

Low friction of superslippy and superlubricity: A review

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Abstract: The issues regarding energy dissipation and component damage caused by the interface friction between a friction pair attract enormous attention to friction reduction. The key-enabling technique to realize friction reduction is the use of lubricants. The lubricants smooth the contact interfaces, achieving an ultralow friction contact, which is called superslippy or superlubricity. At present, superslippy and superlubricity are two isolated research topics. There is a lack of unified definition on superslippy and superlubricity from the viewpoint of tribology. Herein, this review aims at exploring the differences and relations between superslippy and superlubricity from their origin and application scenarios. Meanwhile, the challenges for developing superslippy surface and superlubricity surface are discussed. In addition, perspectives on the interactive development of these two surfaces are presented. We hope that our discussion can provide guidance for designing superslippy or superlubricity surfaces by using various drag-reduction technologies.

Keywords: low friction; superslippy; superlubricity; tribology; lubricants

1 Introduction

Friction is a double-edged sword since it works for you in some cases while it works against you at other times [1–3]. For example, we need friction to help us move forward when we walk on the road, but meanwhile friction will be a drag on our acceleration. Friction existing objectively among the contact interfaces can be controllably increased or decreased according to the application scenarios. Generally, maintaining the stability for a static object requires increasing friction while reducing energy dissipation and abrasion for a dynamic process requires decreasing friction. The phenomena for the friction reduction with the help of lubricants are denoted as superslippy and superlubricity. According to statistics, nearly 5%–7% of the gross national product is lost due to the unnecessary friction [4, 5]. Hence, adopting reasonable

strategies to reduce friction and wear is crucial and urgent [6–8].

Superslippy and superlubricity mean that objects move on a surface under an ultralow friction force, which are applicable to different application scenarios. Superslippy mainly refers to the liquid–solid interface while superlubricity mainly refers to the solid–solid interface. Since friction strongly depends on the smoothness of substrates, lubricants, such as air, liquid lubricants, and solid lubricants, are widely adopted to smooth the surface of substrates. The design of superslippy surface is inspired by lotus and *Nepenthes alata* [9, 10]. For instance, a lotus leaf surface that shows ultrasmall adhesive force toward droplets and enables droplets move freely and quickly with the aid of air lubricant is called superslippy surface. The droplets commonly exhibit very low contact angle hysteresis and sliding angle (below 5°) toward the

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superslippery surfaces. The special structure of *Nepenthes alata* inspires researchers to adopt liquid lubricants to smooth the surface of substrate [11]. Considering the durability of lubricants, solid lubricants are the more desirable candidates in the near future. In designing superslippery surface, two crucial issues in terms of the interaction between droplets and lubricants together with the roughness of substrate surface should be noted. The interaction between the droplets and the lubricants should not be too strong to allow droplets move freely. In contrast, the substrates should have enough roughness to enable a strong binding with lubricants. The as-prepared superslippery surface shows outstanding repellent ability toward droplets, which can be utilized in various fields such as fog collection [12–14], anti-fouling [15–17], anti-icing [18–20], anti-biofouling [21–23], and fluids transport [24–26]. Superlubricity is widely applied in mechanical engineering field, referring to a state that the friction and wear of moving mechanical systems are negligible [27–29]. A similar strategy—adopting lubricants to smooth the contact interface has been followed in designing superlubricity. Considering the operating conditions of lubricants, the selection criteria remain difference. The adopted lubricants can weaken the solid–solid interactions, preventing the atomic level contact between two opposing surfaces. Experimentally, coefficient of friction (COF) below 0.01 is defined as a superlubricity state [30]. Clearly, making the moving mechanical system work under a superlubricity state is a perfect scenario, which can largely reduce the unnecessary energy consumption as well as engineering materials losses. With the rapid development of mechanical components miniaturization and preciseness, lubrication performance has become increasingly important. The realization of superlubricity provides a good solution to overcome lubrication challenges for a large number of nanotechnologies, such as atomic force microscopy (AFM) [31], micro/nano-electromechanical systems (MEME/NEMS) [32], and other precision instruments [33].

The amazing phenomenon of superslippery and superlubricity (Fig. 1) attracts enormous attention from both academia and industry. Although great progresses have been achieved for superslippery and

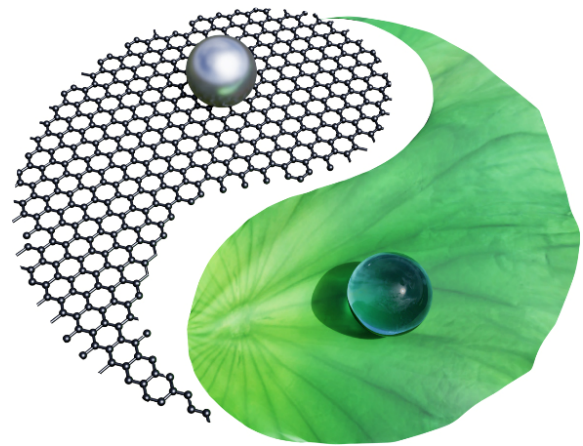


Fig. 1 Schematic illustration of superlubricity surface (left: friction pairs slide freely on the surface of graphene) and superslippery surface (right: liquid droplets move quickly alongside the surface of lotus leaf).

superlubricity, the discussion on the differences and relations between superslippery and superlubricity has not yet explored. Hence, this review tries to explore their differences from the perspectives of the origins, characteristics, and application scenarios. In addition, the designing perspectives for the superslippery and superlubricity surfaces are also compared. We hope the contrastive study of these two concepts will boost the deeper understanding of friction reduction technology.

2 Superslippery

Inspired by the natural phenomenon that water droplet rolls off easily on the surface of lotus leaf, researchers proposed a superslippery surface [34, 35]. The intrinsic liquid-repellent property of lotus is caused by their superhydrophobic surfaces composing of a wax layer and micro-nanostructures [36–38]. The epicuticular wax shows low surface energy, endowing the lotus leaf hydrophobic property. Meanwhile, the micro-nanostructures enhance the surface roughness and make the hydrophobic surface become superhydrophobic. The micro-nanostructures accommodate abundant air medium inside their spaces and act as an air lubrication layer, shifting the contact mode between water droplets and lotus leaf from liquid–solid contact to the liquid–air contact. The bonding between water and air is poorer than that of water and solid substrate, which can facilitate

the rolling back and forth of water droplets on lotus leaf. Motivated by the lotus effect, a series of superhydrophobic surfaces have been developed [39–41]. The sketch map of superhydrophobic surfaces was shown in Fig. 2(a). Although water droplets roll off freely on those surfaces, others, such as organic liquids and complex mixtures with low surface tension fail to roll like water. Hence, Tuteja and co-workers [42] proposed a superamphiphobic surface by designing overhangs on the fluorinated rough surfaces. Figure 2(b) shows the schematic of superamphiphobic surface. The surface overhangs can slow down the wetting of liquid droplets toward the surface by confinement of air inside the local surface curvature. However, the large-scale application of superhydrophobic and superamphiphobic surfaces is impeded by the poor durability, high fabrication costs, and difficulties in maintaining the air cushions. Therefore, it is urgent to develop the other lubricants to substitute air to stabilize the surface.

Liquid lubricants outperform the air lubricant in mature processing technique, anti-pressure capability, and self-repairing ability. Hence, various liquid lubricants have been developed to fabricate superslippery surfaces [43–45]. The seminal work of developing the liquid lubricant as the superslippery surface was inspired by the *Nepenthes* [46]. *Nepenthes* has a digestive organ, which is called pitcher. The pitcher features with peristome structures, as shown in Fig. 3(a). It is reported that directional water transport occurs on the peristome surface due to the multiscale structure of peristome (Fig. 3(b)), endowing peristome the ability to store water from rain or dew [46]. Hence, *Nepenthes's* surface shows superslippery with the aid of water, which can help capture insects. Motivated by the peristome structures of *Nepenthes*, artificial slippery surfaces are designed to cater for the practical application, as schematic shown in Fig. 2(c). Although water droplets can quickly remove from these three

typical superslippery surfaces, their movement modes are different. The movement of liquid droplets depends on the contact area, which is further determined by the interfacial interaction between droplets and surfaces. The water droplets tend to roll off on the superhydrophobic surface and superamphiphobic surface due to the weak liquid–air interfacial interaction [44]. Although most droplets tend to slide on the lubricant-infused surfaces, in reality, the movement of liquids on the lubricant-infused surfaces strongly depends on the viscosities of the two liquids [47]. On a lubricant-infused surface filled by high viscosity lubricant, the droplets tend to roll rather than slide over the lubricant [48–50].

The pioneering work of a slippery liquid-infused porous surface (SLIPS) prepared via infusing Fluorinert FC-70 into Teflon nanofibrous was conducted by Aizenberg and co-workers [11], as vividly shown in Fig. 3(c). The optical images in Fig. 3(d) show that the adopted liquid lubricant demonstrates excellent self-repairing ability. The adopted liquid lubricant features low-surface-tension ($17.1 \text{ mN}\cdot\text{m}^{-1}$), which shows excellent liquid-repellent property against liquids with higher surface-tension. Even after physical damage, the designed SLIPS can quickly restore the liquid repellency ability, as shown in Fig. 3(e). Then, our group designed a series of SLIPSs followed by this groundbreaking work [51–55]. By grafting PDMS onto the surface of ZnO nanorods using ultraviolet irradiating (Fig. 3(f)) and then infused silicone oil as lubricant, the SLIPSs exhibited a superior anti high temperature performance. Attributing to the strong intermolecular interactions between lubricant and PDMS together with the high viscosity of lubricant, the modified surface shows ultralow sliding angle (less than 2°) and excellent boiling water repellency, as shown in Fig. 3(g). The as-constructed material shows excellent water collection ability and the collected water demonstrate low oil content. Furthermore, we

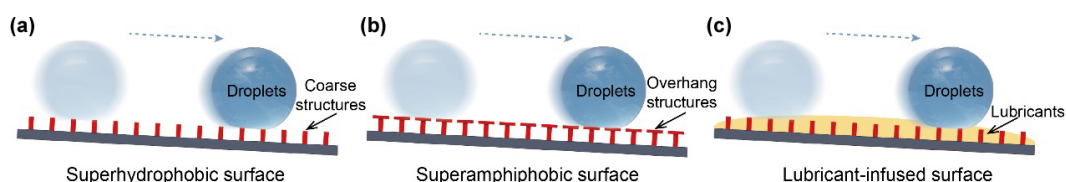


Fig. 2 Sketch map of three typical superslippery surfaces: (a) superhydrophobic surfaces, (b) superamphiphobic surfaces, and (c) lubricant-infused surfaces.

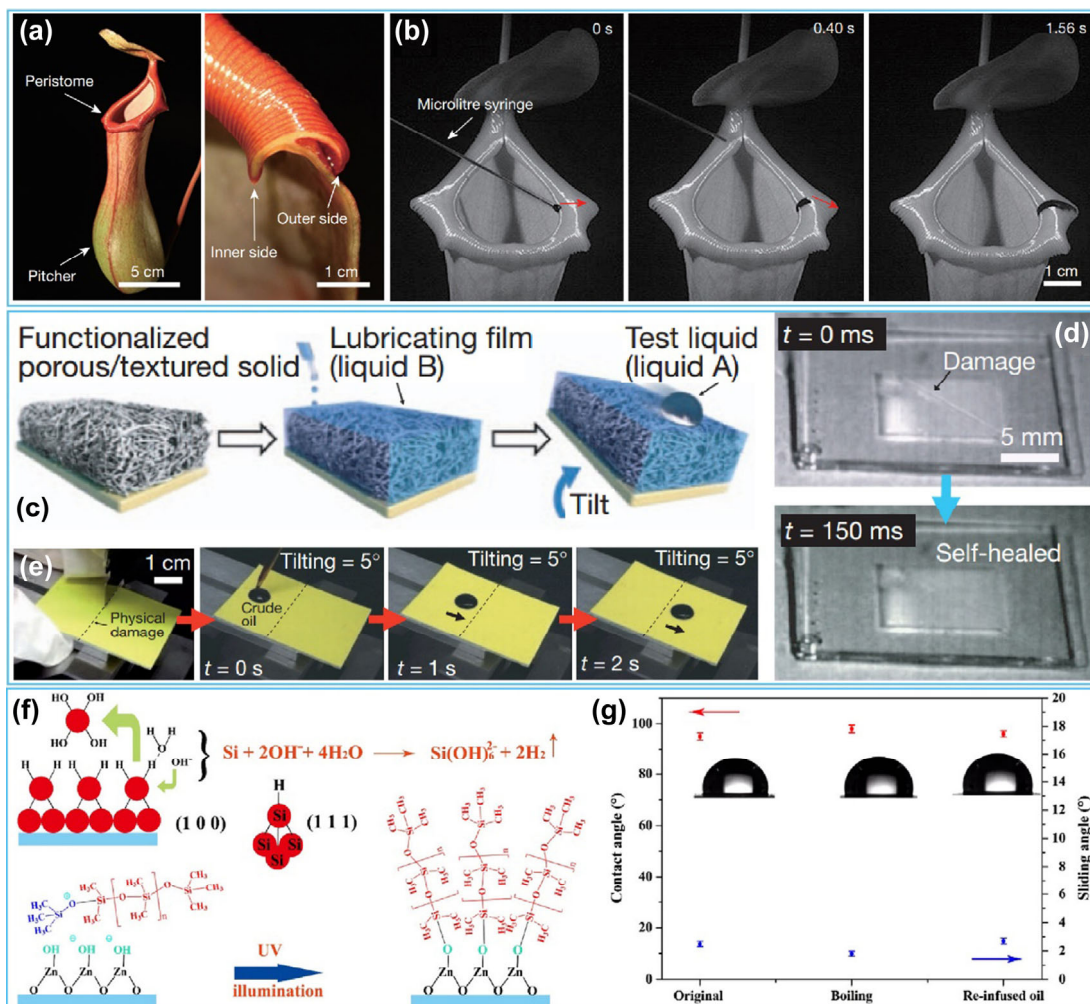


Fig. 3 (a) Optical images of a pitcher (left) and an enlarged image of the peristome (right). (b) Directional water transport on the peristome surface. Reproduced with permission from Ref. [46], © Springer Nature 2016. (c) Schematic images of the preparing process of liquid-infused surface. (d) Self-repairing ability of liquid lubricant. (e) The restoration of liquid repellency ability after physical damage. Reproduced with permission from Ref. [11], © Springer Nature 2011. (f) Schematic process of chemical reaction between PDMS and ZnO. (g) Contact angle and sliding angle of original surface, boiling treatment, and re-infused treatment. Reproduced with permission from Ref. [51], © American Chemical Society 2019.

designed an anisotropic slippery surface by introducing microgroove structure onto the surface of PDMS through a simple template transfer method. The experimental results verify that the as-constructed slippery surface can transport both of water in air and bubbles under water.

However, the volatilization or the migration along with the moving droplets of liquid lubrications shortens the application durability of SLIPS. Replacing the traditional liquid lubricants with nonvolatile ionic liquids, or enhancing the binding between liquid lubricants with substrate, or exploring solid lubricants are considered effective in decreasing the depletion

of lubricant layer [56–58]. In this text, our group fabricated a robust and temperature stable SLIPS by infusing unpolymerized ionic liquids into polyionogel modified porous aluminum oxide [59]. The 3D surface profile images of ionic liquids infused surface are shown in Fig. 4(a). The enhanced interaction between lubricant and substrate and the negligible vapor pressure (below 10^{-10} Pa) ensures the thermal stability (Fig. 4(b)) and shear resistance ability (Fig. 4(c)). McCarthy and co-workers [60] chemically bonded polydimethylsiloxane onto the surface of substrate, avoiding the dissolution or displacement of lubricant by contacting droplets. Atomic force microscope

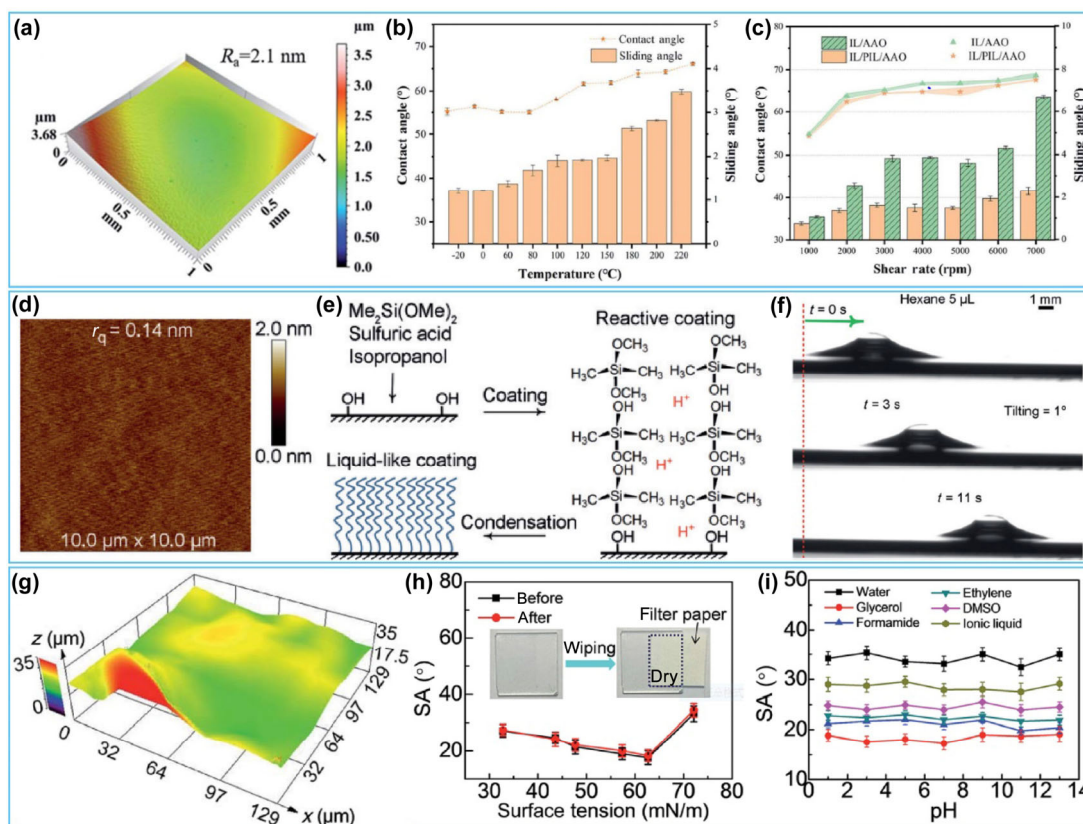


Fig. 4 (a) 3D surface profile images of ionic liquids infused surface. (b) The varies of contact angle and sliding angle as function as temperature. (c) The varies of contact angle and sliding angle as function as shear rate. Reproduced with permission from Ref. [59], © Royal Society of Chemistry 2020. (d) Atomic force microscope topographic image of the PDMS coated surface. (e) The overall process of preparing PDMS coating layer. (f) Optical images demonstrating the mobility of a hexane drop on a tilted PDMS surface. Reproduced with permission from Ref. [60], © WILEY-VCH Verlag GmbH & Co. KGaA Weinheim 2016. (g) 3D surface profile images of paraffin wax layer at room temperature. (h) The varies of sliding angles of all droplets on solid slippery surface before and after wiping with filter paper. (i) pH stability of all droplets on solid slippery surface. Reproduced with permission from Ref. [61], © Royal Society of Chemistry 2018.

images in Fig. 4(d) show the prepared coating layer is extremely smooth. The overall chemical process is shown in Fig. 4(e). The liquid-like coating shows outstanding liquid-repellent property toward liquids with surface tension ranging from 78.2 to 18.4 mN·m⁻¹. A 5 mL hexane drop can quickly slide down the as-formed coating layer tilted by 1°, as vividly shown in Fig. 4(f). Heng and co-workers [61] reported a stable solid slippery surface composing of paraffin wax and a porous film, as shown in Fig. 4(g). The wiping test in Fig. 4(h) shows that the designed solid slippery surface demonstrates the steady lubrication capacity, avoiding of contaminating the contacting droplets. Besides, the coating layer exhibited excellent pH resistance, as convinced by the pH test in Fig. 4(i). Although the measured sliding angle was higher than

the criteria of superslippy surface, their innovative work provided a guidance for designing stable lubricant layer.

In a word, there are three strategies in terms of superhydrophobicity, superamphiphobicity, and lubricant-infused to construct a superslippy surface. Superhydrophobicity uses the air as the lubricant, which can realize the pure collection of liquid free from contamination, but their surface microstructures are instability. Superamphiphobicity outperforms the superhydrophobicity in enabling the simultaneous glide of water and oil droplets. However, superamphiphobicity also shows poor structure stability. Compared with the superhydrophobic surface and superamphiphobic surface, the SLIPS shows the following advantages: a more stable liquid lubrication layer, a simpler

surface modification process, and the self-repairing property of slippery surfaces. Two design principles for fabricating a novel SLIPS should be considered: a certain degree of surface roughness to stick the introduced lubricating liquids, and the immiscible between lubricating liquids and test liquids. Because of the different architectural feature, these three superslippery surfaces show distinct application scenarios. Superhydrophobicity surfaces have applications in such fields as waterproof materials and self-cleaning materials. Superamphiphobicity surfaces can extend the application from waterproof to oilproof, which can be applied in crude oil transportation and industrial/biological processes. Lubricant-infused surfaces can be used in a wider scope, depending on the infused lubricants. Presently, superslippery surfaces are mainly designed for the rapid sliding of droplets. Once the upper objects shift from droplets to solid particles or even huge mechanical components, the designed superslippery surface will inevitably suffer more destruction. In this case, another kind of surface featuring ultralow friction force is needed, which is called superlubricity surface.

3 Superlubricity

The increasing wastage of primary energy resources (about 30%) and the increase in mechanical components (nearly 80%) ruined by unnecessary friction arouse the attention on superlubricity [62, 63]. Superlubricity refers a state that the friction and wear between friction pair is negligible, which means that friction occurs between two absolutely or mathematically smooth surfaces. However, it is impossible to reach the ideal state on a macroscale since there still exist 0.1 nm height differences between neighbor atoms for the smoothest crystal surface. Therefore, we can only try our best to reduce friction by smoothing the contact area or switching the contact interface. Introducing a thin lubricant layer on the mechanical component surface is a reasonable method to reduce friction by switching contact interface. Coefficient of friction (COF) is widely adopted to judge the practical effect of different lubricants. Since it remains a challenge to measure the COF values below 0.001 for

the present technique, herein, the state of COF value that is less than 0.01 is defined as superlubricity [30]. The concept of superlubricity stemmed from a theoretical calculation of Shinjo and Hirano in the early 1990s [64]. Since then, researchers have tried their best to discover superlubricity state experimentally.

Martin and co-workers [65] firstly observed the superlubricity of molybdenum disulphide in ultrahigh vacuum conditions, inferring that the frictional anisotropy during intercrystallite slip contributes to the vanish of friction force. Later, Frenken and co-workers [66] reported the superlubricity phenomenon by recording the friction force between the nanoscale graphite sheet adhered in a tip and the highly oriented pyrolytic graphite at various rotation angle by a novel frictional force microscope, as shown in Fig. 5(a). Figure 5(b) shows that the average friction force is lower than 15 pN, except for two narrow peaks of high friction corresponding to the rotation angle at 0° and 61° . The experimental results agree well with the calculation results originating from a modified Tomlinson model, as shown in Fig. 5(c) [67]. However, it remains a challenge to realize the superlubricity state at microscale due to the effect of contaminants from testing environment. Inspired by the self-retraction behavior of graphite mesas after shearing, Zheng and co-workers [68] fabricated a superlubricity at microscale, as displayed in Fig. 5(d). Driven by the minimization of interfacial energy, the separated flakes spontaneously returned to their original position due to superlubricity. During the self-retraction process, the edges of graphite crystal can wipe the introduced contaminations, guaranteeing the absolutely clean of contact interface so as to achieve superlubricity [69]. The *in-situ* SEM test shows that the self-retraction effect highly depends on the atomic geometries of the contacted surfaces. At certain rotation angles, the flakes demonstrate lock-in states, as shown in the blue arrow of Fig. 5(e). The self-retraction behavior of flakes above at various rotation angles is summarized in Fig. 5(f), showing that the self-retraction happens between lock-in orientations. Sumant and co-workers [70] reported that superlubricity can be achieved on a macroscopic scale with the synergistic effect of graphene and nanodiamond particles. The schematic of superlubricity test is shown in Fig. 5(g). During the shearing process,

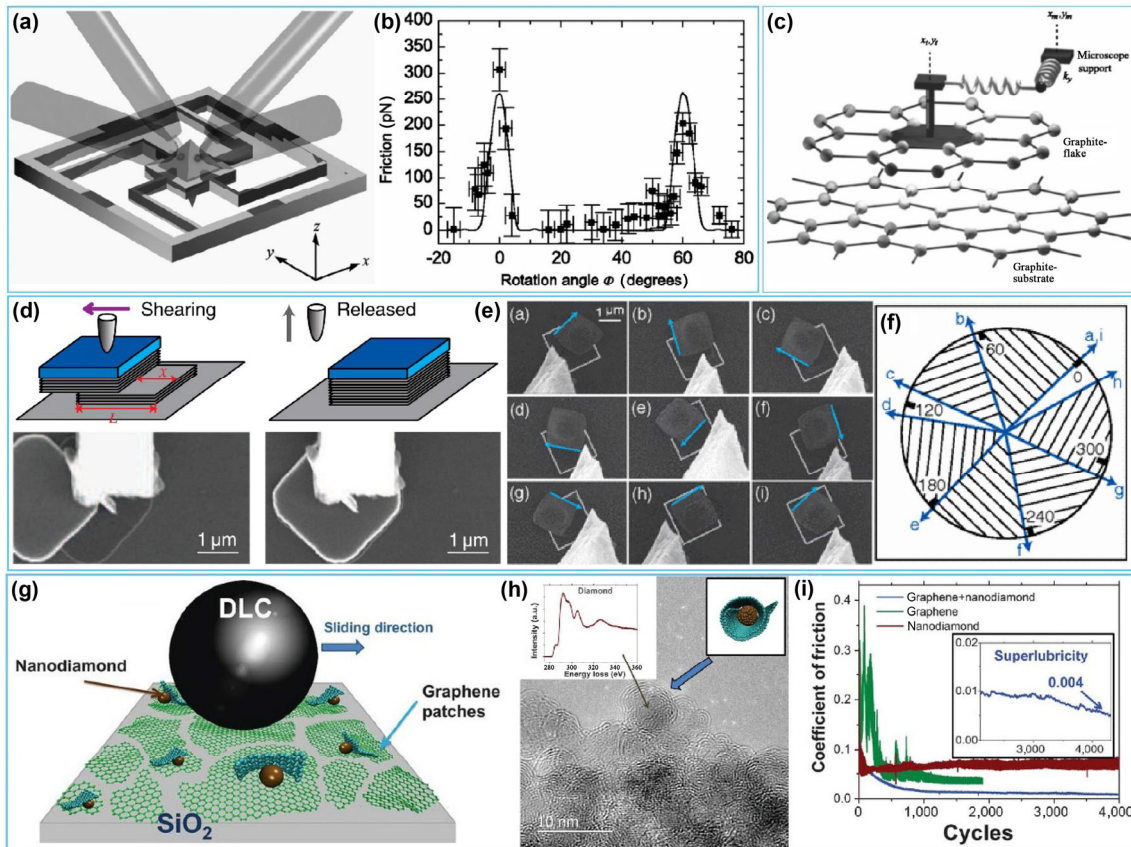


Fig. 5 (a) Silicon tribolever model of the frictional force microscope. (b) Average of friction force as function as rotation angles. Reproduced with permission from Ref. [66], © American Physical Society 2004. (c) Schematic images of the modified Tomlinson model. Reproduced with permission from Ref. [67], © American Physical Society 2004. (d) Schematic images and SEM images of the self-retraction process. (e) SEM images of lock in orientations of graphite flake. (f) Self-retraction behavior of flakes above at various rotation angles. Hatched areas indicate the self-retraction regions, and the arrow denotes the lock in orientation. Reproduced with permission from Ref. [68], © American Physical Society 2012. (g) Schematic of superlubricity test. (h) TEM images of *in-situ* formed nanoscrolls. (i) COF of DLC ball sliding against graphene-plus-nanodiamonds, graphene alone, and nanodiamond alone. Reproduced with permission from Ref. [70], © American Association for the Advancement of Science 2015.

the graphene patches wrap around the nanodiamond nanoparticles, forming a nanoscroll structure, as convinced by the TEM images in Fig. 5(h). The *in-situ* formed nanoscrolls contribute to a reduced contact area by showing an ultralow coefficient of friction of ~ 0.004 , as displayed in Fig. 5(i). Subsequently, various two-dimensional (2D) materials, such as hexagonal boron nitride, molybdenum disulfide, black phosphorus, hydrotaalcites, and other 2D materials, have been developed as solid lubricants [71, 72].

Nanomaterials with different spatial structures, such as 0D, 1D, 2D, and 3D architectures, can be adopted as solid lubricants [73]. 0D nanomaterials including carbon-based nanoparticles [74–76] and Sb nanoparticles [77] mainly take effect on lubrication

attributing to their size effect, which changes the contact mode of friction pair from commensurate contact to incommensurate contact. The reduced contact area significantly minimizes the friction force. The same principle can be used to promote the superlubric state by adopting 1D nanomaterials, such as carbon nanotubes (CNTs). However, the disorder structure affects their lubrication effect when directly used. Presently, the superlubric behavior of double-walled CNTs exists between the inner layer and outer layer due to their weak interplane interactions [78]. In this text, Wei and co-workers [79] reported that superlubricity is realized under ambient conditions in centimeters-long double-walled CNTs. Schematic of the pulling out process and TEM images of the

different part of double-walled CNTs are displayed in Fig. 6(a). The small intershell friction force in Fig. 6(b) demonstrates the macroscale superlubricity of the double-walled CNTs. Besides, the experimental results are coincident with the calculated results, showing the perfect structure of the prepared double-walled CNTs. There are a couple of reasons for the superlubricity of double-walled CNTs. First, incommensurate contact is existed between the shells. Second, the van der Waals interaction between the shells is length-independent. As shown in Fig. 6(c), the shear stress in overlapped area is negligible due to the constant destruction and reorganization

of van der Waals interaction between the inner and outer layers. During the pulling out process, it only needs to overcome the van der Waals interaction at edge section. 2D nanomaterials show their intrinsic lubrication effect due to the low interlayer bonding energy and high intralayer strength. Noteworthily, integrating multiscale nanomaterials to construct a 3D structure is an effective method to cater for the realization of superlubricity in high loading force [80]. For example, Zhang and co-workers [81] reported that the graphitic-like/MoS₂ films with the thickness of about 243 nm show low friction coefficient (about 0.004) and superior wear resistance even under a

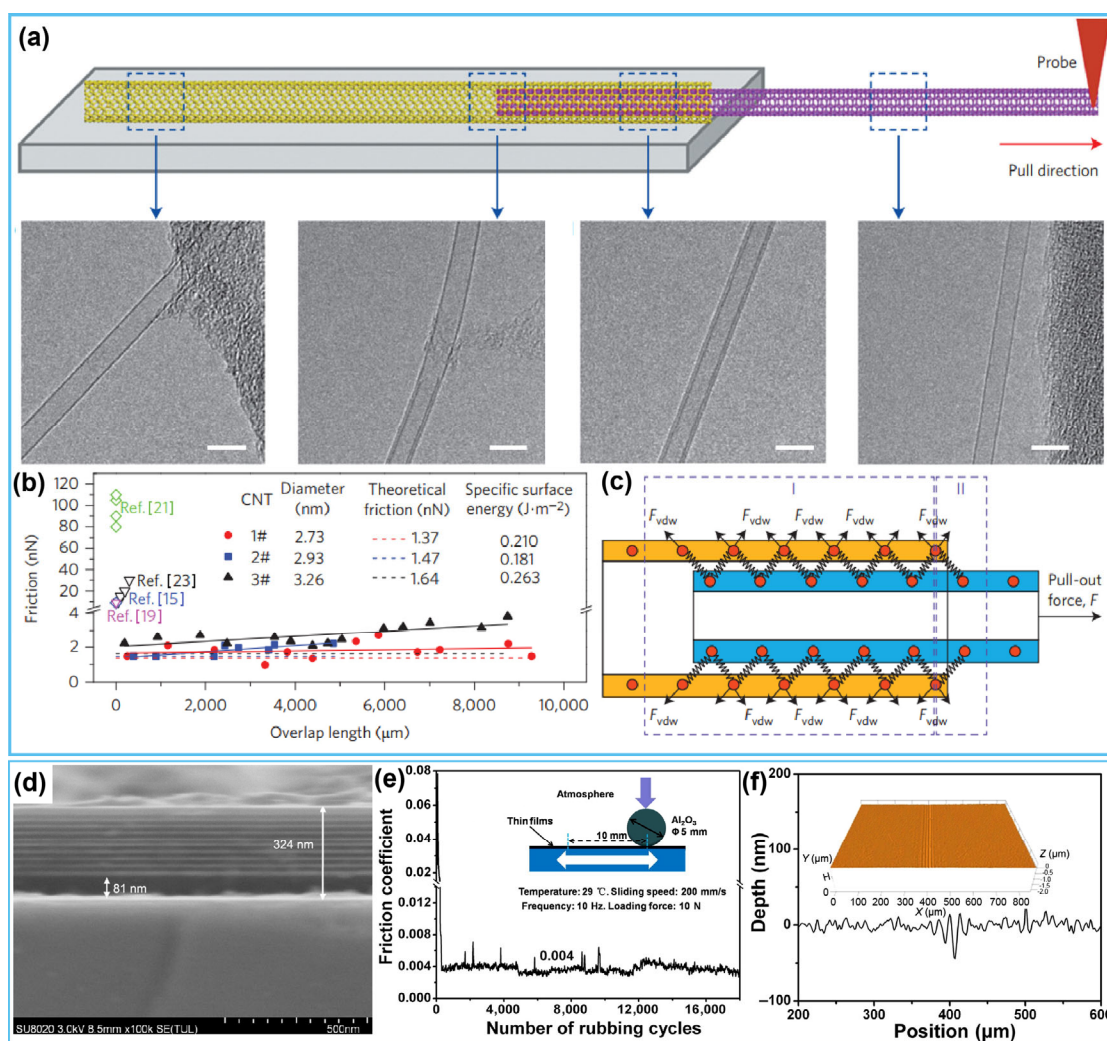


Fig. 6 (a) Sketch map of the pulling out process of the inner layer from double-walled CNTs, and TEM images of different part of double-walled CNTs during the pulling out process. (b) Intershell friction force of three double-walled CNTs with different outer size. (c) Schematic of the interfacial interaction between the inner and outer part of double-walled CNT. Reproduced with permission from Ref. [79], © Springer Nature 2013. (d) SEM image of the prepared 3D hierarchical structure. (e) Friction coefficient and (f) wear track of the as-prepared coating in air under 10 N. Reproduced with permission from Ref. [81], © Elsevier Ltd 2017.

high contact pressure (about 10 N), Figs. 6(d), 6(e), and 6(f).

Despite great achievements, the practical application of solid lubricants in fabricating superlubricity surface is confronted with the challenges of ultrahigh contact pressure and side reactions of lubricants. The increasing contact pressure would alter the existing form of solid lubricants, resulting in the failure of superlubricity. In this context, Luo and co-workers [82] designed an AFM tip decorating with transferred graphene nanoflakes with a thickness about 2.2 nm, as illustrated in Fig. 7(a). At a certain sliding speed ($3 \mu\text{m}\cdot\text{s}^{-1}$) and with a loading force ranging from 0–2,300 nN, the state of superlubricity can be realized, as shown in Fig. 7(b). However, once the loading force exceeds 2,300 nN, the friction force increases rapidly, corresponding to a signal for the failure of superlubricity. During the unloading process, the friction force gradually reduces and superimposes with the measure friction force during the loading process, inferring the structure stability of the decorated graphene nanoflakes. Finite element method (FEM) is applied

to discover the failure mechanism, as shown in Figs. 7(c) and 7(d). The simulation results showed that a lifted region formed ahead of the tip when the deformation reaches 7.7 nm, resulting in the enhanced friction force. The side reaction of solid lubricants is another obstacle to hinder the application of solid lubricants. During the sharp friction process, the elevated temperature and the high chemical activity of oxygen molecules can reduce the structure stability of solid lubricants. Taking tungsten disulfide (WS_2) as an example, the already existed unsaturated bonds in the edge plane and the newly created unsaturated bonds during sliding will constantly react with moisture and oxygen from air, forming WO_3 [83]. The as-formed WO_3 will deteriorate the performance of the lubricants, and even lead to their failure. Luo and co-workers [84] studied the side reaction of hydrogenated amorphous carbon (a-C:H) during the friction process. The result in Fig. 7(e) shows that the COF of a-C:H gradually increases as a function of sliding cycles. The TEM images in Figs. 7(f) and 7(g) show that the bilayer structure keeps stable at dry N_2

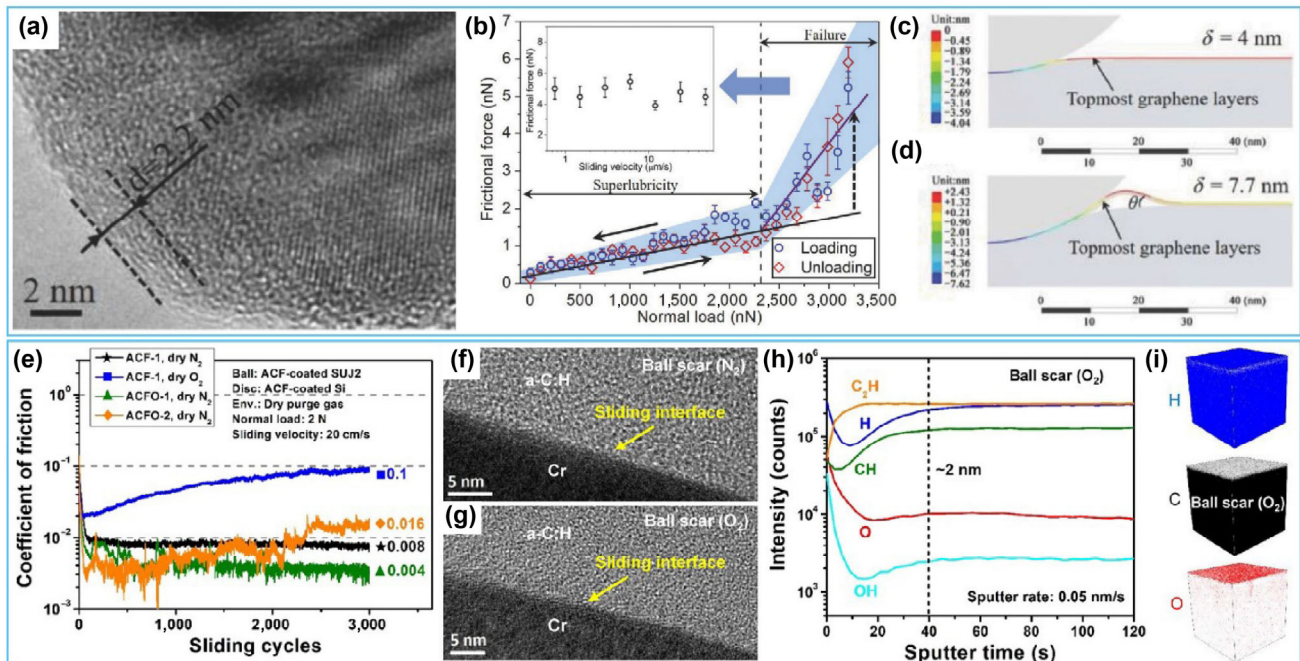


Fig. 7 (a) High-resolution transmission electron microscope (HRTEM) image of the modified silicon tip. (b) Friction force between modified AFM tip and highly ordered pyrolytic graphite (HOPG) at various loading forces. The state of topmost graphene layers acquired from FEM simulation at (c) the deformation equal to 4.0 nm, and (d) the deformation equal to 7.7 nm. Reproduced with permission from Ref. [82], © WILEY-VCH Verlag GmbH & Co. KGaA Weinheim 2018. (e) COF of varied films in dry N_2 and O_2 gaseous atmospheres. (f, g) HRTEM images of sliding interface in dry N_2 and O_2 gaseous atmospheres. (h) TOF-SIMS depth-profiling results. (i) 3D TOF-SIMS images of H, C, O element. Reproduced with permission from Ref. [84], © American Association for the Advancement of Science 2020.

and O_2 atmosphere during friction, indicating the side reaction occurs in the upper carbon layer. The depletion of hydrogen occurs in the topmost 2-nm-thick region in combination with the increase of oxygen-related species such as O and OH in the time-of-flight secondary ion mass spectroscopy (TOF-SIMS) depth-profiling in Fig. 7(h). 3D TOF-SIMS images in Fig. 7(i) further convince the formation of oxygen invaded sublayer. The *in-situ* side reaction changes the chemical composition of solid lubricants and weakens the lubricant effect. Therefore, it is highly desirable to pay more attention to this aspect.

Compared to solid lubricants, liquid lubricants show distinct advantages in compatibility and extensive use from engineering viewpoint [85]. A well-designed liquid lubricant can directly use between friction pairs at ambient temperature on the macroscale. For example, phosphoric acid solution was used to facilitate the superlubricity between silicon nitride (Si_3N_4)

and glass substrate, as shown in Fig. 8(a) [86]. Owing to the electric double layer and hydration effect, the superlubricity can maintain about 3 hours under high contact pressure (the maximum pressure is about 1.6 GPa), as illustrated in Fig. 8(b). Their further research reported that hydrodynamic effect and *in-situ* formed silica layer also contribute to the superlubricity of acid based liquid lubricants [87, 88]. Phosphoric acid superlubricity is also applicable to other friction pairs, such as Si_3N_4/SiO_2 , ceramic/sapphire, and sapphire/ruby [87, 89, 90]. However, the accumulated pressure and heat from friction will inevitably damage the liquid based tribofilm [91–93]. Therefore, it is urgent to strengthen the protective film to resist high contact pressure in fabricating superlubricity surface. Introducing a small amount of 2D nano-additives into the liquid lubricants is proven effective in enhancing the strength of the protective film [94–96]. During the friction process, the 2D materials

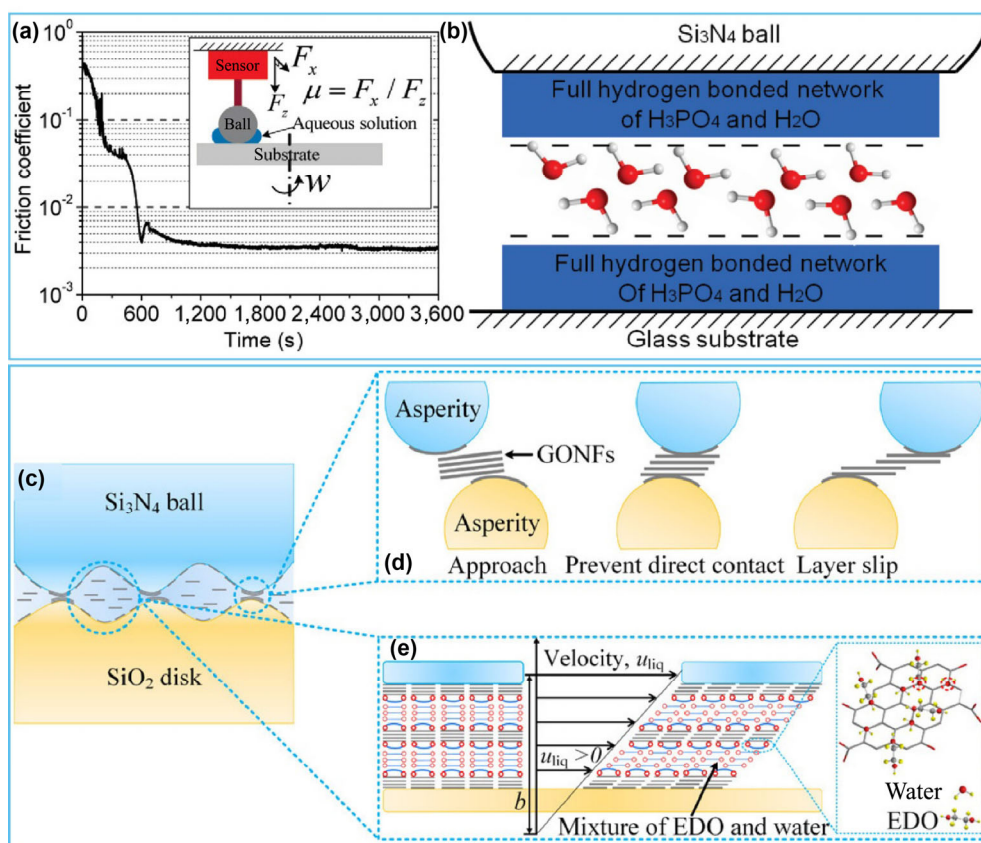


Fig. 8 (a) Friction coefficient with time between Si_3N_4 ball and glass slide under phosphoric acid solution. (b) Sketch map of the *in-situ* formed structure on the two surfaces. Reproduced with permission from Ref. [86], © American Chemical Society 2011. (c) Model of the measurement system. (d) Proposed mechanism at asperity contact region during friction. (e) Proposed mechanism at liquid-contact region during friction. Reproduced with permission from Ref. [97], © American Chemical Society 2018.

absorb on the solid surface of friction pair to form a smooth and robust protective layer. For example, Li and co-workers [97] investigated the lubrication effect of a mixed solution of graphene oxide and ethanediol between Si_3N_4 ball and SiO_2 disk, as illustrated in Fig. 8(c). During friction, the absorbed graphene–oxide nanoflakes on the friction pair surfaces can prevent the direct solid–solid contact between surface asperities, as shown in Fig. 8(d). Meanwhile, the hydrated graphene oxide–ethanediol networks formed via hydrogen-bond interactions result in an ultralow shear stress at liquid–contact region, as vividly illustrated in Fig. 8(e). Benefiting from the synergistic effect of graphene-oxide and ethanediol at Si_3N_4 – SiO_2 interfaces, a robust macroscale superlubricity state is realized. In brief, due to the protective effect of solid lubricants toward substrates and the excellent lubrication effect of liquid lubricants, at the present stage, solid–liquid combined lubricants show more notable advantages than pure liquid lubricants or pure solid lubricants in load-bearing capacity improving, wear reducing, and running-in time shorting [94].

In all, the key to realize superlubricity is high polished surface, low contact pressure, and low rotational speed, however, the current researches are still lag far behind the demand of practical application. Therefore, it remains a crucial issue in low-friction development to realize superlubricity under rigorous conditions. Adopting advanced engineering materials with high temperature resistance, fatigue resistance and, permanent deformation resistance, and enhancing machining precision condition to prepare low defect friction pair is a fundamental condition. Developing high performance lubricants is an eternal theme. Presently, pure liquid lubricants show their advantages due to their strong permeability, chemical stability, and matured process techniques. However, the as-formed liquid-state tribofilms are vulnerable to the increased contact pressure. Solid lubricants can overcome the above challenges in some extent, but their inner structure will still suffer from broken by the increasing contact pressure and the *in-situ* generated high temperature. Solid–liquid hybrid lubricants show outstanding advantages at present. Decorating the friction pair with solid-state materials is ultra-important to *in-situ* formed robust protective

layer to further guarantee the long effectiveness of superlubricity. Infusing a small quantity of liquid lubricants into the friction pairs to reduce the wear of protective layer during friction is absolutely necessary. Besides, tribochemical reactions are another obstacle because of their destructive effect on the introduced lubricants. From this point, inert liquids such as siloxanes or ionic liquids are the reasonable candidates as liquid lubricants. With the combined effect of mechanical processing and lubrication system, the realization of superlubricity under severe conditions is no longer far away.

4 Connections and differences

Overall, the use of lubricants is the key to fabricate superslippy and superlubricity surface. The lubricants can reduce the frictional resistance, smooth the contact surface, and decrease friction and wear between mechanical components. The commonly lubricants contain gaseous, liquid, and solid lubricants. However, superslippy and superlubricity show distinct differences in the following three aspects.

From the view of application scenarios, superslippy surfaces are mainly applied to regulate the movement behavior of liquid droplets on a solid surface, while superlubricity surfaces are mainly applied to reduce the friction and wear between two mechanical components. Therefore, the underlying force exerted on the lubricants varies. For the superslippy surface, lubricants are aimed at reducing the friction of droplets on the corresponding surface by smoothing the contact surface. The fraction force of droplet gravity on lubricating oil is negligible; thus, the lubricating oil layer is statical and stable. The thickness of lubricating layer is in line with lubricant dosage. The permanent lubrication can be maintained when a high dosage lubricant was introduced. Locking the introduced lubricants is a crucial task in fabricating superslippy surface. As for superslippy surfaces, there mainly exist two interfacial interactions: substrate/lubricant interfacial interaction and lubricant/droplet interfacial interaction. The former is mainly depended on capillary forces, which can be strengthened by increasing surface roughness. Recently, chemical bonds are also adopted to reinforce the substrate/lubricant

interfacial interaction. The latter mainly refers to the intermolecular force, namely Vander Waals force, between droplets and lubricants. During the superslippery process, these two interfacial interactions almost keep constant until the lubricant layer loses effect. Strengthening the substrate/lubricant interfacial interaction and weakening the lubricant/droplet interfacial interaction is the key point in designing superslippery surfaces. Since superlubricity surface mainly refers to two adjacent mechanical components, the interfacial interaction between lubricants and solid substrates is extremely important. As for superlubricity surfaces, there exist two processes during friction: ruining-in process and steady process. During the ruining-in process, extremely complex tribochemical reactions take place on the substrate/lubricant interfaces. Thus, there exists multiple chemical/physical interfacial interaction between lubricant and substrate. During the steady process, the interfacial interaction between lubricants and substrates is the same as superslippery surfaces. Besides, the lubricants face the external loading force. The ever-increasing loading force from the friction of adjacent mechanical components seriously affects the stability of lubricating layer.

The difference application scenarios for superslippery and superlubricity surface also affect the choice of lubricants. For superslippery surface, air as a costless and environmentally friendly lubricant is adopted. However, the complicated surface structure requirements and the poor durability of surface structure hinder its practical application. Solid lubricants outperform gas lubricants in durability, but the exploration of slippage effect remains a challenge at present stage. Liquid lubricants are the most welcomed lubricants due to their excellent sliding effect, self-healing property, wide application scope, and undemanding surface structure. However, liquid lubricants suffer from the puzzle of volatilization and decomposition under high operating temperature. Therefore, it seems that solid lubricants featuring 2D structure will be the mainstream of superlubricity in future. Likewise, solid lubricants suffer from the structural damage under high temperature and the side reaction between created unsaturated bonds and air. Inert gases are optional choice in the near future

in preparing superlubricity surface due to their costless, eco-friendly, as well as protective effect toward metallic materials [98].

Another significant difference for superslippery and superlubricity surface is their failure mechanism of lubricants. For the superslippery surface, liquid lubricants are widely used and they face the following challenges including lubricant's depletion, lubricant's aging, and lubricant's contamination. The main causes for the lubricant's depletion are the inevitable evaporation of small organic molecules and the removal along with the moving droplets. The intrinsic poor weather resistance of organic liquid lubricants and the constant pollution from air contaminants also deteriorate the lubrication effect even make them lose efficacy. Therefore, it is urgent to develop proper substrates to lock the lubricants as well as suitable lubricants with low evaporation rate and excellent weatherability to fabricate high performance superslippery surface. For the superlubricity surface, surface cleanliness of friction pairs is an essential prerequisite. During friction, the thin lubricating layer faces the toughest test of high temperature arising from the drastic friction of working parts. The increased working temperature will aggravate the evaporation and aging property of liquid lubricants. Functional additives are introduced to delay the evaporation and aging of liquid lubricants. Solid lubricants show superiority in structural stability, but they face the issues of the chemical bond breaking of internal crystalline structure as well as the side reaction between the ensuing created active sites and atmosphere. In all, the lubricants in superslippery surface face the challenges from their working environment, while the lubricants in superlubricity surface face the challenges from high contact pressure and the ensuing created high temperature during friction. Although great achievements in both subjects are achieved, additional research is needed before application.

Although there exist differences, the design principles of superslippery and superlubricity surface can inspire mutually. Presently, the design criterion of superslippery and superlubricity is different, making these two surfaces demonstrate distinctly different. Typical superslippery surface infusing with liquid lubricants shows a series of advantages such as

anti-fouling ability, while the durability is a challenge. Typical superlubricity surface decorating with 2D solid lubricants shows excellent weatherability, while the cleanliness is hard to sustain. Fabricating a surface featuring superslippery and superlubricity is a reasonable choice, since the drawbacks of superslippery and superlubricity surface can be canceled each other out. In future, the fabrication of low friction surface needs overall consideration to co-ordinate the features of superslippery and superlubricity surface.

5 Summary

Reducing the unnecessary friction is a hot topic from the viewpoint of energy conservation and pollution reduction. Constructing superslippery surface and superlubricity surface is the most feasible method to realize the friction reduction. The key point in fabricating these two special surfaces is the rational use of lubricants, such as gas lubricants, liquid lubricants, and solid lubricants. Three strategies regarding superhydrophobicity, superamphiphobicity, and lubricant-infused was adopted to design superslippery surface. However, both of the superhydrophobicity and superamphiphobicity have the issues of poor structure stability. SLIPs show superiority in structure stability and preparing process, but more attention should be paid on the loss during the prolonged use. Liquid lubricants and solid lubricants are proven effective in fabricating superlubricity surface. However, there exists a challenge of the volatilization and decomposition for liquid lubricants under high operating temperature. By contrast, solid lubricants can resist relative high temperature and high pressure. Despite the immature research on gas lubricants at present stage, the merits of gas in costless and environmentally friendly attract much attention. The design of superslippery surface and superlubricity surface in the near future should consult the three principles in terms of the underlying force exerted on the lubricants, the choice of lubricants, and the failure mechanism of lubricants. Ultimately, fabricating a well-designed surface simultaneously fulfilling the criteria of superslippery and superlubricity is the eternal pursuit in low-friction development.

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