



Electrotunable interfacial friction: A brief review

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ABSTRACT

Using different external stimuli to control interfacial friction, rather than just pursuing low friction, is a highly attractive research regime due to its economic and scientific importance. One option to achieve such a goal is to use external stimuli that modulate the energy dissipation pathways. In particular, electric stimuli such as surface potential has gained remarkable interest for two reasons: Electrotunable friction has the potential for real-time, *in situ* manipulation of friction, and external electric stimuli is relatively easy to apply and to remove for reversible change. In this review, we explore the emerging research area of electrotunable friction mainly under the boundary lubrication situation, when the contacting surfaces are separated by a molecularly thin layer, reviewing typical achievements from experiments using electrochemical atomic force microscopy and modified surface force balances, as well as molecular dynamics simulations. Additionally, we explore the theoretical and practical challenges that may need to be tackled in the future.

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1. Introduction

Friction is the energy dissipation when two or more surfaces are in contact and in relative motion, often leading to undesirable energy consumption, surface damage [1], and disease such degenerative osteoarthritis [2]. Although the record of reducing friction could be dated back to 3000 BC, our understanding of friction starts much later, by the phenomenological Amonton's law [3] that describes the linear relation connecting the normal load F_n and dynamic friction F_s , as $F_s = \mu F_n$, where μ is the friction coefficient. Surprisingly, such simple scale relation, originated from measurements between dry rough solid surfaces, works well at describing the majority of rubbing pairs, involving both dry and lubricated; and the friction coefficient μ is still the most useful parameter to characterize the function of lubricants [4].

The early work between dry surfaces by Euler and Columb [5,6] suggested that friction coefficient μ is the maximum mean slope of the asperities, rather than the contact area. However, Hertz [7] pointed out that the contact area A between non-adhesive asperity contacts scales as $F_n^{2/3}$ with the assumption of elastic deformation, which is inconsistent with the observed linear relation. Bowden and Tabor [8,9] explained the inconsistency by assuming the

plastic deformation of asperity contacts, which indicates that contact area $A \propto F_n$. Another explanation was proposed by Greenwood [10]: When assuming that the height of asperities obeys Gaussian distribution and non-adhesive asperity contact, the contact area will scale to the normal load. Such argument is highly model dependent, due to the assumptions that asperity contacts occur between rough and ideally flat surfaces, and the height of asperities obeys Gaussian distribution. The test and analysis of friction, in terms of Amonton's law, in different scales are still an interdisciplinary and attractive topic, as discussed later.

The study of friction between lubricated surfaces, which involves two surfaces separated by a finite layer of liquid, is a topic of great interest due to its application in engineering. One good description for such system is to imagine two simple dry surfaces are in contact and a pulling force is applied to one of the surfaces. Initially, as the pulling force increases, the relative motion will be first hindered by static friction, as described by Morin in 1833 [11]. However, with an increased force, the relative sliding, mediated a liquid layer, occurs and the friction becomes velocity-dependent, as observed by Reynold [12]. A more systematic study in the low shear velocity regime was conducted by Stribeck [13], and the results are now known as the Stribeck diagram, which divides lubrication situation three scenarios [14]. The region of boundary lubrication, where the friction coefficient μ exhibits a plateau at lowest speed (below *ca.* $10^2 \mu\text{m/s}$ [15]), is controlled by the intermolecu-

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lar forces between surface-attached molecules at so-called “asperity contacts” [16–18]. As the shear velocity increases, the friction coefficient μ starts to decrease, as the hydrodynamic lubrication starts to build up and limit the contact between such boundary layers [19]. At higher speeds, μ increases with shear speed due to the increasing shear stress of the lubricants.

In this brief review, we will primarily focus on the realm of boundary lubrication, in which the intermolecular forces are influenced by external electric stimuli, through the charged or dipolar structures carried by the lubricants. Therefore the friction coefficients are modulated. The other external stimuli, such as solvent polarity [20–22], temperature [23–25], ionic strength [26,27], light [28,29], pH [30], are also well studied but will not be included in this review. The experiment setups to induce external electric stimuli will be described briefly in the second section. In the third and fourth sections, typical examples will be given to show the friction manipulation between bare and modified surfaces and their mechanisms. Then the main challenges of calculating the external electric field will be described in the fourth section, followed by the conclusion and outlook of such electric stimuli-responsive friction manipulation materials.

2. Experimental configurations

Conductive surfaces, such as smooth metal [31,32], graphene (bare or modified) [33], semi-conductive surfaces [34], and conductive glasses [35], of which the surface potentials are controlled externally, are required to induce external electric stimuli into the system. Depending on the configuration used to manipulate the surface potential, the friction could be measured symmetrically using a two-electrode configuration, or asymmetrically using a three-electrode configuration. In the two-electrode configuration, two similar conductive surfaces (electrodes) are facing each other, with a potential bias applied between them; thus, the actual surface potentials of the electrodes are not clear, and both electrodes are working and counter electrodes with respect to each other [36]. A third electrode, of which the potential is constant at a given temperature (so-called “reference electrode”) [37], is induced into the system to determine the potential of the working electrode, forming a three-electrode system including a working electrode, a reference electrode and a counter (or auxiliary) electrode [38]. The friction between the working electrode and another surface that is usually isolated from the circuit could be measured, therefore called asymmetric measurement (or “asymmetric polarization”), or the two contacting surfaces are both used as working electrolyte, thus called symmetric measurement (or “symmetric polarization”) [39]. It is important to mention that the electric field is essentially zero at the midplane of symmetric polarization configuration, as the symmetric potential distribution in the gap. These two configurations could be applied to different apparatuses, measuring the friction on different scales, which will be discussed below.

2.1. Atomic force microscope (AFM)

Atomic force microscopy (AFM) is a force-based scanning probe technique in which a sharp tip, attached to a cantilever, is moved across the specimen surface while in contact, noncontact or intermittent contact (tapping mode). The tip-specimen normal interaction will bend the cantilever vertically, and such bending is recorded by the displacement of the reflected laser from the cantilever (Figs. 1A and B) [40,41], therefore generating the topography at the height accuracy <0.1 nm [42] and lateral accuracy of 10–50 nm depending on the setup [43,44]. The lateral displacement of the laser beam along the scan direction implies lateral frictional forces by the (Figs. 1C and D) [40,45].

A bias potential can be applied between the probe and the substrate using a two-electrode configuration (Fig. 1E), which is named “Conductive-AFM (C-AFM)”, as such setup is used widely in measuring the current between tip and substrate [41] and extensively used in the surface characterization of electrodes in research of batteries [46–48]. It is important to mention that in the friction measurement, usually the voltage applied is limited carefully, usually within the “ideally polarized region”, in which the current is provided by the motion of counter ions in the electric double layer (EDL) [49–52], to avoid the electrochemical reaction of confined lubricants, especially when measuring between modified surfaces.

One possible three-electrode configuration modified AFM is shown in Fig. 1F, in which the substrate (sample) is the working electrode [53]. Another typical setup is that the substrate is isolated from the circuit, while the tip is used as the working electrode [54–56]. The application of such configurations, similarly to C-AFM, is in the *in-situ* characterization of electrode surfaces, where the current from redox reactions plays an important role [55,57]. However, in the friction measurements, the range of applied potential is limited for the same reason mentioned above.

The advantage of modified AFM is that the real-time topography could be acquired together with the frictional force signals when an electric field is applied [58]. However, a sharp tip is required to ensure spatial resolution, leading to sample damage [59], especially when the substrate is covered by soft organic layers like liposomes [60–62]. Using colloidal tips, made of commercial silica particles or metal beads from the arch-etching technique [52,63], could avoid such damage while losing the spatial resolution. Another disadvantage is that the electric field, formed between the flat substrate and atomically or nanoscale sharp tip, is not uniform, causing tip discharge which limits the accuracy of results [64].

2.2. Surface force balances (SFB)

Compared with AFM, SFB could provide a much larger contact area and absolute separation of sliding pairs for friction measurement. The conventional SFB setup (Fig. 2A) is mainly composed of two fused-silica lenses in cross-cylinder configuration, two sets of springs for the measurement of normal and lateral forces, and a sectorized piezo tube (PTZ) [65,66]. A beam of white light is shined through and the interfered light beam between two curved back-silvered mica surfaces is then projected into a spectrometer, in which the wavelengths of fringes of equal chromatic order (FECO) are measured, determining the separation D between two surfaces [67] with 0.1 nm resolution [68,69]. Normal and lateral motion, provided by the sectorized PTZ, will bend the normal and shear leaf spring sets (spring constants K_n and K_s , respectively), of which the amplitudes of normal and shear motion, ΔD and Δx , are monitored through the wavelengths of FECO and the air-capacitor probe. Then the normal interactions F_n and shear forces F_s could be calculated accordingly as $\Delta F_n = K_n \Delta D$, $F_s = K_s \Delta x$.

Due to its atomic smoothness and relative easy preparation, back-silvered mica surfaces are used in conventional SFB measurements [70]. However, external electric stimuli could be only induced using conductive materials, such as metal or graphene, which is enabled by the template stripping method (Fig. 2B) [71–74], since this method assures the large area and low roughness of the prepared surface [32]. Generally, a sheet of atomically smooth material, such as mica, is prepared as the template (step i, Fig. 2B). Then a layer of conductive material, such as gold will be deposited (step ii, Fig. 2B). The template, together with the deposited material will be fixed to the substrate (step iii, Fig. 2B). The template will be finally gently peeled to expose the smooth surface of deposited material (step iv, Fig. 2B). The acquired surfaces could be directly used in two/three-electrode configuration, as shown in Figs. 2C and E [75,76]. It is important to mention when two differ-

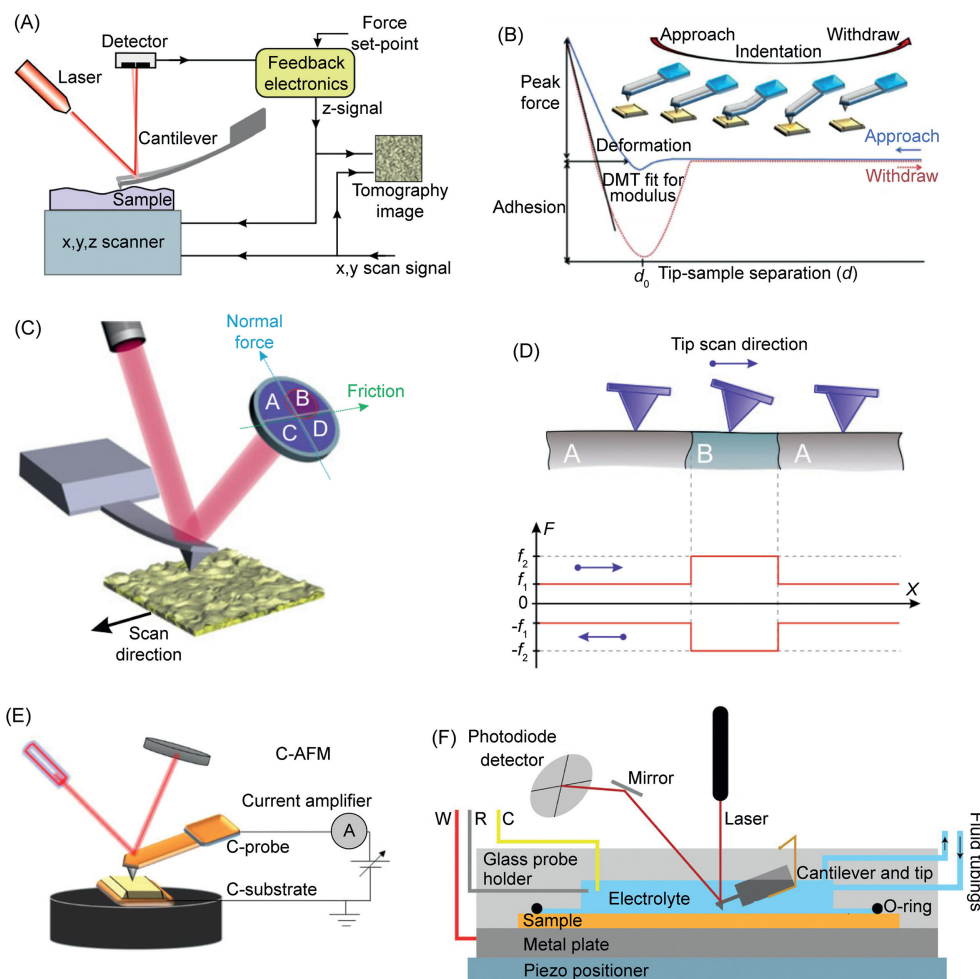


Fig. 1. Different AFM setups for the measurement of topography and lateral frictional forces. (A) Typical AFM configuration showing the control loop, the deflection, and the signal generating process. A reflected laser beam, of which position displacement due to cantilever bending caused by the tip-sample interaction is recorded, from the cantilever is collected by the detector to generate the topography image of surface. Reproduced with permission [40]. Copyright 2019, Springer Nature. (B) Force-separation curve between tip and samples that separates different modes of AFM. Depending on the working mode, the tip-sample separation d is different: For contact mode, $d < d_0$ (d_0 is the and is controlled in the linear regime of approach force curve; For tapping-mode, $d \gg d_0$, and the amplitude of motion is larger than d ; In non-contact mode, $d \approx d_0$. Reproduced with permission [41]. Copyright 2021, John Wiley and Sons. (C) Mechanism of force measurements. The forces are measured by the distortion of cantilever. Reproduced with permission [40]. Copyright 2019, Springer Nature. (D) Lateral force caused axial distortion of the tip and the force curves. Reproduced with permission [40]. Copyright 2019, Springer Nature. (E) The two-electrode configuration (C-AFM), in which the bias voltage is between tip and substrate. Reproduced with permission [41]. Copyright 2021, John Wiley and Sons. (F) The three-electrode configuration, in which the sample is usually the working electrode (EC-AFM). Reproduced with permission [53]. Copyright 2021, John Wiley and Sons. In two/three-electrode configurations, electrodes could be grounded to provide a zero potential.

ent surfaces (so-called “asymmetric”, Figs. 2C and E) are mounted to face each other, the calculation of separation from FECO is different from symmetric systems [67] and the “multilayer matrix method [77]” should be used. The reflective silver layer could also be used directly as electrodes, as shown in Fig. 2D [78]; however, the cross-gap electric field could hardly be determined, as discussed in Section 5.

As mentioned above, the typical contact area in the SFB experiments is roughly $10^3 \mu\text{m}^2$, which is much larger than the AFM (at *ca.* 10^2 nm^2 for a commercial tip and at *ca.* 10^3 nm^2 for a colloidal tip) [79,80]. The difference, decreasing the normal pressure of measurement, could lead to the scale effect in the measurement [79]. Meanwhile, the difficulty of the SFB experiment and the molecularly smooth requirement could also hinder the application of SFB in research.

2.3. Tribometers

Modifying tribometer is relatively easy since surfaces in the macroscale are easy to prepare and have a relatively large space for

modification. However, compared with well-defined nanometer-scale gap in AFM and SFB, the relatively rough surface [81,82] in tribometers suggests that the lubrication paradigms in such experiments are the mixture of boundary lubrication, which occurs near the asperities, and hydrodynamic lubrication, where the surface separation is far beyond the molecular size of lubricant molecules [83,84]. Therefore, the measured friction coefficient μ could hardly be directly connected to the information of confined lubricant molecules, as discussed below in Sections 3 and 4.

As an example, the typical modification with two and three electrode-configuration on a ball-on-disc setup is shown in Fig. 3A [85]. Different configurations, such as pin-on-disc [86] or disc-on-disc [87], could be used but will not be discussed here since their designs are similar. Generally, the modification is similar to the AFM and SFB: Two contacting surfaces are directly connected to a potentiostat in a two-electrode configuration (Fig. 3A), and usually, only one surface in the contacting pair will be used as a working electrode of which the surface potential will be controlled, in the three-electrode configuration (Fig. 3B) [88], similar to the AFM and SFB.

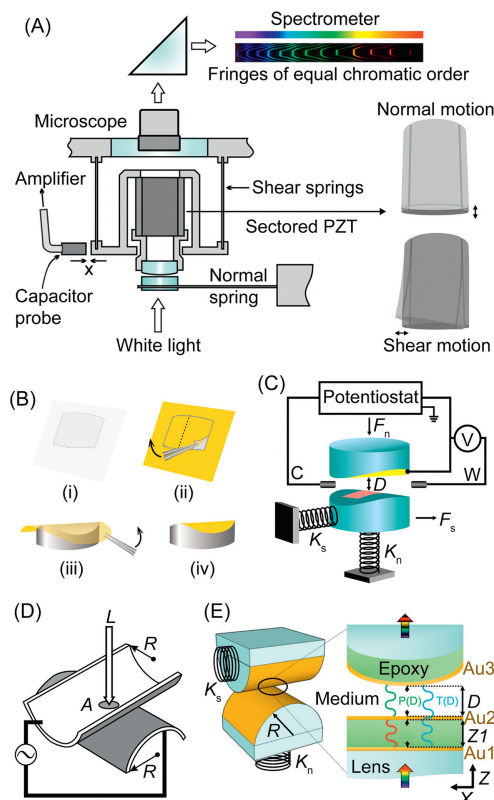


Fig. 2. Schematic of SFB and the modification with two/three-electrode configuration to induce electric stimuli. (A) The novel SFB setup. Reproduced with permission [66]. Copyright 2007, American Chemical Society. Two back-silvered atomically smooth mica surfaces are mounted in cross-cylinder geometry and a beam of white light is projected through, enabling the measurement of separation through fringes of equal chromatic order (FECO). The sectorized piezo tube (PZT) generates the normal and shear motion, so that the normal and lateral forces could be measured through motion-induced bending of spring sets. (B) Schematic of preparation of molecularly smooth metal surfaces using template stripping method. Reproduced with permission [74]. Copyright 2021, AIP Publishing. Single crystal mica facets are cleaved and used as template (i), then a layer of metal is evaporated on the template (ii), then fixed to the fused silica lens using glue, and finally the template is stripped off (iii), exposing the smooth metal surface (iv). (C) Three electrode configurations, where molecularly smooth metal surface is used as the working electrode. Reproduced with permission [75]. Copyright 2018, Springer Nature. (D) Two-electrode-modified SFB. The reflective silver layers on the backside of mica are used as electrodes. Reproduced with permission [78]. Copyright 2012, American Physical Society. (E) Two metal surfaces prepared using template-stripping method are used as electrodes in two-electrode-modified SFB. Reproduced with permission [76]. Copyright 2018, AIP Publishing.

The range of surface potential in modified tribometers is not limited to the “ideally polarized regime” in the study of corrosion and wear performances of the surface [86], and other techniques, such as optical/fluorescent microscope [85,89], attenuated total reflection Fourier-transform infrared spectroscopy (ATR-FTIR) and Raman spectrometer [90] are added to the setup for the *in situ* characterization, which is almost impossible to achieve in modified AFM and SFB. Meanwhile, it is essential to mention that the cross-gap electric field in a modified tribometer will be much smaller and non-uniform compared with AFM and SFB, due to the roughness of contacting surfaces and relatively large gap.

3. Friction manipulation between bare surfaces

Two methods are reported to achieve electro tunable friction manipulation between bare surfaces, depending on whether an electrochemical reaction, usually oxidation, occurs on the surface. Within the range of “ideally polarized region” (*i.e.*, no electrochem-

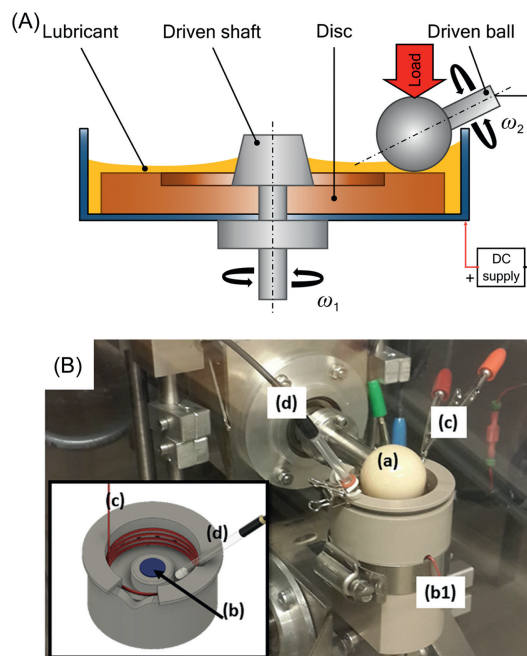


Fig. 3. Modified tribometers using ball-on-disc setup. (A) Typical two-electrode configuration is often achieved through connecting two surfaces to a power supply while immersing both surfaces in the lubricant. Reproduced with permission [85]. Copyright 2020, Springer Nature. (B) Three-electrode-modified tribometer. Three electrodes (b—working, c—counter and d—reference) are immersed in the lubricants and the potential of working electrodes are controlled by a potentiostat (not shown), while the other surface (the ball surface, a) is insulated from the circuit. Copied with permission [88]. Copyright 2019 Elsevier. The load could be applied directly, or through a lever (b1).

ical reaction), friction manipulation is achieved by the rearrangement of confined charged or dipolar species. The electrochemical reaction (usually surface oxidation) will occur when the potential goes beyond the “ideally polarized range” and the energy dissipation changes accordingly, changing the friction coefficient. We notice that the electron-phonon coupling of 2D materials, such as graphene and MoS₂ could be modulated by a bias voltage, through which the friction in atomic scale, such as between AFM tips and such layers could be modulated [91,92]. This field is a large attractive field by itself so that beyond the traditional scope of lubrication and friction of this brief review.

3.1. Friction manipulation without electrochemical reaction

The underlined mechanism for such friction manipulation is that the external electric stimuli, usually electric potential, induce the cross-gap electric field that change the structure of confined lubricants, therefore varying the way of energy dissipation and changing the friction coefficient. Interestingly, to the best of our knowledge, the studies of friction manipulation using the mentioned mechanism are primarily done in aqueous media, where simple ions or polyelectrolytes used, or in ionic liquids, which are melted salts at room temperature.

The fluidity of water under confinement is an essential factor that could, in principle, change the interfacial friction. Unlike organic liquids showing solid-like layered structures [93,94], the fluidity of water is retained under nanoconfinement, with a viscosity of three times the value of bulk, as shown by Raviv *et al.* [95,96] using a conventional SFB. Moreover, such fluidity is also observed in the molecular dynamics (MD) simulations by Leng *et al.* [97,98], while the viscosity of the confined water layer is about 5–16 folds of the bulk value [97]. Compared with the factor of 1–3 measured

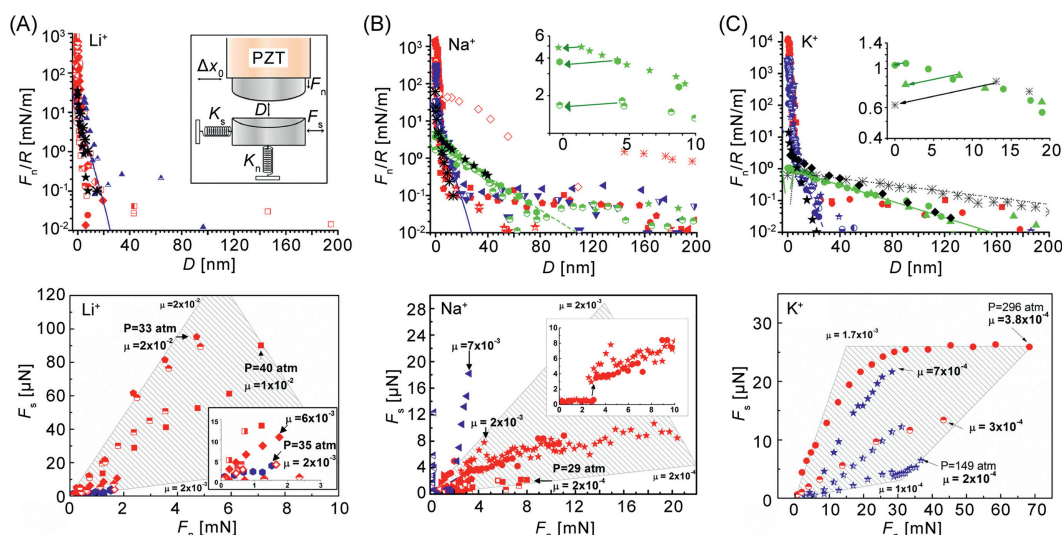


Fig. 4. The normal force $F_n(D)/R$ profiles and corresponding sliding frictions between two mica surfaces in different concentrations of alkali metal nitride salts, measured using conventional SFB. (A) Normal (upper panel) and frictional force (lower panel) for Li^+ . Insert is the schematic of SFB (upper) and magnification of low compression regime (lower). (B) Force profiles for Na^+ . The insert is the magnification showing the “jump-in” and friction at relatively low compression. (C) Force profiles for K^+ . The insert is the magnification showing the “jump-in”. Different colors correspond to different cation concentration and the half-filled symbols are the subsequent approaches. The solid curves are the best DLVO fitting for the normal force profiles. The low friction, down to $\mu \approx 10^{-4}$ is attributed to the hydration lubrication from confined cations. Reproduced with permission [106]. Copyright 2016, American Chemical Society.

in SFB experiments [67], the simulated values are slightly bigger, which is attributed to the thinner layer in simulation. Similar water fluidity is seen on graphene surfaces and carbon nanotubes, due to the coupling of charge fluctuations in the liquid to electronic excitations in the solid [99].

When exposed to the external electric field, the fluidity of water should be changed due to its dipolar nature (so-called “viscoelectric effect”), as other dipolar organic liquids [100,101]. Hunter and Leyendekkers [102] estimated the viscoelectric coefficient f , according to the expression of $\eta = \eta_0(1 + fE^2)$ (η_0 is the bulk viscosity, E is the electric field), to be $(0.5\text{--}1.0) \times 10^{-15} \text{ V}^{-2} \text{ m}^{-2}$ using the neutron scattering data [103]. Moreover, the value has been directly measured to be $(9.9 \pm 2.8) \times 10^{-16} \text{ V}^{-2} \text{ m}^{-2}$ using a three-electrode modified SFB recently [68]. Such effect allow manifested in the sliding friction between gold/ SiO_2 microparticles pairs, measured using AFM [104]. It is important to mention that the ion concentration in such measurements should be carefully determined for two reasons as follows: The overlapping of EDL leads to the accumulation of counterions near the charged surfaces, causing the electroviscous effect of water [68]; Meanwhile, as will be shown later, highly hydrated cations, such as Na^+ , are suitable boundary lubricants when their concentrations are beyond some threshold [105,106]. Therefore the potential-dependent friction between an AFM tip and Au (111) surface, reported by Pashazanusi *et al.* [107,108] and Li *et al.* [104], in which the potential-dependent frictional behavior of nanometer thick water layer is attributed to the freezing caused by the cross-gap electric field, thus increasing the viscosity, could be hardly persuasive.

One way to maintain the lubricating water layer is to use highly hydrated species such as cations, of which the motion could be manipulated by the external electric potentials [78]. Due to charge-dipole interactions, the cations tenaciously hold a layer of water molecules, therefore are resistant to considerable normal pressures. When trapped between negatively charged mica surfaces under nanometer confinement, such highly hydrated cations induce the “hydration repulsion” from the water layers and separate the surfaces from being in contact due to van der Waals (vdW) attractions [106,109], as shown in Fig. 4 left panels. Meanwhile, hydration water molecules retain their fluidity, indicated by the viscosity

of hydration water, which is *ca.* 250-fold larger than the bulk value measured by SFB [105]. So that when confined between surfaces, such highly hydrated ions are excellent lubricants [105,106,110–115], as shown in Fig. 4 right panel as an example. As is provided by the hydration water molecules, this lubrication mechanism is called “hydration lubrication” in literature [116,117]. Recently, this concept has expanded to anions. Li *et al.* [118] reported a layered structure, formed near positively charged $\text{Mg}(\text{OH})_2$ surface by hydrated halogen anions, reducing the friction coefficient down to *ca.* 4×10^{-3} and almost independent of anion species, as shown in Fig. 5. However, the friction coefficient in 0.2 mol/L electrolyte solution is orders of magnitude lower compared with 4 mol/L electrolyte solution and water, which is attributed to the different adsorption states of anions, varying with concentrations. The authors explain that hydration lubrications of anions are barely reported as follows. Since the size of hydrated anions (*ca.* 0.33 nm) is slightly larger than the lattice constant, the anions interact with $\text{Mg}(\text{OH})_2$ mainly by the electrostatic attractions, which is weaker compared with the cation-mica coordination interactions. So the anions can be squeezed out easily, and the interfacial friction can hardly be measured.

The concept of “hydration lubrication” is also used to explain the low friction provided by other highly hydrated species, such as surfactants [119,120], polymer brushes [21,22,121,122], lipids [123–125] and liposome-contained hydrogels [126]. Although charged or dipolar structures could be found in all of these species as the foundation of hydration shell formation, the number of studies about electro-tunable friction bases on these species is limited.

Ma *et al.* [127], Tivony *et al.* [128], and Gao *et al.* [129] reported the manipulation of friction between negatively charged surfaces (silica colloidal tip or mica) and gold surfaces by changing the surface potential of gold using three-electrode modified AFM and SFB. The friction results are similar to each other (Fig. 6) [127,128]. The interfacial friction is lower when hydrated cations, K^+ and Li^+ respectively, are confined between negatively charged gold surface (negative gold potential) and other negatively charged surface, like silica colloidal AFM probe (Fig. 6A) or mica surface (Fig. 6E). Such low friction, $\mu \approx 0.08$ for AFM and $\mu \approx 0.05 \pm 0.03$ for

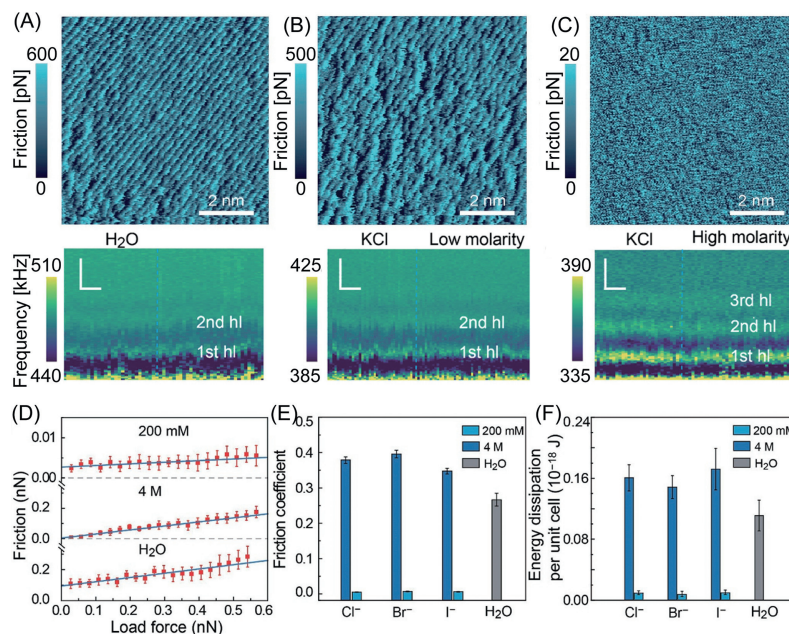


Fig. 5. The layered structure of halogen anions near positively charged $\text{Mg}(\text{OH})_2$ crystal (001) surface and their lubrication properties. (A) Friction map measured in pure water and the vertical frequency shift map, showing layered structures. (B) Friction map and vertical frequency shift measured at 0.2 mol/L KCl, showing slightly reduced friction and layered structure. (C) Friction map and vertical frequency shift measured at 4 mol/L KCl, showing reduced friction and layered structure. (D) Friction vs. load plot, showing the reduction of friction coefficient. (E) Summary of friction coefficients of halogen ions. The friction coefficient reduces significantly in high halogen ion concentration. (F) Calculated energy dissipation per unit area based on (E). Reproduced with permission [118]. Copyright 2022, Tsinghua University Press.

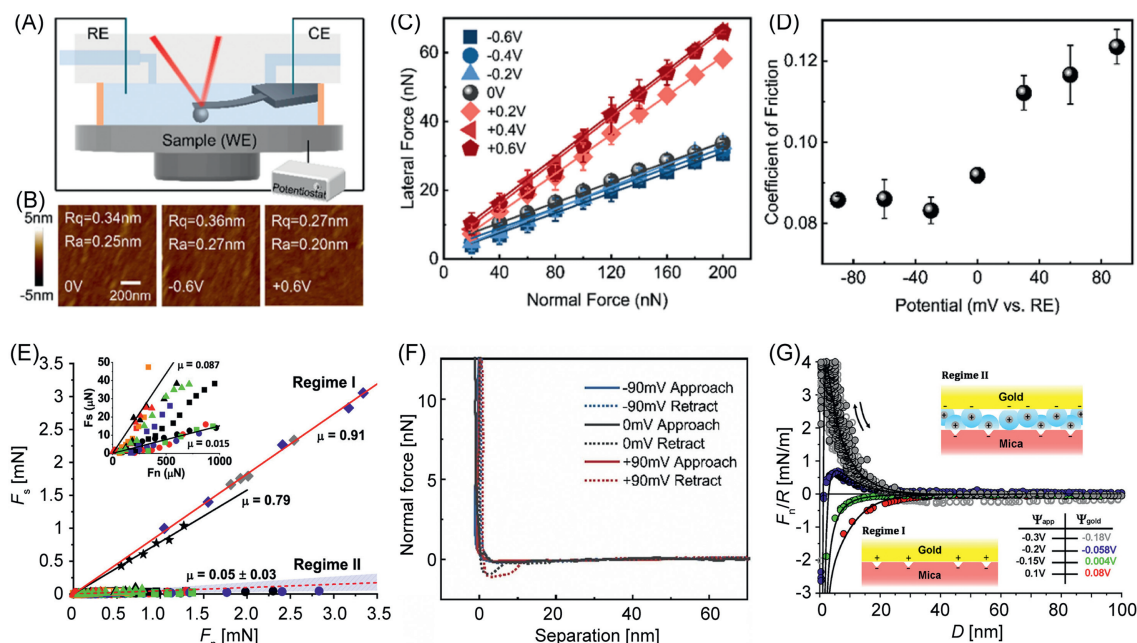


Fig. 6. Electrotunable friction using cations in aqueous media. (A) Three-electrode-modified AFM. (B) Gold surface topographies at different potentials, showing molecularly smooth surface. (C) Lateral frictional force vs. normal force, between a colloidal particle tip and gold surface, mediated by K^+ cations. A 1.5-fold modulation of friction coefficient is observed. (D) Summary of friction coefficient at the different potential, showing the change of friction modulation by the potential, mediated by K^+ cations. (E) Friction $F_s(F_n)$ at different potentials, showing the modulation of friction by potentials, mediated by Li^+ cations, measured using modified SFB (Fig. 1C). This shows a ca. 16-fold change of friction coefficient. (F) The normal force as a function of separation, measured using setup in (A). (G) Normal force profiles between gold and mica surface in 2 mmol/L Li^+ , showing two regimes: adhesive contact (regime I) and hydration repulsion (regime II). (A-D, F) Reproduced with permission [128]. Copyright 2023, Elsevier. (E, G) Reproduced with permission [129]. Copyright 2021 American Chemical Society.

SFB, is attributed to the confined hydrated cations, as confirmed using sum-frequency generation (SFG) spectroscopy by Ma *et al.* [127]. However, the range of friction manipulation measured using AFM, ca. 1.5-fold, is much smaller than those measured using SFB, which is ca. 16-fold. The normal force profiles may explain such difference: In the AFM case, all measured forces are

repulsive (positive), regardless of the potential of the gold surface, diverging from the Poisson-Boltzmann theory; however, in the SFB case, the normal forces are tunable by the applied potential and could be described well using Poisson-Boltzmann equation. Gao *et al.* [129] attributed the repulsion to the surface-attached hydrated anions and cations. Noticing that the ion concentra-

tions are different in the two studies, the explanation seems plausible.

Ionic liquids are liquids composed of pure ions, like melted salts, but stay fluid liquid phase at room temperature or even lower (so-called room temperature ionic liquids or RTILs) [130]. Although shearing a similar charge property, to the best of our knowledge, the electro-tunable friction using room temperature ionic liquids (RTILs) solution has not been reported yet. Using MD simulation, Fajardo *et al.* [131] pointed out that water molecules could perturb the layered structures formed by oppositely charged components of RTILs by competing adsorption on the surface and screen the electrostatic interactions between ions. Therefore, RTILs could be easily squeezed, and the packing of ions in the slip plane would be disturbed, leading to increased friction [132]. Such phenomena are also observed experimentally: lubricating layers thickness reduces upon exposing to water [133,134]. To the best of our knowledge, RTILs with long alkyl chains are used as additives to water or oil-based lubricants. Zheng *et al.* [135] and Khanmohammadi *et al.* [136] used glycerol-water mixture with *ca.* 1 wt% fatty acid-derived RTIL additives, observing that the friction between steel surfaces could be reduced by 67% due to the formation of stable tribofilm under boundary lubrication conditions. Furthermore, Khan *et al.* [137] used pure water-RTILs emulsion as lubricants, finding that the friction could be reduced by 85% due to the formation of a tribo-induced ionic liquids-derived tribochemical thin film. RTILs, as additives, are used widely in oil-based lubricants under the mechanism of forming stable boundary lubricating thin liquid films. For example, Gusain *et al.* [138] and González *et al.* [139] reported that the formation of thin oil films, under boundary lubrication conditions, between two steel surfaces, and the friction is reduced by *ca.* 15%. However, to the best of our knowledge, there is no report on whether the friction could be tuned electrically in both water- or oil-based RTIL-added lubricants. Furthermore, the “dry” RTILs are widely reported to show potential-dependent lubrications, especially under boundary lubrication, attracting lots of interest from both experiment and simulation perspectives, as discussed below.

Surface-attached surfactant micelles, composed of amphiphiles, are good lubricants in aqueous media due to the hydration lubrication paradigm, as mentioned above [119,120,140]. However, their potential-dependent lubrication properties are barely reported. Gao *et al.* [141] reported that hexadecyltrimethylammonium bromide (C_{16} TAB) micelles would adsorb on a gold surface, forming a bi-layer structure under negative potential due to electrostatic interactions. Therefore, when two micelle-covered silica surfaces rub against each other, sliding will occur between two layers of hydrated quaternary ammonium, and low friction is observed due to hydration lubrication. He *et al.* [142] reported, in both macroscopic and microscopic measurements, that the negatively charged sodium dodecyl sulfate (SDS) micelles will adsorb on positively charged steel surfaces, reducing the friction by *ca.* 90%, while on a negative surface charge, such lubricating layer is expelled, and the friction is high ($\mu \approx 0.45$); and the low friction is attributed to the tightly attached SDS micelles array that forms a thin lubricious film. The number of such studies are also very limited to the best of our knowledge.

The electro-tunable friction using “dry” RTILs has been well-studied (Fig. 7), of which the mechanism depends on direct electric potential or alternating electric field is applied [39]. The direct electric potential, usually applied in symmetric polarization configuration, could switch the local lubricant composition, modulating the friction [143,144]. As mentioned above, the cross-gap electric field is essentially zero in this case: The composition changes due to the charge redistribution. The effect of alternating electric field depends on its frequency: Low frequency (slow a.c. timescale) allows the ions reorganization and screen-

ing, which leads to low friction [145,146]; and high frequency (faster than ions self-organization) leads to an unscreened electric field; therefore adhesion and high friction are expected [147,148].

RTILs are known to form alternating layered structures when confined between two charged surfaces in a gap of nanometer scale (Fig. 7A) [149], as shown by Rotenberg [150] and Krame [151] using scanning probe microscopy and Nemoto *et al.* [152–154] using neutron or X-ray scattering techniques. Such structure is due to the over-screening effect of the surface charges: The surface charge pulls ‘too many’ counterions in the first layer, the following layer over-compensating with the counterions of the first layer, and so on (with gradually decreasing magnitude) [155]. Furthermore, the layered structure could be perturbed by amphiphilic ions. For example, Perkin *et al.* [149,156] reported a monolayer-like structure composed of amphiphilic cations with alkyl chains, in which relatively small anions are located close to the opposite charges but discontinuously. The lubricating properties of the RTILs are both normal load and velocity dependent and could be sorted into three categories [157]: (i) At low normal load and slow shear rate (usually more than one layer is confined), the energy is dissipated through in-layer relaxation, as it is faster than the shear rate, resulting velocity-independent low friction; (ii) At high load, the in-layer relaxation is suppressed due to the confinement, leading to higher velocity-dependent friction than case (i); (iii) At the highest load (one-layer structure), the lubricating is from the lateral motion of ions within the layer, leading to velocity-independent low friction.

As all three lubricating mechanisms are related to the shear-relaxation process that is influenced by the molecular structure of confined molecules [158,159], it is natural to expect that the electric stimuli that could alter the molecular structure through expelling coions and modulate the interfacial friction. Li *et al.* [160] reported potential-dependent friction *in situ* between highly ordered pyrolytic graphite (HOPG) and AFM tip and quantitatively measured the energy dissipation (Fig. 7B). Upon applying positive potential, the friction coefficient was reduced by *ca.* 95% due to the enrichment of anions on the surface (Fig. 7B). Sweeney *et al.* [161] showed that a similar friction modulation (*ca.* 71%) could be achieved using gold substrate. Furthermore, Li *et al.* [162] showed the influence of molecular orientation experimentally by comparing different lubrication behavior of lithium tetraglyme bis(trifluoromethylsulfonyl)amide (Li(G4) TFSI) on Au (111): The anion-rich boundary layer is less lubricating compared with cation-rich layer, which implies the importance of ion reorientation upon electric potential. The Urbakh group also observes a similar effect in their simulation work (Fig. 7C) [163–166].

Very recently, phosphatidylcholine (PC) lipid layers are reported to change its planar structure by forming transmembrane pores and cross-membrane lipid bridges (stalks) in the electric field [167]. These changes cause dehydration of PC groups and force part of sliding occurs between strongly interacting acyl tails [168,169]. As a result, the friction coefficient is modulated reversibly by 200 folds.

External electric stimuli could also be used in dry friction scenarios through various strategies. Park *et al.* [170] reported that the friction between the pn junction and AFM tip could be reduced by *ca.* 60% by applying bias potential out of the substrate plane. The applied electric potential would dampen the motion-induced lattice vibration by exciting electron-hole pairs. Recently, Song *et al.* [171] showed that the stick-slip energy barrier could be tuned using similar out-plane bias potential through electron redistribution and transfer. An in-plane bias potential also shows a similar result, but the underlying mechanism is that the in-plane bias potential suppresses the stick-slip motion [172]. Zhu *et al.* [173] used the piezo-electric effect to change the surface roughness for ma-

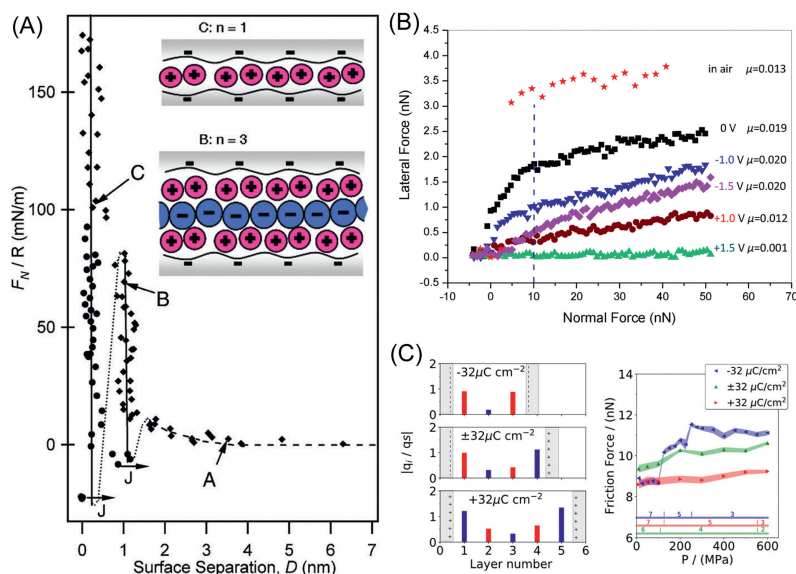


Fig. 7. Layered structure of confined ionic liquids and the modulation of friction using electric potential from experiment and MD simulation. (A) Layered structures of RTIL that confined between two mica surfaces. While the normal pressure increases, layers are squeezed out. Copied with permission [149]. Copyright 2010, Royal Society of Chemistry. (B) Modulation of sliding friction using potential, mediated by RTILs. Copied with permission [160]. Copyright 2014, Royal Society of Chemistry. (C) The change of RTIL composition with the surface charge density (left panel) and the change of friction at different normal pressures (right panel), from MD simulation results. Copied with permission [166]. Copyright 2020, American Chemical Society.

nipulation of friction between gold and lead zirconium titanate ceramic on a macroscale. Choi *et al.* [174] reported that the friction between a silica colloidal tip and anodic alumina was dependent on the porosity of the anodic alumina film. This property was then used by Kim *et al.* in porous nickel films, of which the pore diameter could be tuned by external potential, showing potential-dependent adhesion and friction.

3.2. Friction manipulation using electrochemical reaction

Electrochemical reaction, especially anodizing of the metal surface, is widely used to reduce friction [175,176] on the macroscale. The underlying mechanism is that the metal surface's anodic oxidation leads to a hard anodized film on the surface that protects the surface from plastic deformation and wear [177–179]. However, on the microscale, the trend is different. Hausen *et al.* [180] reported that the friction increased as the Au (100) surface was oxidized. Similar results were shown by Labuda *et al.* [181] on Au (111) surfaces. The low friction, measured in both studies, is attributed to the smoothness of the surface, and the high friction, on the contrary, is attributed to the roughness of the amorphous structure of the oxo-hydroxide surface and the extra dipole-tip interaction [181]. It is important to mention that Hausen *et al.* [180] pointed out that the Au (100) surface is expected to reconstruct after oxidation–reduction cycles and the reconstruction rate could influence the friction manipulation directly. Valtiner *et al.* [182,183] did systematic studies on the effect of electrochemical oxidation–reduction cycles on friction. They found that the surface roughness increased after several electrochemical cycles, leading to a larger surface area, which is more favorable for the counterion adsorption and decreases the interfacial adhesion [182]. Donaldson *et al.* [184] showed the same results quantitatively by binding the counterion into the other mica surface and measuring the pulling-off forces between the gold surface, of which the roughness was controlled electrochemically. Again, the microscopic scale studies using SFB and AFM in this regime are limited to the best of our knowledge. Furthermore, the structural superlubricity of 2D materials, such as WS_2 quantum dots [185] and graphene [186], has attracted many interests recently. Though most of such materials show properties

of conductor or semiconductor [187], electromodulation of friction of these materials has not been achieved yet.

4. Friction manipulation between modified surfaces

The underlying idea for modifying the surface for the electro-tunable friction properties is to coat the surface with charged or dipolar molecules. The bond between the covering molecules and substrates could be physical, such as vdW interaction, or chemical bond, like Au–thiol bond. A high concentration of charged or dipolar structures is needed to amplify the effect of the electric field or potential. Thus, self-assembled monolayer (SAM) or surface-attached polymer brushes are commonly used in such systems.

SAMs' lubricating properties are extensively studied both experimentally and using MD simulations, in dry friction or between lubricated surfaces. The lubricating properties of SAMs layers depend on several factors, such as substrate-layer binding, molecular structure of SAMs components. Ruths *et al.* [188] compared the boundary friction between two different aromatic silane monolayers, finding that the relatively low friction ($\mu \approx 0.3$) could be measured between two SAMs-covered surfaces, and covalently-bonded layers were more lubricating. Houston and Kim [189] revealed that good lubricity ($\mu \approx 10^{-3}$) could be acquired when molecules were closely packed, and the normal pressure was below the threshold of SAMs damage. Brewer *et al.* [190] showed that the structural similarity of two contacting SAMs could lead to high friction, and this trend was also observed between SAM and the graphene layer [191]. This phenomenon is attributed to the increased adhesion between two structurally similar SAM layers. Another factor that influences the lubricity of SAMs is the solvation of the membrane. Li *et al.* [192] reported that the better lubrication ($\mu \approx 10^{-4}$) between perfluorocarbon SAM and graphene compared with hydrocarbon SAM ($\mu \approx 10^{-3}$), which is due to a more robust water layer held by perfluorocarbon SAM. However, the results from the Martini group showed the opposite: hydrophobic SAMs lubricate better in water [193,194], which they attributed to the energy penalty of breaking hydrogen-bond between water molecules and terminal groups of hydrophilic SAM. Therefore, it is clear that the mechanism of SAM boundary lubrication is still under discussion.

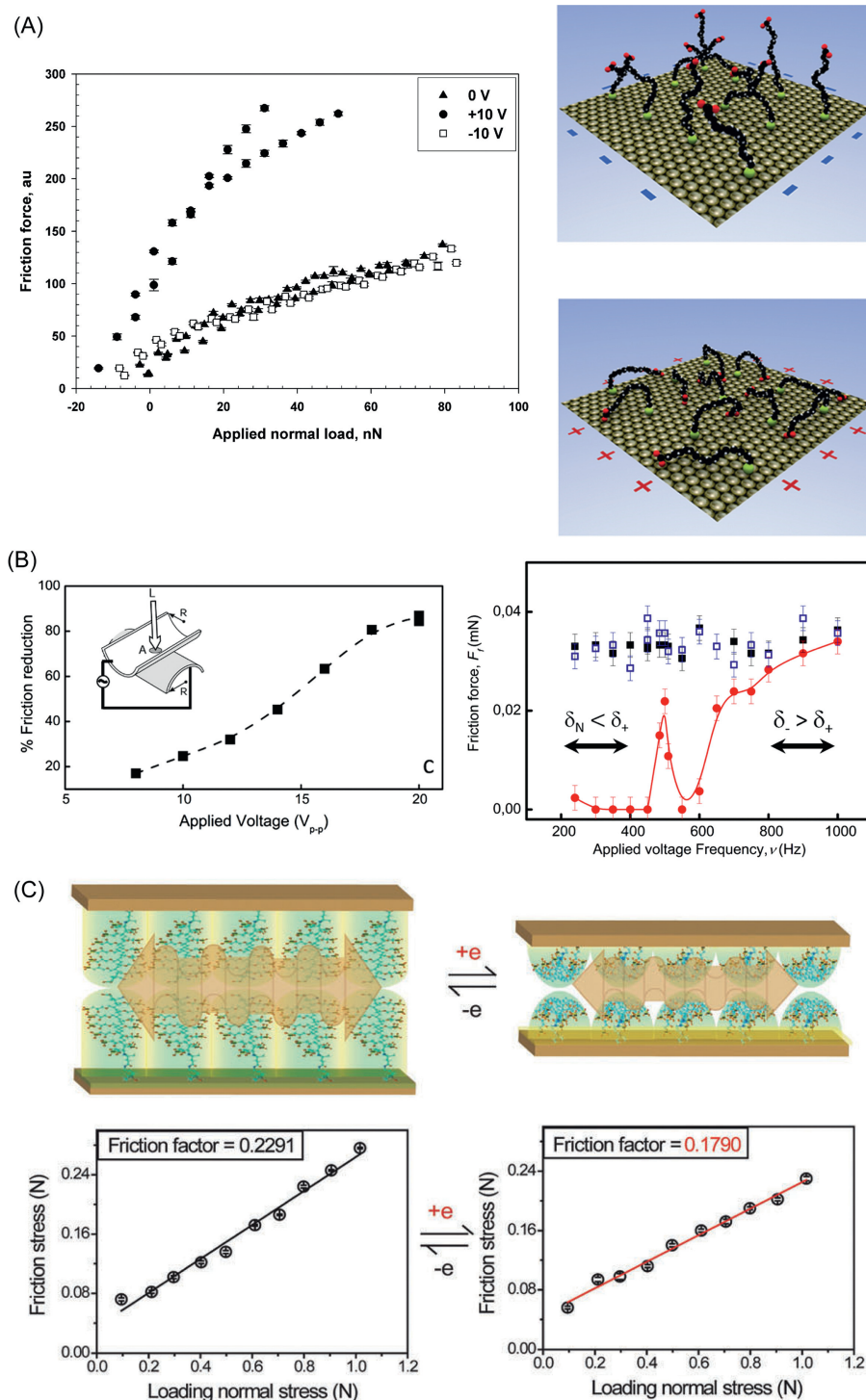


Fig. 8. Electrotunable friction between SAM or polymer-brush covered surfaces. (A) Electrotunable friction using low density 16-mercapto-hexadecanoic acid SAM. The friction change is due to the surface charged induced bending of the hydrophobic hydrocarbon chains. Reproduced with permission [196]. Copyright 2009, American Chemical Society. The simulated conformational change is shown on the right. Copied with permission [197]. Copyright 2012, American Chemical Society. (B) Manipulation of friction between poly-anion brush covered mica surfaces using alternating electric field. The left panel shows that the amplitude of friction reduction is dependent on the amplitude of applied ac signal, and the right panel shows the frequency dependency of the friction reduction. Reproduced with permission [78]. Copyright 2012, American Physical Society. (C) Manipulation of friction between polyelectrolytic brush covered conductive glass surfaces by transferring charges to the glass. Reproduced with permission [35]. Copyright 2017, Royal Society of Chemistry.

The electrotunable friction of SAMs is achieved by changing the molecular conformation using a differently charged surface (Fig. 8). The charge-conformation was first reported by Lahann *et al.* in 2003 [195]. Since then, Karuppiyah *et al.* [196,197] used this property to control the friction between 16-mercaptohexadecanoic acid

SAM-covered gold surface and commercial Si_3N_4 tips (Fig. 8A), and attributed this friction change to the electric field-induced crystalline structure change of the SAM: The hydrophobic alkyl chains exposed themselves when a positive potential was applied to the gold surface. Experimental studies and simulation studies showed

that such conformational change could only occur in low grafting densities when enough space is guaranteed for the change [195,197,198]. To the best of our knowledge, the number of studies in this field is limited, probably due to the inconsistency of the results and lubricating mechanisms mentioned above.

Polymer brushes are long polymer molecules attaching to the surface or interface by one of their ends, with a density of attaching points high enough so that the chains are forced to stretch away from the interface [199]. Such layers can be fabricated using “grafting to” method, where the long (blocked) polymer chains are deposited to the surface from its good solvents [22,200], or “grafting from” method, where the polymerization occurs at the solid/water interface. A typical polymerization method is surface initiated atom transfer radical polymerization (SI-ATRP), where Br-containing initiators are immobilized onto a solid support and the growth of the chain is catalyzed by $\text{Cu}^{\text{I}}/\text{Cu}^{\text{III}}$ and amide containing ligands [201].

When two brush-covered surfaces are set in the opposite configuration in good solvent and the separation decreases, repulsive interactions are expected since the interpenetration between brushes is suppressed due to entropy penalty [202,203]. When immersed in good solvent, polymer brushes are good boundary lubricants, as solvent layers are confined in the gap due to the conformational entropy penalty when the pressure is low [21,22,204] and relaxation when the pressure is high enough to induce interpenetration [205,206]. Particularly, when the interchain friction during the relaxation process is mediated by the hydration lubrication from highly hydrated monomers, extremely low friction ($10^{-4} \leq \mu \leq 10^{-3}$) is measured, as reported by several different groups using different brushes-coated hard surfaces [122,207–211]. Such polymer (polyelectrolyte)-brushes have also been used to covalently coat surface of articular cartilage-mimic crosslinked polymer hydrogels, whose modulus are tuned for better load-bearing capacities, less shear strain and lower sliding friction coefficient [212–214]. However, the study of tuning friction between such charged or dipolar brushes using electric stimuli is very limited.

To the best of our knowledge, there are only two reports about manipulating friction between polymer brush-covered surfaces, as shown in Figs. 8B and C. Drummond [78] reported that the friction between diblock polystyrene-polyacrylic acid copolymer brushes on mica could be tuned using square-wave alternating electric field at low pressure. The amplitude of the electric field controlled the interpenetration degree, as shown in Fig. 8B, left panel. The frequency-dependent friction reduction (Fig. 8B, right panel) is attributed to the relaxation time of the polyelectrolyte (PE) chains under confinement, and the small window at *ca.* 500 Hz is attributed to the charge neutralization of PE from the counterions. Zeng *et al.* [35] reported an opposite friction change using static electric potential on conductive ITO glass substrates (Fig. 8C): when the polyanionic brush collapsed due to the positive charge, the friction coefficient was low, and the friction coefficient was high when two substrates are negatively charged. The author attributed such friction change to the collapse of the brush layer and the exposure of hydrophobic backbones upon the positive charge. However, the reason is not clear, as lubrication is the combination of hydrodynamic friction and boundary lubrication while only the boundary lubrication is described. The manipulation of friction using electric stimuli is still challenging at present; therefore, the number of published studies is very limited.

5. The missing concept: electric field

In all the experimental studies discussed above, the critical parameter, cross-gap electric field, is missing in most of the published works. Instead, the applied surface potential (with respect to a reference electrode, such as Ag/AgCl in a three-electrode con-

figuration), or the voltage (in a two-electrode configuration) is usually reported. Such missing is, to some extent, understandable: The reported parameters are usually enough to describe the charging situation of the surface, as the surface charge and surface potential are connected by the Grahame equation [215], and the surface potential (or applied potential) is enough for others to repeat the experiment. There are two limitations to use applied potential. First, the Grahame equation assumes an infinite separation between surfaces, which is not necessarily true when under confinement. Second, when charged species exposing to an external electric field, it is important to compare its energy of thermal motion, which is $\sim k_{\text{B}}T$ (k_{B} is the Boltzmann constant and T is the absolute temperature) [216] with the energy it gained from the electric field $\Delta G (= q\psi$ for the charge q and $E \cdot u$ for the dipole u , where q is the charge, ψ is the potential, E is the field and u is the dipole moment. Both E and u are vectors). The effect of the electric field should only show itself when ΔG is comparable to $k_{\text{B}}T$ [217–219]. However, it is hard to make this comparison using the reported applied potential.

From MD simulation, the external electric field is described in two equivalent manners: A force on the particles or a charge-imbalance on the boundaries [220], and the electric field is then estimated using Gauss's theorem for electrostatic field [221]. On the other hand, the mean-field Poisson-Boltzmann Equation (PBE) is commonly used to describe the cross-gap potential distribution (in other words, the gradient of the electric field) in a continuum media and to calculate the normal interactions [65,105,222] when two surfaces are set in liquid. As a nonlinear differential equation, the boundary conditions, namely constant surface charge density (cc) or constant surface potential (cp), will change the calculated result greatly. McCormack *et al.* summarized the solutions for PBE all the combination of boundary conditions: cc vs. cc, cp vs. cp, and cc vs. cp, and provided a useful graphic method to qualitatively describe the normal interactions in three conditions mentioned above [223]. In the same paper and other papers [224,225], they also pointed out that charge-inversion of the surface caused by confinement on constant potential surfaces, which disobeys the Grahame equation (first assumption mentioned above) and measured experimentally later using SFB [226,227]. Besides the analytical solutions, McCormack *et al.* [223] also presented a uniform grid numerical method for the nonlinear PBE based on an analytical solution for linearized PBE. However, this method diverges when applied in the short range and high electrolyte concentration conditions. A more robust adaptive multigrid Newtonian method could be found in the paper by Holst *et al.* [228] and James *et al.* [229].

Furthermore, the constant surface charge density boundary condition, which is usually used to describe surfaces like mica surface, is over-simplified for most cases, as the surface charge is from reversible ionizable groups. The charge-regulation boundary condition is used instead of constant charge density in these cases. Carnie *et al.* [230] gave an elegant description of the charge-regulation boundary condition as follows: When two identically charged surfaces were brought into contact, counterions would be confined in the gap. As the ionization of charged surface was reversible under a constraint of an equilibrium constant, part of the counterions would adsorb on the surface, changing the surface potential accordingly; therefore, the surface charge was “regulated”. The adsorption was described using Langmuir isotherm, and the surface potential was regulated according to the Nerst equation. Such boundary condition was then used to describe simple surface interactions, such as two identical mica surfaces in dilute LiNO_3 solution at different pH, showing a much better description of the normal force profiles at short range [231]. In more recent studies, such boundary condition was also found to be quite accurate in the normal forces in dissimilar surfaces [68,232], between weakly ionized polyelectrolyte brushes [233,234].

Another barricade to fully calculate the electric field is the dielectric constant of the medium. A lattice method, in which different dielectric constants were given to each lattice to calculate the potential accordingly, is usually used to solve this problem, as reported by Rocchia *et al.* [235]. However, to the best of our knowledge, this method is limited to the spatial scale of small protein molecules [236] or lipid membranes [237] without the externally applied electric field; and no detailed study has been reported in this issue.

6. Conclusions and outlooks

In this short review, we summarize the recent studies, mainly experimental works, on controlling the interfacial friction using electric stimuli. The main idea underlying the presented studies is to use external electric stimuli to change the physiochemical properties of the surfaces. Two or three-electrode configuration could be used. For the bare surface, the electric stimuli could change its surface charge, roughness, *etc.*, to control the friction. For the lubricant that carries charge or dipole, bound to the surface or free in motion, external electric stimuli could change its composition, conformation, *etc.*, therefore modulating the interfacial friction. Modifications could be made on different scales to induce electric stimuli under confinement. Different scales enable the measurement under different lubrication, ranging from atomistic friction in modified AFM, to the mixed mechanisms of hydrodynamic and boundary lubrication in modified tribometer.

We also found that, interestingly, the cross-gap electric field is somehow missing in most of the reported studies as an essential parameter for both analyses of the experiment results and MD simulation. Such missing could be attributed to the difficulty of fully describing the potential distribution across the gap, which is filled with layers of materials with different dielectric constants. A lot of work could be done in this research area.

Generally, the electro-tunable interfacial friction shows great potential in the application, especially in micro/nanoelectronics and devices, and needs more investigation in its application and in the theoretical description of the system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- [1] H. Liu, B. Yang, C. Wang, *et al.*, *Friction* 11 (2023) 839–864.
- [2] W. Lin, J. Klein, *Adv. Mater.* 33 (2021) e2005513.
- [3] B.N.T. Persson, *History of tribology*, in: T. Mang (Ed.), *Encyclopedia of Lubricants and Lubrication*, Springer Berlin Heidelberg, Berlin, Heidelberg, 2014, pp. 791–797.
- [4] Z. Zou, H. Li, K. Yu, *et al.*, *Exploration* 3 (2023) 20220132.
- [5] V.P. Zhuravlev, *Mech. Solids* 48 (2013) 364–369.
- [6] B. Armstrong-Hélouvy, P. Dupont, C.C. De Wit, *Automatica* 30 (1994) 1083–1138.
- [7] Q.J. Wang, D. Zhu, *Hertz theory: contact of spherical surfaces*, in: Q.J. Wang, Y.W. Chung (Eds.), *Encyclopedia of Tribology*, Springer US, Boston, 2013, pp. 1654–1662.
- [8] F.P. Bowden, L. Leben, *Proc. R. Soc. London, Ser. A* 169 (1939) 371–391.
- [9] F.P. Bowden, D. Tabor, *Proc. R. Soc. London, Ser. A* 169 (1939) 391–413.
- [10] J.A. Greenwood, *Contact of rough surfaces*, in: I.L. Singer, H.M. Pollock (Eds.), *Fundamentals of Friction: Macroscopic and Microscopic Processes*, Springer, Netherlands, Dordrecht, 1992, pp. 37–56.
- [11] E. Rabinowicz, *Friction fluctuations*, in: I.L. Singer, H.M. Pollock (Eds.), *Fundamentals of Friction: Macroscopic and Microscopic Processes*, Springer, Netherlands, Dordrecht, 1992, pp. 25–34.
- [12] O. Reynolds, *Philos. Trans. R. Soc. London* 177 (1997) 157–234.
- [13] B. Jacobson, *Tribol. Int.* 36 (2003) 781–789.
- [14] M. Kalin, I. Velkavrh, J. Vižintin, *Wear* 267 (2009) 1232–1240.
- [15] H.A. Spikes, *Boundary lubrication and boundary films*, in: D. Dowson, C.M. Taylor, T.H.C. Childs, M. Godet, G. Dalmaz (Eds.), *Tribology Series*, Elsevier, 1993, pp. 331–346.
- [16] W.B. Hardy, I. Doubleday, *Proc. R. Soc. London, Ser. A* 100 (1997) 550–574.
- [17] B.N.J. Persson, *Phys. Rev. B: Condens. Matter* 48 (1993) 18140–18158.
- [18] J. Gao, W.D. Luedtke, D. Gourdon, *et al.*, *J. Phys. Chem. B* 108 (2004) 3410–3425.
- [19] S.H. Loring, R.E. Brown, A. Gouldstone, J.P. Butler, *J. Biomech.* 38 (2005) 2390–2396.
- [20] Z. Xu, H. Tsai, H.L. Wang, M. Cotlet, *J. Phys. Chem. B* 114 (2010) 11746–11752.
- [21] F.T. Limpoco, R.C. Advincula, S.S. Perry, *Langmuir* 23 (2007) 12196–12201.
- [22] M.T. Müller, X. Yan, S. Lee, *et al.*, *Macromolecules* 38 (2005) 5706–5713.
- [23] A. Dedinaite, E. Thormann, G. Olanya, *et al.*, *Soft Matter* 6 (2010) 2489–2498.
- [24] Y. Wu, X. Pei, X. Wang, *et al.*, *NPG Asia Mater.* 6 (2014) e136–e136.
- [25] Y. Wu, M. Cai, X. Pei, *et al.*, *Macromol. Rapid. Commun.* 34 (2013) 1785–1790.
- [26] E.B. Zhulina, M. Rubinstein, *Soft Matter* 8 (2012) 9376–9383.
- [27] Y. Higaki, M. Kobayashi, A. Takahara, *Langmuir* 36 (2020) 9015–9024.
- [28] D. Liu, D.J. Broer, *Soft Matter* 10 (2014) 7952–7958.
- [29] D. Liu, D.J. Broer, *Angew. Chem.* 126 (2014) 4630–4634.
- [30] J. Kang, X. Yang, X. Yang, *et al.*, *Chin. Chem. Lett.* 35 (2024) 109297.
- [31] J.J. Blackstock, Z. Li, M.R. Freeman, D.R. Stewart, *Surf. Sci.* 546 (2003) 87–96.
- [32] N. Vogel, J. Zieleniecki, I. Koper, *Nanoscale* 4 (2012) 3820–3832.
- [33] J. Wang, J. Li, L. Fang, *et al.*, *Tribol. Lett.* 55 (2014) 405–412.
- [34] J. Liu, M. Miao, K. Jiang, *et al.*, *Nano Energy* 48 (2018) 320–326.
- [35] H. Zeng, Y. Zhang, S. Mao, *et al.*, *J. Mater. Chem. C* 5 (2017) 5877–5881.
- [36] C. Joachim, M.A. Ratner, *Nanotechnology* 15 (2004) 1065–1075.
- [37] P. Spitzer, S. Wunderli, K. Maksymiuk, *et al.*, *Reference electrodes for aqueous solutions*, in: G. Inzelt, A. Lewenstam, F. Scholz (Eds.), *Handbook of Reference Electrodes*, Springer, Berlin Heidelberg, Berlin, Heidelberg, 2013, pp. 77–143.
- [38] N. Elgrishi, K.J. Rountree, B.D. McCarthy, *et al.*, *J. Chem. Educ.* 95 (2017) 197–206.
- [39] F. Bresme, A.A. Kornyshev, S. Perkin, M. Urbakh, *Nat. Mater.* 21 (2022) 848–858.
- [40] B. Voigtländer, *Atomic Force Microscopy*, 2nd ed., Springer, Cham, Jülich, 2019.
- [41] Z. Zhang, S. Said, K. Smith, *et al.*, *Adv. Energy Mater.* 11 (2021) 2101518.
- [42] G. Binnig, C.F. Quate, C. Gerber, *Phys. Rev. Lett.* 56 (1986) 930–933.
- [43] Y.F. Dufrene, T. Ando, R. Garcia, *et al.*, *Nat. Nanotechnol.* 12 (2017) 295–307.
- [44] R. Delalande, D. Garcia-Sanchez, L. Belliard, *Phys. Rev. B: Condens. Matter* 107 (2023) 085409.
- [45] D.F. Ogletree, R.W. Carpick, M. Salmeron, *Rev. Sci. Instrum.* 67 (1996) 3298–3306.
- [46] S.Y. Luchkin, M.A. Kirsanova, D.A. Aksyonov, *et al.*, *ACS Appl. Energy Mater.* 5 (2022) 7758–7769.
- [47] A. Jetybayeva, N. Schön, J. Oh, *et al.*, *ACS Appl. Energy Mater.* 5 (2022) 1731–1742.
- [48] L. Wang, A. Menakath, F. Han, *et al.*, *Nat. Chem.* 11 (2019) 789–796.
- [49] C.L. Wirth, R.M. Rock, P.J. Sides, D.C. Prieve, *Langmuir* 27 (2011) 9781–9791.
- [50] P.B. Ishai, M.S. Talary, A. Caduff, *et al.*, *Meas. Sci. Technol.* 24 (2013) 102001.
- [51] J.P. Badiali, J. Goodisman, *J. Phys. Chem.* 79 (1975) 223–232.
- [52] T. Kamijo, M. Kasuya, M. Mizukami, K. Kurihara, *Chem. Lett.* 40 (2011) 674–675.
- [53] Y. Liang, J.H.K. Pfisterer, D. McLaughlin, *et al.*, *Small Methods* 3 (2019) 1800387.
- [54] J. Abbou, C. Demaille, M. Druet, J. Moiroux, *Anal. Chem.* 74 (2002) 6355–6363.
- [55] M.R. Nellist, F.A.L. Laskowski, J. Qiu, *et al.*, *Nat. Energy* 3 (2017) 46–52.
- [56] A. Anne, A. Chovin, C. Demaille, M. Lafouresse, *Anal. Chem.* 83 (2011) 7924–7932.
- [57] E. Aleksandrova, R. Hiesgen, K.A. Friedrich, E. Roduner, *Phys. Chem. Chem. Phys.* 9 (2007) 2735–2743.
- [58] H. Lang, Y. Peng, G. Shao, *et al.*, *J. Mater. Chem. C* 7 (2019) 6041–6051.
- [59] C. Filoni, K. Wandelt, L. Marfori, *et al.*, *Appl. Surf. Sci.* 611 (2023) 155542.
- [60] S. Li, F. Eghiaian, C. Sieben, *et al.*, *Biophys. J.* 100 (2011) 637–645.
- [61] K. Engelhardt, E. Preis, U. Bakowsky, *Methods. Mol. Biol.* 2622 (2023) 253–263.
- [62] K. Wieland, G. Ramer, V.U. Weiss, *et al.*, *Nano Res.* 12 (2019) 197–203.
- [63] M.A. Lantz, S.J. O'Shea, M.E. Welland, K.L. Johnson, *Phys. Rev. B: Condens. Matter* 55 (1997) 10776–10785.
- [64] E. Aleksandrova, S. Hink, R. Hiesgen, E. Roduner, *J. Phys. Condens. Matter* 23 (2011) 234109.
- [65] G.E.A. Jacob, N. Israelachvili, *J. Chem. Soc. Faraday Trans. 1* 74 (1978) 975–1001.
- [66] L. Tsarkova, X. Zhang, N. Hadjichristidis, J. Klein, *Macromolecules* 40 (2007) 25392547.
- [67] J.N. Israelachvili, *J. Colloid Interface Sci.* 44 (1973) 259–272.
- [68] U. Raviv, S. Perkin, P. Laurat, J. Klein, *Langmuir* 20 (2004) 5322–5332.

- [69] D. Jin, Y. Hwang, L. Chai, et al., *Proc. Natl. Acad. Sci. U. S. A.* 119 (2022) e2113690119.
- [70] S. Perkin, L. Chai, N. Kampf, et al., *Langmuir* 22 (2006) 6142–6152.
- [71] J.K. Liraz Chai, *Langmuir* 23 (2007) 7777–7783.
- [72] C.D. van Engers, N.E.A. Cousens, V. Babenko, et al., *Nano Lett.* 17 (2017) 3815–3821.
- [73] J. Britton, N.E. Cousens, S.W. Coles, et al., *Langmuir* 30 (2014) 11485–11492.
- [74] W. Lin, J. Klein, *Appl. Phys. Rev.* 8 (2021) 031316.
- [75] R. Tivony, S. Safran, P. Pincus, et al., *Nat. Commun.* 9 (2018) 4203.
- [76] C.D. van Engers, M. Balabajew, A. Southam, S. Perkin, *Rev. Sci. Instrum.* 89 (2018) 123901.
- [77] M.T. Clarkson, *J. Phys. D: Appl. Phys.* 22 (1989) 475–482.
- [78] C. Drummond, *Phys. Rev. Lett.* 109 (2012) 154302.
- [79] P.M. McGuiggan, J. Zhang, S.M. Hsu, *Tribol. Lett.* 10 (2001) 217–223.
- [80] J. Israelachvili, Y. Min, M. Akbulut, et al., *Rep. Prog. Phys.* 73 (2010) 036601.
- [81] C. Leriche, S. Franklin, B. Weber, *Wear* 498–499 (2022) 204284.
- [82] S. Korres, M. Dienwiebel, *Rev. Sci. Instrum.* 81 (2010) 063904.
- [83] L. Shi, V.I. Sikavitsas, A. Striolo, *Ann. Biomed. Eng.* 39 (2011) 132–146.
- [84] J. Wu, T. Liu, N. Yu, et al., *Tribol. Lett.* 69 (2021) 36.
- [85] M. Michalec, P. Svoboda, I. Krupka, et al., *Friction* 8 (2020) 982–994.
- [86] Y.P. Ding, R. Liu, L. Wang, et al., *Prot. Met. Phys. Chem. Surf.* 56 (2020) 392–404.
- [87] S. Kawada, S. Ogawa, S. Sasaki, M. Miyatake, *Tribol. Online.* 14 (2019) 71–77.
- [88] S. Radice, T. Holcomb, R. Pourzal, et al., *Biotribology* 18 (2019) 100090.
- [89] B. Weber, T. Suhina, T. Junge, et al., *Nat. Commun.* 9 (2018) 888.
- [90] F. Mangolini, A. Rossi, N.D. Spencer, *Tribol. Lett.* 45 (2011) 207–218.
- [91] G. Greenwood, J.M. Kim, S.M. Nahid, et al., *Nat. Commun.* 14 (2023) 5801.
- [92] B. Shi, X. Gan, K. Yu, et al., *npj 2D Mater. Appl.* 6 (2022) 39.
- [93] J.N. Israelachvili, *J. Colloid Interface Sci.* 110 (1986) 263–271.
- [94] J.M. Gregoire, D. Dale, A. Kazimirov, et al., *Rev. Sci. Instrum.* 80 (2009) 123905.
- [95] U. Raviv, P. Laurat, J. Klein, *Nature* 413 (2001) 51–54.
- [96] U. Raviv, S. Giasson, J. Frey, J. Klein, *J. Phys. Condens. Matter* 14 (2002) 9275–9283.
- [97] Y. Leng, *J. Phys. Condens. Matter* 20 (2008) 354017.
- [98] Y. Leng, P.T. Cummings, *Hydration Structure and Shear Viscosity of Water Nanoconfined Between Mica Surfaces* (2006) 505–510.
- [99] N. Kavokine, M.L. Bocquet, L. Bocquet, *Nature* 602 (2022) 84–90.
- [100] E.N.D.C. Andrade, C. Dodd, *Proc. R. Soc. London, Ser. A* 187 (1997) 296–337.
- [101] E.N.D.C. Andrade, C. Dodd, *Nature* 143 (1939) 26–27.
- [102] R.J. Hunter, J. Leyendekkers, *J. Chem. Soc., Faraday Trans. 1* 74 (1978) 440–455.
- [103] E.N.D.C. Andrade, C. Dodd, *Proc. R. Soc. London, Ser. A* 204 (1997) 449–464.
- [104] S. Li, P. Bai, Y. Li, et al., *Friction* 9 (2020) 513–523.
- [105] L. Ma, A. Gaisinskaya-Kipnis, N. Kampf, J. Klein, *Nat. Commun.* 6 (2015) 6060.
- [106] A. Gaisinskaya-Kipnis, L. Ma, N. Kampf, J. Klein, *Langmuir* 32 (2016) 4755–4764.
- [107] L. Pashazanusi, M. Oguntoye, S. Oak, et al., *Langmuir* 34 (2018) 801–806.
- [108] L. Pashazanusi, K. Kristiansen, S. Li, et al., *Front. Mech. Eng.* 5 (2019), doi:10.3389/fmech.2019.00039.
- [109] R.M. Pashley, J.N. Israelachvili, *J. Colloid Interface Sci.* 97 (1984) 446–455.
- [110] U. Raviv, J. Klein, *Science* 297 (2002) 1540.
- [111] Z. Li, Q. Liu, D. Zhang, et al., *Nanoscale Horiz.* 7 (2022) 368–375.
- [112] T. Han, C. Zhang, J. Luo, *Langmuir* 34 (2018) 11281–11291.
- [113] T. Han, C. Zhang, J. Li, et al., *J. Phys. Chem. Lett.* 11 (2019) 184–190.
- [114] P. Ma, Y. Liu, K. Han, et al., *Friction* 12 (2023) 591–605.
- [115] T. Han, W. Cao, Z. Xu, et al., *Sci. Adv.* 9 (2023) ead3902.
- [116] S. Jahn, J. Seror, J. Klein, *Annu. Rev. Biomed. Eng.* 18 (2016) 235–258.
- [117] J. Klein, *Friction* 1 (2013) 1–23.
- [118] Z. Li, Q. Liu, Q. Li, M. Dong, *Nano Res.* 16 (2022) 1096–1100.
- [119] J. Li, C. Zhang, P. Cheng, et al., *Langmuir* 32 (2016) 5593–5599.
- [120] N. Kampf, C. Wu, Y. Wang, *J. Phys. Chem. Lett.* 32 (2016) 11754–11762.
- [121] M. Chen, W.H. Briscoe, S.P. Armes, J. Klein, *Science* 323 (2009) 1698.
- [122] O. Tairy, N. Kampf, M.J. Driver, et al., *Macromolecules* 48 (2015) 140–151.
- [123] R. Sorkin, Y. Dror, N. Kampf, *J. Klein, Langmuir* 30 (2014) 5005–5014.
- [124] R. Goldberg, A. Schroeder, Y. Barenholz, J. Klein, *Biophys. J.* 100 (2011) 2403–2411.
- [125] Y. Cao, N. Kampf, W. Lin, J. Klein, *Soft Matter* 16 (2020) 3973–3980.
- [126] W. Lin, M. Kluzek, N. Iuster, et al., *Science* 370 (2020) 335–338.
- [127] P. Ma, Y. Liu, Y. Tian, L. Ma, *Colloids Surf. A* 660 (2023) 130862.
- [128] R. Tivony, Y. Zhang, J. Klein, *J. Phys. Chem. C* 125 (2021) 3616–3622.
- [129] T. Gao, J. Li, S. Yi, J. Luo, *J. Phys. Chem. C* 124 (2020) 23745–23751.
- [130] R.D. Rogers, K.R. Seddon, *Science* 302 (2003) 792–793.
- [131] O.Y. Fajardo, F. Bresme, A.A. Kornyshev, M. Urbakh, *ACS Nano* 11 (2017) 6825–6831.
- [132] X. Gong, L. Li, *Chin. Chem. Lett.* 28 (2017) 2045–2052.
- [133] R.M. Espinosa-Marzal, A. Arcifa, A. Rossi, N.D. Spencer, *J. Phys. Chem. C* 118 (2014) 6491–6503.
- [134] R.M. Espinosa-Marzal, A. Arcifa, A. Rossi, N.D. Spencer, *J. Phys. Chem. Lett.* 5 (2014) 179–184.
- [135] D. Zheng, X. Wang, M. Zhang, C. Ju, *Tribol. Lett.* 67 (2019) 47.
- [136] H. Khanmohammadi, W. Wijnarko, N. Espallargas, *Tribol. Lett.* 68 (2020) 130.
- [137] A. Khan, O.P. Sharma, O.P. Khatri, *Ind. Eng. Chem. Res.* 60 (2020) 333–342.
- [138] R. Gusain, A. Khan, O.P. Khatri, *J. Mol. Liq.* 301 (2020) 112322.
- [139] R. González, D. Ramos, D. Blanco, et al., *Friction* 7 (2018) 282–288.
- [140] W. Lin, N. Kampf, J. Klein, *ACS Nano* 14 (2020) 7008–7017.
- [141] T. Gao, J. Li, W. Wang, J. Luo, *Friction* 11 (2022) 513–523.
- [142] S. He, Y. Meng, Y. Tian, *Tribol. Lett.* 41 (2010) 485–494.
- [143] F. Gatti, T. Amann, A. Kailer, et al., *Sci. Rep.* 10 (2020) 17634.
- [144] G.A. Pilkington, A. Oleshevych, P. Pedraz, et al., *Phys. Chem. Chem. Phys.* 22 (2020) 19162–19171.
- [145] Z. Wang, L. Zhu, L. Si, et al., *J. Mater. Eng. Perform.* 29 (2020) 5718–5727.
- [146] W. Huang, L. Kong, X. Wang, *Tribol. Lett.* 65 (2016) 17.
- [147] C.S. Perez-Martinez, T.S. Groves, S. Perkin, *J. Phys. Condens. Matter* 33 (2021) 31LT02.
- [148] Y. Zhang, C. Wang, L. Shi, et al., *Intelligent friction testing for lubricating properties of ionic liquids under an external electric field*, in: *2022 IEEE 2nd International Conference on Power, Electronics and Computer Applications (ICPECA)*, 2022, pp. 989–993.
- [149] S. Perkin, T. Albrecht, J. Klein, *Phys. Chem. Chem. Phys.* 12 (2010) 1243–1247.
- [150] B. Rotenberg, M. Salanne, *J. Phys. Chem. Lett.* 6 (2015) 4978–4985.
- [151] G. Krämer, R. Bennewitz, *J. Phys. Chem. C* 123 (2019) 28284–28290.
- [152] F. Nemoto, M. Kofu, M. Nagao, et al., *J. Chem. Phys.* 149 (2018) 054502.
- [153] C. Hardacre, J.D. Holbrey, C.L. Mullan, et al., *J. Chem. Phys.* 133 (2010) 074510.
- [154] H.K. Kashyap, C.S. Santos, H.V. Annappureddy, et al., *Faraday Discuss.* 154 (2012) 133–143.
- [155] S. Perkin, *Phys. Chem. Chem. Phys.* 14 (2012) 5052–5062.
- [156] S. Perkin, L. Crowhurst, H. Niedermeyer, et al., *Chem. Commun.* 47 (2011) 6572–6574.
- [157] O. Werzer, E.D. Cranston, G.G. Warr, et al., *Phys. Chem. Chem. Phys.* 14 (2012) 5147–5152.
- [158] C.M. Roland, S. Bair, R. Casalini, *J. Chem. Phys.* 125 (2006) 124508.
- [159] T. Yamaguchi, S. Miyake, S. Koda, *J. Phys. Chem. B* 114 (2010) 8126–8133.
- [160] H. Li, R.J. Wood, M.W. Rutland, R. Atkin, *Chem. Commun.* 50 (2014) 4368–4370.
- [161] J. Sweeney, F. Hausen, R. Hayes, et al., *Phys. Rev. Lett.* 109 (2012) 155502.
- [162] H. Li, M.W. Rutland, M. Watanabe, R. Atkin, *Faraday Discuss.* 199 (2017) 311–322.
- [163] O.Y. Fajardo, F. Bresme, A.A. Kornyshev, M. Urbakh, *J. Phys. Chem. Lett.* 6 (2015) 3998–4004.
- [164] S. Di Lecce, A.A. Kornyshev, M. Urbakh, F. Bresme, *Phys. Chem. Chem. Phys.* 23 (2021) 22174–22183.
- [165] K. Pivnic, O.Y. Fajardo, F. Bresme, et al., *J. Phys. Chem. C* 122 (2018) 5004–5012.
- [166] S. Di Lecce, A.A. Kornyshev, M. Urbakh, F. Bresme, *ACS Appl. Mater. Interfaces* 12 (2020) 4105–4113.
- [167] Y. Zhang, D. Jin, R. Tivony, et al., *Nat. Mater.* 23 (2024) 1720–1727.
- [168] J.K. Di Jin, *ArXiv* (2023) arXiv:2303.08555v08555, doi:10.48550/arXiv.2303.08555.
- [169] D. Jin, Y. Zhang, J. Klein, *ArXiv* (2023) arXiv:2303.08551v08552, doi:10.48550/arXiv.2303.08551.
- [170] J.Y. Park, D.F. Ogletree, P.A. Thiel, M. Salmeron, *Science* 313 (2006) 186–186.
- [171] A. Song, R. Shi, H. Lu, et al., *Nano Lett.* 22 (2022) 1889–1896.
- [172] F. He, X. Yang, Z. Bian, et al., *Small* 15 (2019) e1904613.
- [173] P. Zhu, H. Peng, G. Zhao, N. Chen, *Rev. Sci. Instrum.* 92 (2021) 055002.
- [174] D. Choi, S. Lee, S. Kim, et al., *Scr. Mater.* 58 (2008) 870–873.
- [175] Y. Meng, H. Jiang, P.L. Wong, *Tribol. Trans.* 44 (2001) 567–574.
- [176] N.P. Brandon, R.J.K. Wood, *Wear* 170 (1993) 33–38.
- [177] H. Jiang, P.L. Wong, Y. Meng, S. Wen, *Lubrication Science* 15 (2003) 275–292.
- [178] Y. Meng, B. Hu, Q. Chang, *Wear* 260 (2006) 305–309.
- [179] P. Snapp, J.M. Kim, C. Cho, et al., *NPG Asia Mater.* 12 (2020) 22.
- [180] F. Hausen, J.A. Zimmet, R. Bennewitz, *Surf. Sci.* 607 (2013) 20–24.
- [181] A. Labuda, F. Hausen, N.N. Gosvami, et al., *Langmuir* 27 (2011) 2561–2566.
- [182] M. Valtiner, X. Banquy, K. Kristiansen, et al., *Langmuir* 28 (2012) 13080–13093.
- [183] M. Valtiner, K. Kristiansen, G.W. Greene, J.N. Israelachvili, *Adv. Mater.* 23 (2011) 2294–2299.
- [184] S.H. Donaldson, M. Valtiner, M.A. Gebbie, et al., *Soft Matter* 9 (2013) 5231–5238.
- [185] Z.-L. Cheng, L. Ma, Z. Liu, *Chin. Chem. Lett.* 32 (2021) 583–586.
- [186] X. Ge, Z. Chai, Q. Shi, et al., *Friction* 11 (2023) 1953–1973.
- [187] M. Rejhon, F. Lavini, A. Khosravi, et al., *Nat. Nanotechnol.* 17 (2022) 1280–1287.
- [188] M. Ruths, N.A. Alcantar, J.N. Israelachvili, *J. Phys. Chem. B* 107 (2003) 11149–11157.
- [189] J.E. Houston, H.I. Kim, *Acc. Chem. Res.* 35 (2002) 547–553.
- [190] N.J. Brewer, B.D. Beake, G.J. Leggett, *Langmuir* 17 (2001) 1970–1974.
- [191] M.B. Elinski, B.D. Menard, Z. Liu, J.D. Batteas, *J. Phys. Chem. C* 121 (2017) 5635–5641.
- [192] J. Li, W. Cao, J. Li, M. Ma, *J. Colloid. Interface. Sci.* 596 (2021) 44–53.
- [193] K. Ahmad, Q. Yang, A. Martini, *Langmuir* 38 (2022) 6273–6280.
- [194] Q. Yang, W. Nanney, X. Hu, et al., *Tribol. Lett.* 68 (2020) 63.
- [195] J. Lahann, S. Mitragotri, T.-N. Tran, et al., *Science* 299 (2003) 371–374.
- [196] K.S.K. Karupiah, Y. Zhou, L.K. Woo, S. Sundararajan, *Langmuir* 25 (2009) 12114–12119.
- [197] M. Luo, A. Amegashie, A. Chua, et al., *J. Phys. Chem. C* 116 (2012) 13964–13971.
- [198] P. Bhadra, S.W.I. Siu, *Langmuir* 37 (2021) 1913–1924.
- [199] S.T. Milner, *Science* 251 (1991) 905–914.
- [200] J. Klein, E. Kumacheva, D. Mahalu, et al., *Nature* 370 (1994) 634–636.
- [201] M. Chen, W.H. Briscoe, S.P. Armes, et al., *ChemPhysChem* 8 (2007) 1303–1306.

- [202] P.A. Schorr, T.C.B. Kwan, S.M. Kilbey, et al., *Macromolecules* 36 (2003) 389–398.
- [203] K. Ohno, T. Sakamoto, T. Minagawa, Y. Okabe, *Macromolecules* 40 (2007) 723–730.
- [204] H. Sakata, M. Kobayashi, H. Otsuka, A. Takahara, *Polym. J.* 37 (2005) 767–775.
- [205] E. Eiser, J. Klein, T.A. Witten, L.J. Fetters, *Phys. Rev. Lett.* 82 (1999) 5076–5079.
- [206] J. Klein, E. Kumacheva, D. Perahia, L.J. Fetters, *Acta Polym.* 49 (1998) 617–625.
- [207] S. Feng, Y. Liu, J. Li, S. Wen, *Macromolecules* 54 (2021) 5719–5727.
- [208] V. Adibnia, M. Olszewski, G. De Crescenzo, et al., *J. Am. Chem. Soc.* 142 (2020) 14843–14847.
- [209] M. Chen, H. Briscoe Wuge, P. Armes Steven, J. Klein, *Science* 323 (2009) 1698–1701.
- [210] U. Raviv, S. Giasson, N. Kampf, et al., *Nature* 425 (2003) 163–165.
- [211] U. Raviv, S. Giasson, N. Kampf, et al., *Langmuir* 24 (2008) 8678–8687.
- [212] Y. Zhang, W. Zhao, X. Zhao, et al., *Friction* 12 (2024) 1757–1770.
- [213] W. Zhao, Y. Zhang, X. Zhao, et al., *Adv. Sci.* (2024) e2401000.
- [214] Y. Zhang, W. Zhao, S. Ma, et al., *Nat. Commun.* 13 (2022) 377.
- [215] D.C. Grahame, *Chem. Rev.* 41 (1947) 441–501.
- [216] J.N. Israelachvili, *Intermolecular and Surface Forces*, Elsevier, Singapore, 2011.
- [217] H. Ouyang, Z. Xia, J. Zhe, *Nanotechnology* 20 (2009) 195703.
- [218] S. Sun, G. Yin, Y.K. Lee, et al., *Biochem. Biophys. Res. Commun.* 404 (2011) 684–688.
- [219] H. Ding, C. Duan, C. Tong, *J. Chem. Phys.* 146 (2017) 034901.
- [220] G. Kasparyan, J.S. Hub, *J. Chem. Theory. Comput.* 19 (2023) 2676–2683.
- [221] R.A. Bockmann, B.L. de Groot, S. Kakorin, et al., *Biophys. J.* 95 (2008) 1837–1850.
- [222] R. Tivony, J. Klein, *Faraday Discuss.* 199 (2017) 261–277.
- [223] S.L.C. Drew McCormack, Derek Y.C.Chan, *J. Colloid Interface Sci.* 169 (1995) 177–196.
- [224] S.L. Carnie, D.Y.C. Chan, *J. Colloid Interface Sci.* 155 (1993) 297–312.
- [225] S.L. Carnie, D.Y.C. Chan, J.S. Gunning, *Langmuir* 10 (1994) 2993–3009.
- [226] R. Tivony, N. Iuster, J. Klein, *Langmuir* 32 (2016) 7346–7355.
- [227] R. Tivony, D.B. Yaakov, G. Silbert, J. Klein, *Langmuir* 31 (2015) 12845–12849.
- [228] M.J. Holst, F. Saied, *J. Comput. Chem.* 16 (1995) 337–364.
- [229] A.E. James, D.J.A. Williams, *J. Colloid Interface Sci.* 107 (1985) 44–59.
- [230] S.L. Carnie, D.Y.C. Chan, *J. Colloid Interface Sci.* 161 (1993) 260–264.
- [231] V.E. Shubin, P. Kékicheff, *J. Colloid Interface Sci.* 155 (1993) 108–123.
- [232] G. Trefalt, S.H. Behrens, M. Borkovec, *Langmuir* 32 (2016) 380–400.
- [233] I. Popa, G. Gillies, G. Papastavrou, M. Borkovec, *J. Phys. Chem. B* 114 (2010) 3170–3177.
- [234] P.M. Biesheuvel, M. van der Veen, W. Norde, *J. Phys. Chem. B* 109 (2005) 4172–4180.
- [235] W. Rocchia, E. Alexov, B. Honig, *J. Phys. Chem. B* 105 (2001) 6507–6514.
- [236] A. Nicholls, B. Honig, *J. Comput. Chem.* 12 (1991) 435–445.
- [237] K.E. Forsten, R.E. Kozack, D.A. Lauffenburger, S. Subramaniam, *J. Phys. Chem.* 98 (1994) 5580–5586.