is found that when the focused light is turned on, the interface temperature of the droplet rises rapidly, and violent evaporation occurs, increasing the concentration of substances in the droplet, and eventually crystallization. Compared with natural evaporation and flat plate uniform heating, the photothermal effect of focused laser beam can promote droplet evaporation and crystallization. At 100 mW of laser power, the time for the droplet to complete evaporative crystallization is seven times shorter than the time for natural evaporation. Hwang *et al.*[98] proposed to control droplet motion by controlling Marangoni flow [Figure 5B]. A temperature gradient is used on the droplet surface to generate a surface tension gradient that drives the droplet. The irradiation position can be precisely controlled by NIR laser to realize the local heating of the droplet and the change of the direction of thermal capillary convection, and the droplet always moves from the heated side to the non-heated side. In addition, because the droplets are directly heated by the polypyrrole (PPy)/NPs inside, even in spherical droplets with small contact areas, there is a strong thermal capillary propulsion, resulting in directional motion. Gao *et al.*[92] proposed a photoresponsive organic gel surface (POS) obtained by embedding Fe_3O_4 NPs in PDMS and injecting lubricating oil [Figure 5C]. Under the irradiation of NIR (wavelength 808 nm), the irradiated part of POS can quickly generate a local dynamic temperature gradient, and the droplet directional transport can be carried out by tilting plane, mixed droplet and curved path.

Electrically responsive microstructure surface

Controlling the directional movement of droplets on solid surfaces by introducing surface wettability gradients or external stimuli has attracted considerable attention. However, due to the slow speed of continuous movement and response of the droplet on the surface of the structure, its directional fast transport still has some challenges. As a non-destructive, fast, simple and reversible external stimulation induction method, electric field has shown unique advantages in the regulation of material surface wetting properties[99-101].

Our group developed a porous polystyrene (PS) film with gradient structure prepared by electric field and breathing pattern method under the humidity field gradient, and realized the titrating movement of underwater oil[22]. When the electric field is applied, the contact area between the droplet and the surface of the gradient structure is reduced, resulting in a decrease in the corresponding viscous resistance between the droplet and the surface of the gradient structure, thus driving the underwater oil droplet to move in a directional and continuous manner. This work provides a new method for controlling and realizing unidirectional movement of underwater oil droplets, and has a broad application prospect in the design of new intelligent interface materials. In addition to realizing an electric field driving oil droplets on a 2D surface, we also propose a new strategy for efficient collection of oil droplets on an anisotropic porous cone surface using an electric field[23]. Under the combined action of Laplace pressure, buoyancy force and electric field, the directional movement of oil droplets along the surface of a cone with a PS-coated gradient hole is realized. With the help of buoyancy, the downward direction of the cone tip is more conducive to the directional movement of the underwater oil droplets. In addition, we combined the superhydrophobic NPs with the boundary electro-elastomer, stretched the dielectric elastomer film by electric field, changed the distance between the surface superhydrophobic NPs, and regulated the dynamic wetting and adhesion of droplets on the surface[102] [Figure 6A].

Chen *et al.*[103] also combined the electric field with the composite surface immersed in liquid, applied and removed the electric field to control the state between the lubricant and the microstructure of the composite surface, and controlled the pinning and sliding of droplets on the surface. If the voltage is applied directly to the substrate, the substrate will be broken down, become charged and experience biological contamination as the voltage increases. Dai *et al.*[104] proposed an integrated method for manipulating the motion of water droplets on a superhydrophobic surface using an electrostatic field [Figure 6B]. The lossless droplet manipulation with high-speed movement and switchable pinning is realized by inducing electrostatic repulsion and gravity. Li *et al.*[105] demonstrated the use of electronic signals to induce the dewetting behavior of a liquid on a conductive substrate without the need for additional conductive layers. In this electrostatic mechanism of action, contrary to the electrowetting phenomenon, the interaction of the liquid substrate is not directly controlled by the electric field, but by the attachment and stripping of the field-

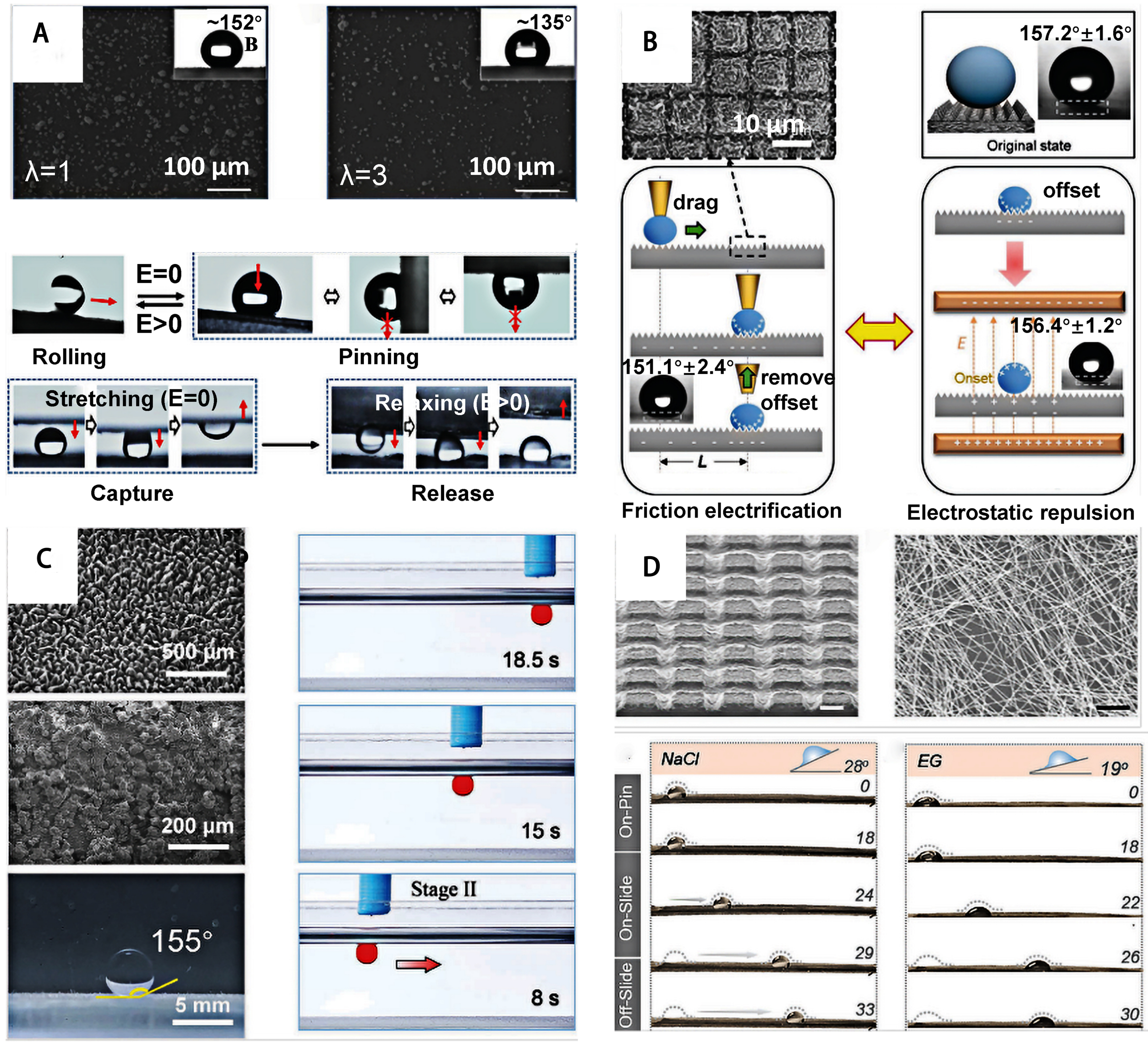

Figure 6. Directional transport of liquid on the surface of microstructure in response to electric field. (A) Droplet adhesion and movement control on the surface of micro-nano multistage structures in response to an electric field. Copyright 2020, Wiley[102]; (B) Out-of-plane electrostatic charging control. Copyright 2019, Wiley[104]; (C) A high-speed "one-piece" lossless droplet operation *via* triboelectrophoresis on a microstructured surface with a superhydrophobic coating. Copyright 2023, Wiley[106]; (D) In situ-controlled wetting and movement of droplets injected with Joule thermal response paraffin with a sandwich structure. Copyright 2021, Wiley[107].

induced ionic surfactant on the substrate; the driving voltage is only 2.5 V, the current is only a few microamps, and the critical micelle concentration of the ionic surfactant is about 0.015 times. The system can also handle common buffers and organic solvents, providing a simple and reliable microfluidic platform. Sun *et al.*[106] introduced a tribo-electrophoresis (TEP)-based method employing a triboelectric nanogenerator (TENG) electrostatic tweezer to efficiently enable human-droplet interactions by charging and enhancing droplet maneuverability, including pipetting alignment and stable transport, controlled solely by hand movement [Figure 6C]. Chen *et al.*[107] developed a Joule-heat-responsive paraffin-impregnated slippery surface (JR-PISS), featuring a superhydrophobic micropillar-arrayed elastomeric membrane and integrated transparent silver nanowire heater, enabling controllable liquid locomotion on both planar and curved surfaces through alternate 6 V electric-trigger application/discharging, due to its flexible design [Figure 6D].

Magnetism-responsive microstructure surface

Droplet control has been widely used in various fields of production and life. Major breakthroughs have been made in droplet manipulation, and different droplet transport strategies have been developed based on various external stimuli. Magnetically responsive surfaces are widely used in droplet control platforms because of their fast response speed and contactless operation[83,108,109].

Our group prepared a magnetically responsive intelligent composite surface by combining the magnetic fluid with the surface of the nano-ZnO array [Figure 7A]. The roughness of the intelligent composite surface can be changed by magnetic field, and the contact angle of the droplet on the surface can be adjusted by magnetic field. In addition, when an asymmetric magnetic field is applied below the intelligent composite surface, the droplet will have a directional motion due to the unbalanced force on both sides, and the response speed of the intelligent composite surface is less than 1 ms[110]. Wen *et al.*[76] used a simple, reagent-free method to fabricate a magnetically asymmetrically deformed tube microactuator that generates an asymmetric capillary force to drive a liquid through a magnetic field-induced tube deformation. These magnetic tube microactuators can drive a variety of droplets at a controlled speed and direction, up to 10 cm/s. In addition to controlling surface deformation, magnetic fields can also control the deformation of surface microstructure. Wong *et al.*[77], inspired by lotus leaves and pitcher plants, designed a magnetically responsive surface that can switch between superhydrophobic and slippery states. The surface consists of a series of magnetically responsive layered microcolumns made of soft polymeric material and infused with a liquid lubricant. The microcolumn can be controlled by magnetic field. When the microcolumn is perpendicular to the base, the droplet is in Cassie state and the surface is in super hydrophobic mode, similar to the lotus leaf. When the microcolumn lies flat on the substrate under the action of an external magnetic field, the droplets interact with the surface of the lubricating oil, which mimics the wet surface on the edge of the pitcher plant, on which the droplets can slide. In addition to manipulating the behavior of the droplets horizontally, the magnetic field can also control the permeability behavior of the liquid horizontally. Yun *et al.*[111] introduces a magnetocontrollable lubricant-infused surface (MCLIS) for liquid-solid (LS) triboelectrification switching, demonstrating sustained power generation under high humidity by toggling wetting states, unlike typical LS-TENGs which suffer from performance degradation [Figure 7B]. This innovation offers a magnetoresponsive triboelectric switching concept, expanding the applicability of TENGs in low-power domains such as wireless switches and self-powered sensors. Zhang *et al.*[112] showcased an active strategy on removal modes-based magnetic-responsive polydimethylsiloxane superhydrophobic microplates (RM-MPSM), enabling varied droplet removal modes (top jumping, side departure) by adjusting microplate parameters and droplet volume, facilitating droplet removal. These efficient removal modes have broad implications for applications in droplet collection, heat transfer, and anti-icing [Figure 7C]. In addition to controlling the horizontal movement of the fluid on the surface of the microstructure, the magnetic field can also control the longitudinal transmission of the fluid.

Multiple fields respond collaboratively to the microstructure surface

Compared with the influence of a single factor on droplet control, the synergistic effect between multiple factors can show greater advantages on droplet motion control. Jun *et al.*[113] reported a method for controlling anisotropic wetting using a pleated dielectric elastomer actuator. The actuator is made of a carbon black electrode with mechanical buckling on the surface of the elastomer by bidirectional prestretching and relaxation process. The dielectric elastomer actuator is driven by directional anisotropy, and the hydrophobic surface of the carbon electrode is controlled by the electric field, which can realize the anisotropic wetting control. Padinjareveetil *et al.*[78] prepared hydrophobic microcolumn array zinc oxide films using femtosecond laser vertical cross-scanning technology. Paraffin wax was successfully injected into zinc oxide thin films by means of spin coating, thermal evaporation and condensation. An intelligent

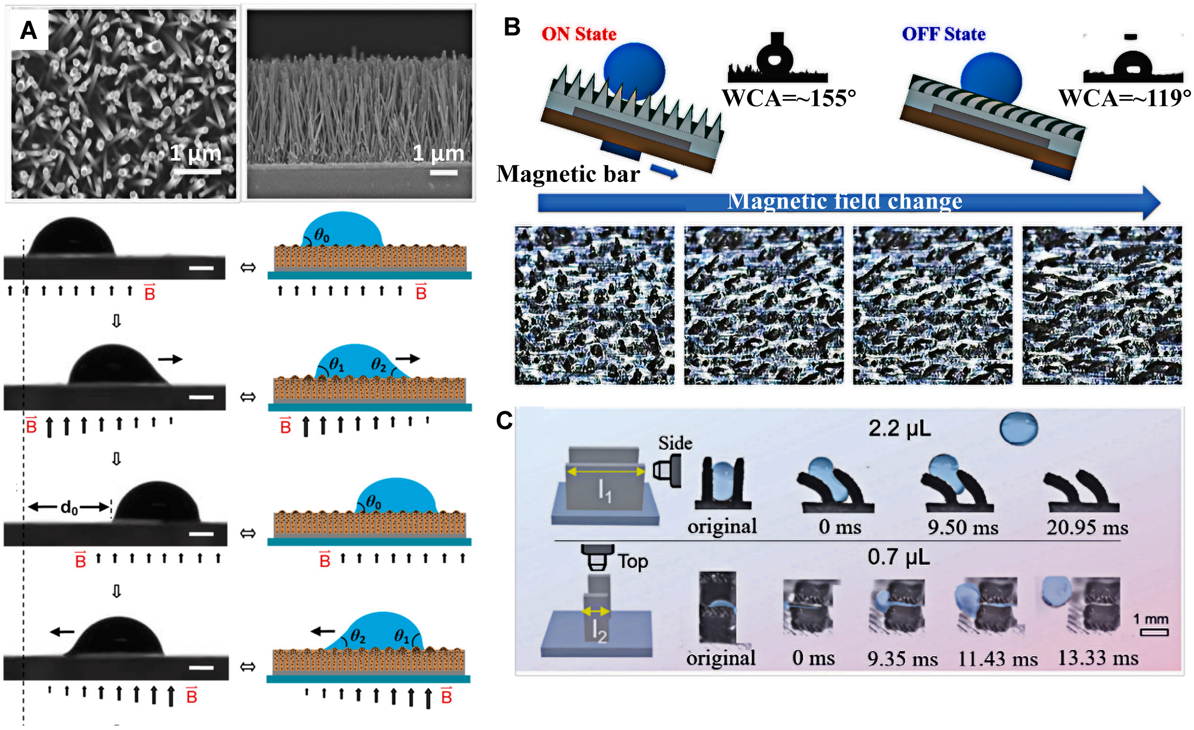

Figure 7. Directional liquid transport on the surface of the magnetic response microstructure. (A) The directional movement of droplets on the surface of the magnetic liquid impregnated nano ZnO array. Copyright 2016, ACS[110]; (B) The solid-liquid triboelectrically controlled magnetic switch to control the movement of droplets is realized by using the magnetron lubricant injected into the surface as the triboelectric layer. Copyright 2022, Elsevier[111]; (C) the effective removal of droplets on the surface of the magnetically responsive polydimethylsiloxane superhydrophobic microplate. Copyright 2024, Wiley[112].

droplet motion control actuator was fabricated by integrating the composite film with a silver nanowire heater. By loading an ultra-low voltage of 12 V, the wettability of various droplets with different surface tension can be controlled *in situ*. This study provides a new research idea for the design of in situ droplet motion control and anti-fog and anti-ice intelligent devices for 2D/3D surfaces.

Furthermore, the fabrication of robust and durable microstructured surfaces is not only a critical requirement for withstanding extreme environments and enhancing material performance but also a key factor in extending service life, reducing maintenance costs, and driving the development of new technologies. Therefore, effectively improving the strength of microstructured surfaces has become a pressing issue that demands immediate attention.

Lu *et al.*[114] develop a dual-sized titanium dioxide NP suspension coated with perfluorosilane. This material maintained stable superhydrophobic properties even after being subjected to finger friction, wiping, knife scratching, and 40 cycles of sandpaper abrasion. Furthermore, Su *et al.*[115] successfully fabricate a superhydrophobic composite microstructured surface, which exhibits excellent hydrophobicity after undergoing various extreme environmental tests, including cyclic mechanical abrasion, ultraviolet (UV) radiation, acid-base treatment, NaCl solution immersion, temperature variations, and knife scratching. Li *et al.*[116] successfully fabricate a highly durable superhydrophobic coating by spraying a fluorine-free suspension composed of epoxy resin (EP), PDMS, and modified silica. The coating maintained stable superhydrophobic properties under extreme conditions, including immersion in boiling water for two hours, immersion in liquid nitrogen for one hour, exposure to intense UV radiation for 48 hours, and strong chemical corrosion. Furthermore, the coating demonstrates exceptional mechanical durability, withstanding extreme tests such as tape peeling, knife scratching, hand grinding, and 100 cycles of sandpaper abrasion, while also exhibiting self-healing capabilities against O_2 plasma etching.

These researches provide new insights and methods for developing robust and durable microstructured surfaces for extreme environments, offering significant theoretical and practical implications for advancing related technological fields.

APPLICATION OF FLUID MANIPULATION ON MICROSTRUCTURED SURFACE

In recent years, the research of micro-structure surface fluid manipulation involves the intersection of chemistry, materials science, fluid mechanics, biology and other disciplines, serving the important fields of energy, information, medicine, and so on[117-120].

Anti-fog and anti-ice

The superhydrophobic surface has a special micro and nanostructure and low surface energy, which can make the water droplets form a high contact angle and a low rolling angle on the surface, so that the water droplets are easy to roll off and not easy to stay on the surface and freeze. Zhou *et al.*[121] pre-coated a template surface with a nanostructure with PDMS. By introducing a "reservoir" of free lubricant at the bottom, which acts as a self-replenishing oil source for the upper layer, the superhydrophobic surface becomes more stable and can heal itself under alkali erosion and O_2 plasma exposure, with a higher icing delay time and faster ability to remove condensation droplets in low-temperature environments. Zhang *et al.*[122] prepared a photothermal synergistic three-scale solar thermal superhydrophobic surface with excellent anti-icing and de-icing properties, so that ice with a thickness of 4 mm can melt and be removed from the surface in 241 s. Zhang *et al.*[123] made the droplet automatically "eject" from the surface when it froze by using the high pressure generated by its own volume expansion of about 9%, by adjusting the matching of the flow field and the force gradient field. The spring-like column could store the work done by the volume expansion of the frozen droplet for several seconds as elastic energy, and then quickly release it as kinetic energy within a few milliseconds. This generates enough kinetic energy to drive the ejection of the frozen droplets.

Fog harvest

Fog harvesting, a technique that captures water vapor or fog from the air to obtain fresh water, is being applied as a sustainable and low-cost method of drinking water acquisition in foggy areas. Ang *et al.*[124] propose a cascade effect that induces water collection from the active water harvesting region (AWHR) and passive water harvesting region (PWHR) through a microstructural design that results in about a threefold increase in water harvest compared to unmodified water collectors, highlighting the need to consider PWHR in future collector designs to achieve efficient water collection. The purified terephthalic acid (pTA)/silica nanofibers (SNFs)/1H,1H,2H,2H-perfluorodecanethiol (PFDT) coating prepared by Zhang *et al.* has excellent superhydrophobicity[125]. The coating has autogenetic hydrophilic Wenzel site during fog collection, and achieves a stable high fog collection rate of 2.13 g cm^{-2} h^{-1} during 192 h of continuous fog collection. Inspired by the behavior of the Namib Desert web-dactylated tiger to avoid thermal radiation and capture water, Zhang *et al.*[126] prepared a biomimetic passive water collection material [power-free cooling moisture harvester (PFCMH)] with integrated radiative cooling and heterogeneous wetting functions. In the one-month outdoor water collection experiment, the water collection system built based on PFCMH can produce about 620.4-1244.4 g m^{-2} fresh water every night, and about 52.2-102.5 g m^{-2} fresh water during the day, and the captured fresh water meets the WHO drinking water standards, and the laying of 2 m^2 can meet the daily drinking water demand of an adult.

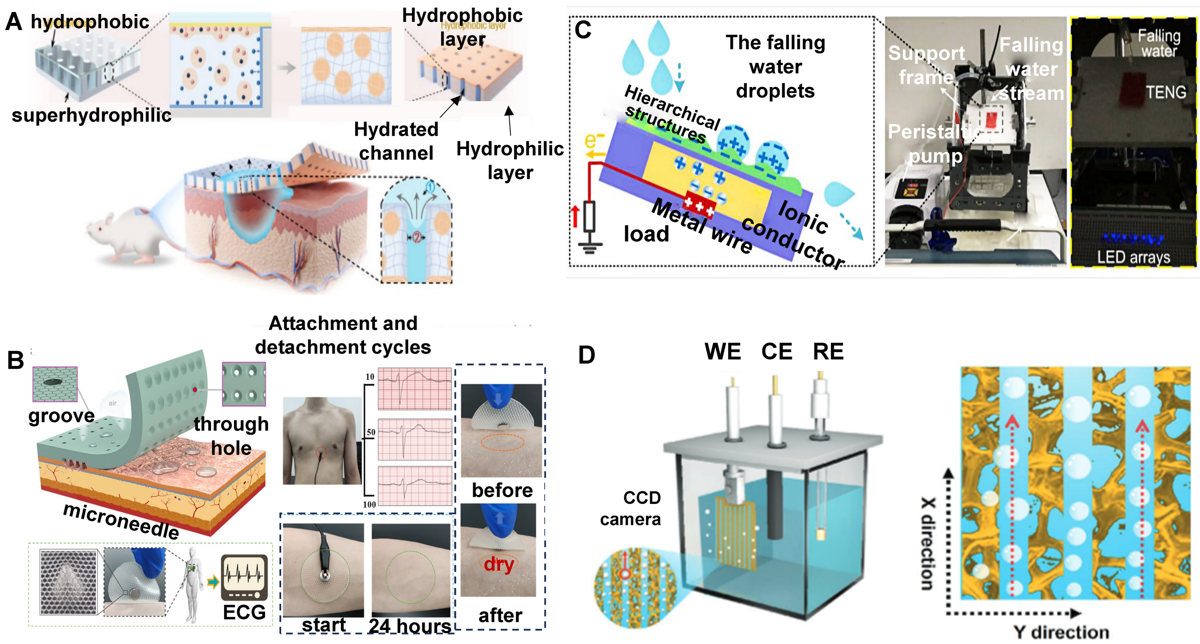

Figure 8. Application of fluid controllable transport on the surface of microstructures.

Biomedicine

Inspired by the self-driven diffusion of liquid membranes on the surface of Nepenthes, Li *et al.*[127] successfully prepared biomimetic microstructures on high-frequency surgical electrodes using laser etching technology, and introduced conductive oil films into the microstructures, which can promote the occurrence of spark effects, thereby preventing short circuits in the tissues of the electrodes. Additionally, suppressing heat transfer during cutting can prevent thermal damage and significantly reduce adhesion problems. Xiao *et al.*[128] developed a self-pumped organic hydrogel dressing with aligned hydrating gel channels for enhanced viscous fluid drainage and accelerated diabetic wound healing. In diabetic rats, compared to commercial dressings, the self-pumping organohydrogel dressing (SPD) reduced inflammation by 70.8%, improved dermal remodeling by 14.3%, and hastened healing by about 1/3 [Figure 8A]. Liang *et al.*[129] have proposed an innovative bionic skin sweat sensor with an advanced sensor system that can monitor a variety of biomarkers in sweat, including glucose, lactic acid, uric acid, pH, temperature and skin impedance. With the newly developed Continuous Analyte Monitoring with Real-time Engagement (CARE) system, real-time data transmission and processing are realized. Zhang *et al.*[130] devised a health-monitoring electrode patch featuring perspiration permeability and multi-mechanism adhesion [Figure 8B]. Its ventilation and sweat management are achieved via a conical through-hole and honeycomb micro-groove integrated design. A Laplacian liquid pressure and microgroove capillary forces drive sweat conductivity autonomously. Adhesion is ensured by an Ag/Ni microneedle array and PDMS-t adhesive, stabilizing the patch-skin contact. High-controlled microneedle-skin contact guarantees safe, reliable bioelectrical signal acquisition.

Other application

In addition, microstructure surfaces also have important applications in energy, self-cleaning, catalysis, and so on. Chen *et al.*[131] pioneered a hierarchical micronanostructure with high transparency, full stretchability, and superhydrophobicity for advanced bimodal TENGs, capable of harvesting mechanical and water energy [Figure 8C]. With superhydrophobic self-cleaning properties, the TENG gains additional water energy harvesting capacity, achieving 36 V and 10 μA output at 11 mL/s water flow. This bifunctional energy harvesting, alongside transparency, stretchability, and robust superhydrophobicity, positions the TENG as a promising energy source for future electronics. Inspired by the layered structure of lotus leaves, Liu *et al.*[132] obtained a coating that integrates surface wettability, optical structure, and temperature adaptation through a simple one-step phase separation process. The coating not only has a self-cleaning function, high infrared emission and heat-exchangeable solar reflectivity, but it can also switch between radiative cooling and solar heating. It opens up new prospects for the large-scale manufacturing of intelligent thermal regulation coatings. Li *et al.*[133] proposed an efficient water decomposition strategy using a bubble-guided electrode [groove-micro/nanostructured porous electrode (GMPE)] with gradient groove micro/nanostructures, inspired by nature's directional fluid transport in pitcher plants and butterfly wings [Figure 8D]. This facilitates rapid bubble transport and detachment, achieving efficient water splitting and offering insights for gas-involved photochemical electrode design.

CONCLUSIONS

To date, the on-demand manipulation of surface fluids has made impressive strides, from material preparation methods to intelligent microfluidic devices, which has considerable significance in the realms of science and engineering and attracted extensive attention in recent years. In this review, the latest progress of fluid manipulation on the surface of microstructure is reviewed. First, the basic theory of fluid wetting state transition and directional driving on the surface of microstructure are introduced. Then, the research and application of preparation, characterization and fluid wetting of various microstructure surfaces under the guidance of the above basic theories are described. The research of fluid control on the surface of microstructures can promote the development of microfluidic technology. By precisely controlling the fluid behavior on the micro and nanoscale, miniaturized, integrated and highly sensitive fluid control can be achieved, which has a profound impact on the research and application in biomedicine, energy, materials and other fields. Fluidic manipulation of microstructure surfaces can also be used to design new types of sensors and actuators that are capable of operating under extreme conditions, such as in optical device design in space, where fluidic manipulation of microstructure surfaces can be used to manufacture optical devices and so on.

Despite significant progress in microstructured surface fluid manipulation research, challenges persist, particularly in practical problem-solving and industrial application. First, large area preparation is one of the difficulties. With the increase of the preparation area, the homogeneity and reproducibility of the structure will become worse, which will greatly affect the wetting characteristics of the surface and limit its application in industrial production. Secondly, in practical applications, high temperature and pressure, low temperature, strong corrosive solution, external impact and other factors will damage the surface of the microstructure, so that it is damaged and lose its excellent function. Consequently, the stability of microstructured surfaces has emerged as a critical issue that necessitates immediate resolution. Future research in microstructured surface fluid manipulation will prioritize innovative design, industrial scaling, and advanced fabrication techniques for a simple, stable, and high-performing process. Specifically, focus on the following three aspects:

(1) New materials and structures: Through the discovery and synthesis of new materials with excellent properties (such as superhydrophobic materials, superhydrophilic materials, and intelligent response materials, *etc.*), combined with innovative structural design (such as gradient structure, multistage structure, and bionic structure, *etc.*), the stability, durability and functionality of the microstructure surface can be significantly enhanced. For example, bionics inspired micronanostructural designs (such as the micromastoid structure on the surface of lotus leaves or the gradient hydrophobic structure of desert beetles) can effectively improve surface resistance to pollution, self-cleaning, and liquid directional

transport. In addition, the introduction of smart responsive materials allows the surface of the microstructure to dynamically adapt to complex environmental changes, thus maintaining excellent performance. The development of these new materials and structures can not only solve the stability problems faced by existing microstructure surfaces in industrial applications, but also expand their application potential in microfluidic chips, biosensors and efficient water harvesting, providing important support for future multifunctional integration and intelligent fluid manipulation.

(2) Process improvement: Currently, the fabrication of microstructured surfaces primarily relies on technologies such as laser etching, chemical etching, 3D printing, and so on. While these methods offer high flexibility and precision, they still face challenges in industrial applications, including low efficiency, high costs, and process complexity. Therefore, it is necessary to optimize and improve existing processes to enhance processing efficiency, reduce production costs, and maximize economic benefits. Specific improvement measures include the following aspects: 1)Process parameter optimization. Through experimental design and data analysis, optimize key parameters such as laser power, scanning speed for laser etching, and solution concentration and reaction time for chemical etching to improve processing accuracy and efficiency; 2) Real-time Monitoring and feedback optimization. Introduce online monitoring systems (e.g., high-speed cameras or optical sensors) to provide real-time supervision of the processing. Combined with feedback control algorithms, dynamically adjust laser parameters to ensure processing precision; 3) Process integration and innovation. Integrate multiple processing technologies (e.g., laser etching and 3D printing) to develop hybrid processes that overcome the limitations of single technologies, enabling more efficient fabrication of microstructured surfaces; 4) Standardization and scalable production. Establish unified process standards and quality control systems to promote the scalable production of microstructured surfaces, further reducing costs.

(3) Integration and application of smart materials: Introducing smart materials to actively adjust the morphology, distribution, and the release and transfer of substances of the surface microstructures, thereby enhancing the controllability and dynamic tunability of fluids on these surfaces and promoting their further development in practical applications.

DECLARATIONS

Authors' contributions

Conceptualization: Li, Y.; Zhang, Q.
Investigation: Li, Y.; Zhang Q.
Writing-original draft: Li, Y.; Zhang, Q
Writing-review & editing: Li, Y.; Zhang, C.; Li, Y.; Zhang, Q.; Li, L.; Song, F.; Tian, D.
Supervision: Li, Y.; Zhang, Q.; Li, L.; Song, F.; Tian, D.
Funding acquisition: Li, Y.; Zhang, Q.; Li, L.; Song, F.; Tian, D.

Availability of data and materials

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Conflicts of interest
All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

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