Current trends in the physics of nanoscale friction

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ABSTRACT
Tribology, which studies surfaces in contact and relative motion, includes friction, wear, and lubrication, straddling across different fields: mechanical engineering, materials science, chemistry, nanoscience, and physics. This short review restricts to the last two disciplines, with a qualitative survey of a small number of recent progress areas in the physics of nanofriction.

ARTICLE HISTORY
Received 6 April 2017
Accepted 9 May 2017

KEYWORDS
Nanotribology; friction and dissipative processes; condensed matter physics

PACS
68.35.Af Atomic scale friction; 46.55.+d Tribology and mechanical contacts
81.40.Pq Friction; lubrication; wear
64.70.Nd Structural transitions in nanoscale materials

1. Introduction

From the elemental surface sliding of an atomically sharp tip, to the squeaking of door hinges, all the way up to the complex evolution of a geophysical fault, friction abounds in nature – spanning, in disparate areas, vastly different scales of length, time, and energy. Despite the fundamental, practical and technological importance of tribology, several key physical aspects of mechanical dissipative phenomena are not yet fully understood, mostly due to the complexity of highly out-of-equilibrium non-linear processes often occurring across ill-characterized sliding interfaces. For centuries, and until quite recently, scientists made only

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modest inroad on the atomic-level physics involved in frictional processes, leaving developments largely to empiricism and engineering. With the on-going quest for ‘holy grails’ such as the control of friction by atomistic design, or the hopeful gap-bridging across the different scales, from fundamental atomic principles to macroscopic description, new avenues of research are being pursued and new discoveries are being made – and that, especially at the nano/meso scales, thanks to remarkable developments in nanotechnology. Progress at the fundamental physics level is going on both through nanofriction experiments, and through theory from computer simulations to non-equilibrium statistical mechanics. Far from covering any of that exhaustively, we merely intend to provide a glance at some themes which in our view contain the seed for further work, and whose development is familiar through our recent research involvement.

In that spirit we will therefore cover: the elementary processes of dry, wearless surface sliding (Section 2); structural lubricity – sometimes called ‘superlubricity’ (Section 3); thermolubricity (Section 4); tribological properties of layered, graphitic-like, materials (Section 5); electronic, magnetic, and quantum effects in friction (Section 6); artificial frictional systems with colloids and ions in optical lattices (Section 7).

### 2. Static and kinetic friction: from depinning to sliding

A slider at rest generally requires a finite force, the static friction force, in order to start sliding. Subsequently, a different force, the kinetic or dynamic friction force, often smaller than the static one, needs to be applied in order to maintain a steady sliding motion.

At face value, the transition from a static strained configuration to full sliding is conceptually as simple as overcoming an energy barrier. However, practical single- and multiple-contact conditions are characterized by complex interaction profiles plus non-trivial internal dynamics. As a result, the interplay of thermal drifts, contact aging, contact–contact interactions, and macroscopic elastic deformations introduce significant complications, and make the depinning transition from static to kinetic friction an active field of research. The depinning dynamics affects in particular the transition between stick-slip and smooth sliding for sliding friction. Following and extending previous literature, this problem is addressed in the context of the viscoelastic dynamics of a spring-block system driven across a rough surface [1]. The proposed mean-field model provides a microscopic basis for the macroscopic description in terms of rate-and-state equations. A series of experimental studies [2–4] shows that the transition from sticking to sliding is characterized by slip fronts propagating along the interface. Several works model this transition using various techniques including a master-equation type of approach [5–10], mesoscopic models [11], and finite-elements techniques [12–14].
The same fundamental problem is being investigated in the framework of lubrication. Mutually sliding macroscopic machines parts need to be kept lubricated, typically by mineral-based oils, to maintain normal operation, and the same is required for the systems at a microscopic scale. An especially efficient state of lubrication for macroscopic machines is that of hydrodynamic lubrication, with surfaces separated by a relatively thick liquid lubricant film so that direct surface contact and wear is prevented. As a result, the friction coefficient due to the shear of liquid films can be relatively low (~ 0.005). In practice, machines operate mostly in a state of boundary lubrication, where the lubricating film is mostly squeezed out, and the surfaces are protected by films of adsorbed lubricant molecules, often sticking there thanks to chemical reactions.

Down to the micrometer or nanometer scale, hydrodynamic lubrication is difficult to achieve because lubricants are unlikely to flow through a nanometer gap because of the increased effective viscosity and a tendency to layering or even solidification [15–17]. Traditional mineral oils with additives used for boundary lubrication are likely to fail in microscopic contacts for two reasons: (i) mineral oil has poorer lubrication properties for the silicon-based materials widely used to build MEMS than for steel; (ii) for devices at the nanometer scale, lubricant additives are easily of the same size as that of the contact itself, so that the molecules could act rather as an obstructor to the motion of nanocomponent than as a lubricant. As a result, solid lubrication becomes an option for protecting the surfaces in microscopic or nanometer-scale systems.

Ordered Langmuir–Blodgett (LB) films and self-assembled monolayers (SAMs) are currently a popular choice for solid lubrication [19]. With such kinds of lubricant, the dependence of friction on applied load and sliding velocity was investigated in detail [20]. Friction on molecular films is usually significantly reduced compared to the bare surface of the substrates, with typical friction coefficients ranging from 0.05 to 0.1. Friction forces increase with increasing normal load, but generally more slowly than predicted by Amonton’s law. Interestingly, under an increasing applied load, it is observed that the film molecules tilts only at discrete angles, due to the ratchet-like intermolecular binding and the zigzagging C–C skeleton in the film chains [18]. These discrete changes in tilt angles result in a stepwise decrease in the film height and corresponding increase in friction as illustrated in Figure 1. Similar quantized changes in film thickness and friction forces are observed also in confined liquid films [21–23], and should therefore be considered as a fundamental feature of highly-ordered closely-packed molecular films [24].

In the presence of surface films, the dependence of friction on the sliding velocity is more intricate. Low-speed stick-slip dynamics of SAM-covered mica surfaces would evolve into smooth sliding when the sliding velocity exceeds a certain threshold [25]. In Atomic Force Microscopy (AFM) experiments, when the tip scans over the monolayers at low speeds, friction force is reported to increase with the logarithm of the velocity, similar to that observed when the tip
Figure 1. Height (top) and friction force (bottom) measured on islands of C16 thiols on Au(111) as a function of applied load. Stepwise changes are observed at critical loads. Some heights in particular are more stable than others, as indicated by the length of the plateaus. From Ref. [18], copyright 2001, Springer.

scans across crystalline surfaces. This velocity dependence is interpreted in terms of thermally activated depinning of interlocking barriers involving interfacial atoms [26].

3. Contact area dependence and new perspectives in superlubricity

The dependence of friction on the contact area stands at the heart of the quantitative understanding of tribology, and it is interlinked to the theory of the load dependence. The macroscopic Da Vinci-Amontons’ law – friction independent of area – is not confirmed at the microscopic scale. In most nanoscale investigations, the friction of a single contact is found to increase linearly with the contact area [27–29]. In contrast, structurally mismatched atomically flat and hard crystalline or amorphous surfaces are expected to produce a sublinear increase of friction with contact area. The frequent finding of friction proportional to area even in some of these cases can be understood as a consequence of softness, either of the interface, or of surface contaminants leading to effectively pseudo-commensurate interfaces [30,31]. A systematic investigation of the dependence of friction on the contact area was carried out recently for nano-sized metal
clusters on graphite in ultraclean and even atmospheric conditions [32,33],
whose results indicate a size dependence of kinetic friction which is scattered.
For certain clusters, a regular linear scaling with area is observed, while others can be
 grouped in sets compatible with sublinear scaling, which match the expectations
 for structural lubricity [34–39], sometimes also called superlubricity [40].

Superlubricity, now a pervasive concept of modern tribology, dates back to the
mathematical framework of the Frenkel–Kontorova model for incommensurate
interfaces [41,42]. When two contacting crystalline workpieces are out of registry,
by lattice mismatch or angular misalignment, the minimal force required to
achieve sliding, i.e. the static friction, tends to zero in the thermodynamic
limit – that is, it can at most grow as a power less than one of the area –
provided the two substrates are stiff enough. A parallel reasoning may apply to flat
hard amorphous interfaces [30,43]. These geometrical configurations prevents
asperity interlocking and collective stick-slip motion of the interface atoms, with
a consequent negligibly small frictional force. Practically, systems achieving low
values of dry sliding friction are of great technological interest to significantly
reduce dissipation and wear in mechanical devices functioning at various scales.

Superlubricity is experimentally rare. Until recently, it has been demonstrated
or implied in a relatively small number of cases [29,44–48]. There are now more
evidences of superlubric behavior in cluster nanomanipulation [32,33,49], sliding
colloidal layers [50–52], and inertially driven rare-gas adsorbates [53,54] (see
Figure 2).

Moreover there exists a vast literature discussing superlubric sliding effects in
the context of graphite/graphene flakes on a graphitic substrate. Free movements
of graphene nanoflakes on graphene are observed at low temperature and in
UHV conditions using Scanning Tunneling Microscopy (STM) [55]. This system
exhibits a completely commensurate or incommensurate interface as a function
of the misfit angle and a systematic computational study of the interlayer inter-
action energy in a rigid bi-layer graphene system [56] confirms that interaction
energy is nearly constant for all incommensurate configurations. By taking into
account the flexibility of the graphene nanoflakes, and their tribological response
under the action of increasing normal loads, atomistic simulations [57,58] show
that the smooth sliding dynamics of these type of adsorbates may turn into a
more dissipative stick-slip regime of motion.

A breakdown of structural lubricity may occur at the heterogeneous interface
of graphene and h-BN. Because of lattice mismatch (1.8%), this interface is
intrinsically incommensurate, and superlubricity should persist regardless of the
flake-substrate orientation, becoming more and more evident as the flake size
increases [59]. However, vertical corrugations and planar strains may occur at
the interface even in the presence of weak van der Waals interactions and, since
the lattice mismatch is small, the system can develop locally commensurate and
incommensurate domains as a function of the misfit angle [60,61]. Nonetheless,
spontaneous rotation of large graphene flakes on h-BN is observed after ther-
Figure 2. Slip time of Xe on Cu(111) as a function of film coverage. The scan is taken at $T = 47$ K with a quartz crystal microbalance oscillating at 5 MHz with an amplitude of the Cu electrode of 7.4 nm. The coverage is deduced from the frequency shift, assuming for the monolayer an areal density corresponding to the completion of the $\sqrt{3} \times \sqrt{3}$ commensurate solid phase. The data show remarkably large slip times with increasing submonolayer coverage, which are attributed to superlubricity of the incommensurate Xe islands, followed by a dramatic drop to zero for the dense commensurate monolayer. The inset shows scans of Xe on Cu(111) taken for different Xe depositions on the same substrate at the same amplitude and temperatures between 47 and 49 K. The observed erratic behavior is associated to the first-order nature of the 2D density jump which destroys superlubricity with increasing adsorbate coverage near one monolayer. As such, it is expected to occur with hysteresis, which implies a difference between atom addition and atom removal, as well as occasional differences between one compressional event and another. From Ref. [53], copyright 2015, Macmillan Publishers Limited.

Structural superlubricity over micrometer length scale is reported on HOPG graphite [64,65]. In these experiments, the cap of micron-diameter graphite pillars is dragged laterally, producing a shear movement of the upper-part relative to the base. After releasing the cap, a self-retraction movement is systematically found that leads the sheared mesas back to the original position. A similar result but at smaller length scales [66] is obtained by laterally moving the tip of an AFM microscope glued to a HOPG graphite cylindrical pillar to cut and shear a planar section of the pillar with respect to its base (cylinder radii between 50 and 300 nm). This system develops a shear force which is composed by two parts, a reversible component connected to the relative displacement and a smaller irreversible part identified as the frictional response to sliding, which is attributed to stochastic events due to the interaction of incommensurate interface lattices.

The current capability of synthesizing and manipulating quasi-1D atomically perfect objects of extended length, such as telescopic nanotubes [67–69], graphene nanoribbons [70–72], aromatic polymers [73], or soft biological
filaments [74], opens now the possibility to transpose the peculiar nano-scale tribological properties to extended contacts and exploit them to control sliding-induced energy dissipation in state-of-the-art technological devices (see Figure 3).

Other experiments [75] have achieved vanishingly small friction coefficients in dry macroscale sliding contacts by adding graphene in combination with crystalline diamond nanoparticles. Simulations show that wrapping of graphene patches around the tiny nanodiamonds leads to nanoscrolls with reduced contact area that slide easily against an amorphous diamond-like carbon surface.

In such expanding scenario towards larger scales, the robustness of the superlubricity phenomenon remains a challenge, and the conditions of its persistence or the mechanisms leading to its failure are cast as key questions to be addressed. Indeed, we know from theory and simulation [76–79] that even in clean wearless friction experiments with perfect atomic structures, superlubricity at large scales may, for example, surrender due to the soft elastic strain deformations of contacting systems.

4. Temperature dependence and thermolubricity

In classical physics, all barriers are surmounted by thermal fluctuations at finite temperature, provided one could wait long enough. While this statement may easily be academic for macroscopic sliders, where the waiting time could exceed the age of the universe, the consequence for microscopic or nanoscopic sliders...
is that friction must vanish in the limit of zero sliding velocity, then growing linearly at nonzero velocity. This is the essence of the substantial suppression of friction due to thermal effects, referred to in recent times as thermolubricity [80]. L. Prandtl first recognized the role of temperature in reducing friction [81]. In general, the energy landscape of an AFM tip dragged along an atomically flat substrate exhibits valleys and barriers, and thermal excitations at sufficiently low speed always provide sufficient energy to overcome local barriers and enable slip [82]. Thus, it is commonly expected that the friction of a dry nanocontact should classically decrease with increasing temperature provided no other surface or material parameters are altered by the temperature changes [80,83-86].

A breakdown of this simple rule is provided by Friction Force Microscopy (FFM) experiments that find a peak in the wearless friction of a point contact at cryogenic temperatures for several classes of materials, including amorphous, crystalline, and layered surfaces [87,88]. Within the Prandtl–Tomlinson (PT) model [89,90], simulations reveal that temperature can affect the slip length resulting in a non-monotonic temperature dependence of friction [91]. Simulations best representing the experimental conditions show that this dependence emerges from two competing processes acting at the interface: the thermally activated formation and the rupturing of an ensemble of atomic contacts [88,92]. In addition, a new competing mechanisms due to a thermal instability inherent in AFM measurement has been proposed [93]. Simulations taking into account only this effect show a friction plateau at cryogenic temperatures. In that limit, one should also worry about quantum effects, an aspect which has not received much attention so far.

An extension of the PT model, incorporating the possibility of thermally activated contact strengthening, reproduces the normal PT-like behavior of the friction force at sufficiently low and high temperatures. In the intermediate temperature range, the model explains the experimentally observed possibility of a minimum and a maximum in the temperature dependence [94].

Thermal effects have also been investigated using a Quartz Crystal Microbalance (QCM). A recent nanofriction experiment reveals that Xe monolayers are fully pinned to a graphene surface at low temperature [95]. Above 30 K, the Xe film slides. The depinning onset coverage beyond which the film starts sliding decreases with temperature. Similar measurements repeated on bare gold show an enhanced slippage of the Xe films and a decrease of the depinning temperature below 25 K. Molecular-dynamics simulations relying on ab-initio-derived potentials indicate that the key mechanism to interpret this thermolubric effect is the size dependence of the island commensurability. The latter quantity is deeply affected also by the lattice misfit, which explains the different frictional behavior of Xe on graphene and gold [96]. All aforementioned investigations are carried out under UHV condition, where probe and sample can be prevented from being polluted. However, the contacting surfaces of moving elements in technological devices are usually in atmospheric
environment and may be covered by very thin water layers. Meniscus bridges might then form when the neighboring surfaces are in contact or close to each other. FFM experiments with cantilever probes featuring an in situ solid-state heater report an increase in friction by a factor of 4 in humid air varying the tip temperature from 25°C to 120°C, while in dry nitrogen friction decreases by ∼ 40 [97]. These trends are attributed to thermally assisted formation of capillary bridges between the tip and substrate in air, and thermally assisted sliding in dry nitrogen [97,98]. Increasing the temperature above ∼ 150°C drives water away from the contact. The friction force then decreases substantially and it becomes equal to that measured in dry nitrogen [99]. The thermally activated growth process of a capillary meniscus also affects the adhesion force between an AFM tip and a hydrophilic surface: it decreases logarithmically with the sliding velocity and vanishes at high sliding velocities [100]. Recent FFM experiments demonstrate that high humidity at low temperature enhances the liquid lubricity, while at higher temperature moisture hinders the thermolubric effect due to the formation of liquid bridges [101]. Friction response to the dynamic lubricity in both high- and low-temperature regimes keeps the same trends, namely the friction force decreases with increasing the amplitude of the applied vibration on the tip regardless of the relative humidity levels [101].

5. Layered materials

Graphene physics was awarded by Nobel Prize in 2010. Since then, experiments and simulations specifically devoted to tribology on graphene and other 2D materials attracted an increasing interest. Evidence of a large reduction of friction force (from 10 to 15 times compared to silicon or metal-oxide surfaces, Figure 4) has been accumulating through FFM experiments in a number of different graphene systems. These systems include graphene epitaxially grown on SiC [102], exfoliated graphene transferred on SiO₂ [103,104], suspended graphene membranes [104,105], and graphene grown by chemical vapor deposition (CVD) on metals [106–108]. Because of this frictional reduction, many studies indicate graphene as the thinnest solid-state lubricant and anti-wear coating [109–111]. Graphene is also an ideal playground for testing basic concepts in tribology, being one of the best crystalline surfaces that is easily accessible both experimentally and in simulation.

At the nanoscale, graphene systems exhibit a number of tribological effects. In few-layer systems, the importance of out-of-plane deformations, the influence of the supporting substrate and the role of van der Waals interactions are subject to an intense debate. Accurate FFM measurements on few-layer graphene systems show that friction decreases by increasing graphene thickness from a single layer up to 4–5 layers, and then it approaches graphite values [102,104,106,112,113]. This phenomenon is attributed to the out-of-plane ‘puckering’ [104] deformation that builds up when the AFM tip pushes and slides over a graphene sheet. Friction
Figure 4. (a) Contact-mode topography image obtained with a normal load of 58.8 ± 0.2 nN in vacuum conditions. The region comprises a graphene monolayer (ML), a bi-layer (BL) and the bare SiO₂ substrate. (b) Friction force \( (F_f) \) map of the same region of panel (a). A marked difference between graphene region and the SiO₂ substrate is clearly visible and it masks the small difference between ML and BL friction force. The analysis of the friction distribution histogram shows that the friction signal is relatively high on SiO₂ \( (F_f = 48 ± 5 \text{ nN}) \) and decreases nearly ten times moving to the graphene covered regions (ML: \( F_f = 5.4 ± 0.7 \text{ nN} \); BL: \( F_f = 4.0 ± 0.5 \text{ nN} \)). From Ref. [107], copyright 2015, IOP Publishing.

increases because graphene deformations enhance the real contact area at the tip apex. In this interpretation, the amount of deformation decreases with increasing number of layers, as revealed by computer simulations [114–117], with the result that friction diminishes for increasing graphene thickness.

A direct evaluation of out-of-plane deformations is a difficult task because the analysis of out-of-plane elasticity of supported 2D films requires indentation depths smaller than the film’s interlayer spacing. Recent sub-Ångström resolution indentation measurements show a dependence on the number of layers composing the system [118] and the influence of graphene-substrate interaction as revealed originally by FFM experiments at ‘negative’ load [119]. Finally, within the intense debate about proper simulation of van der Waals interactions in h-BN and graphene, a new thickness-dependent friction mechanism is introduced where the interlayer interactions of the sliding top graphene sheet with the bottom layers depend on the number of layers [120].

Many efforts aim at taking advantage of the exceptional lubricant properties of graphene for micro or macro-mechanical systems. Millimeter-large graphene films grown on Cu or Ni by CVD and then transferred on SiO₂ effectively reduce adhesion and friction forces, as revealed by experiments performed with contact size \( ~100 \mu \text{m} \) and loads in the tens of mN [110]. Wear tracks are visible at the end of these tests and the question arises whether the pristine graphene sheet or the accumulation of graphene debris on the counterparts are responsible for the difference. Extensive ramping force scratch tests carried out on exfoliated and epitaxial graphene at ambient conditions, on SiO₂ and SiC respectively, exhibit
a very low friction force before coating failure, thus on presumably pristine graphene, and yield a friction coefficient of 0.03 before rupture for all graphene samples [109]. A similar work on single-layer graphene grown epitaxially on SiC indicates that intact graphene coverage provides, initially, a very low friction coefficient, which quickly evolves to a nearly stable value five times lower than that of SiC [121]. An analysis of the sliding track by means of FFM, i.e. with nano-scale lateral resolution, reveals that the stable lubrication regime is a mixed effect due to a covalently bound graphitic interface layer (always present beneath graphene epitaxially grown on SiC) and genuine graphene patches remaining attached to the substrate.

Atomistic simulations are used to shed light into the failure mechanisms [122]. A spherical asperity with radius of 2 nm is moved over a graphene monolayer placed in registry on a perfectly rigid substrate. Applying a nominal load up to a few hundred nN, graphene never delaminates and a low substrate-membrane adhesion seems to reduce the overall damage to the graphene layer, allowing a substantial recovery of the load-bearing capability of the graphene post tearing. Simulations and experiments on nano indentation, sliding and scratching of graphene covered Pt(111) surfaces are carried out using a repulsive interaction between tip and the surface [123] and a deformable substrate. The simulations show, in agreement with experiments, three indentation and sliding regimes. At low loads, the deformation is purely elastic and sliding is almost frictionless. As the load is increased, the Pt substrate yields plastically but graphene remains undamaged and friction increases due to Pt plowing. Finally, graphene ruptures. The ability of graphene to increase the load carrying capacity of this soft interface is particularly remarkable. Additionally graphene shows a self-healing capacity during sliding that seems to contribute to maintain stable lubrication effects.

6. Electronic, magnetic, exotic, and quantum friction

Beside ordinary frictional mechanisms such as phonon generation, mechanical stick-slip, viscous and viscoelastic dissipation, all the way to wear and plastic deformation, there are also less conventional mechanisms, connected with electronic, spin, or phase degrees of freedom, including quantum dissipative processes.

Among them the most notable is electronic friction. Electronic friction arises when, upon sliding on a metal surface, a tip or other moving agent dissipates mechanical energy by exciting local currents in metals, or electron-hole pairs in semiconductors. Since ideally the motion of a tip alone suffices to cause electron scattering generating heat in the metal underneath, the tip’s motion will be damped when sliding on or near a metal [124]. In wearless nanofriction on metals, the relative importance of the phononic and electronic contributions is still a matter of debate. To quantify this ratio experimentally has proven difficult
because the phononic and electronic dissipation channels are generally both active.

One approach to investigate the electronic contribution to friction is to induce large changes in the electronic density in one of the bodies in contact. In doped semiconductors, it is possible to vary the electronic carrier concentration in the space charge region by several orders of magnitude by a bias voltage, essentially switching the behavior from insulating to metallic. With an atomic force microscope tip sliding on a silicon sample patterned with p and n regions, a variation in friction is observed as a function of the bias voltage [125]: a substantial increase in friction is found in the p-doped regions presenting a high carrier concentration near the surface. It appears however that the main contribution to the measured excess friction in contact is not due to the generation of electron-hole pairs but to the force exerted by trapped charges in the oxide surface [126].

Arguably, the most direct way to estimate the relative magnitude of the phononic and electronic contributions to friction is to work across the superconducting transition of a metal sample. Following private suggestions by B.N.J. Persson in the 1990s, this was first experimentally attempted with a quartz-crystal microbalance technique [127]. The results show that the friction between a lead substrate and a few-layers-thick adsorbate film made of solid nitrogen decreases by a factor $\sim 2$ when lead becomes superconducting. However, the transition in the friction coefficient observed in this experiment is quite abrupt, in contrast with the predictions of the Bardeen-Cooper-Schrieffer (BCS) theory, which estimates that thermally excited quasiparticles should lead to a more continuous drop below $T_c$ [128]. Moreover, the same system investigated in a different QCM experiment [129] with improved cryogenics and a controlled Pb surface yields only complete pinning of the nitrogen film to the lead substrate at low temperatures. Subsequent measurements with a more controlled set-up confirm that nitrogen films are quite susceptible to pinning [130]. Further investigations point out important differences in the frictional response of sliding adsorbates. Experiments on nitrogen and helium films on superconducting lead relate electronic friction to the electric polarizability of the adsorbate species [131]. On the other hand, measurements employing lighter elements such as neon, which does slide on a lead surface even at very low temperatures [132], do not show any rise of electronic friction while crossing the superconducting transition, probably because of the small polarizability of Ne atoms [133]. More polarizable adsorbates like nitrogen, krypton and xenon are instead found to be completely pinned to lead below 10 K [134].

A convincing confirmation of electronic friction and of its suppression in the superconducting state is provided by non-contact friction measurements on niobium films carried out across the critical temperature using a highly sensitive cantilever oscillating in the pendulum noncontact geometry in ultrahigh vacuum [135].
Figure 5. Temperature variation of the friction coefficient $\Gamma$ across the critical point $T_c = 9.2$ K of Nb. The red squares correspond to a distance 0.5 nm between the tip and the sample. The error bars represent the deviation of the decay-time raw data from the exponential fit. The data are well fitted by the analytic curve expected from the BCS theory (green line). The black dots correspond to the temperature dependence of the friction coefficient $\Gamma_0$ measured at a separation of several micrometers (free cantilever). For figure clarity, the friction coefficient $\Gamma$ is shifted vertically by a constant ($2.5 \times 10^{-12}$ kg s$^{-1}$) value. Reproduced with permission from Ref. [135]. Copyright 2011, Macmillan Publishers Limited.

The friction coefficient drops by a factor between 2 and 3 when the sample enters the superconducting state (see Figure 5). In this case, the temperature decay of the friction coefficient is found to be in good agreement with the BCS theory [128]. Noncontact friction on Nb has an electronic nature in the metallic state, whereas phononic friction dominates in the superconducting state. This is also supported by different dependences of friction on the probe-sample distance and on the bias voltage in the metallic and superconducting states. The normal-state noncontact electronic friction may proceed in two different ways. One is direct excitation of electron-hole pairs by the van der Waals or Coulomb potential exerted by the tip on the metal surface electrons. The second mechanism is the tip-induced potential-mediated generation of a local deformation of the substrate lattice, i.e., a local phonon, which then decays into electronic excitations of the metal, rather than surviving and carrying energy away as in the superconducting state. Experimental evidence does not clarify which of the two mechanisms is at work.

The same non-contact pendulum technique is applied above the surface of NbSe$_2$ [136], a layered compound exhibiting an incommensurate charge density...
wave (CDW). A multiplicity of dissipation peaks arising at certain distances few nanometers above this surface is reported. Each peak appears at a well-defined tip-surface interaction force of the order of 1 nN, and persists up to 70 K, where the short-range order of CDWs is known to disappear. Comparison of the measurements with a theoretical model suggests that the peaks are associated with local, tip-induced $2\pi$ phase slips of the CDW incommensurate order parameter, and that dissipation maxima arise from hysteretic behavior of the CDW phase as the tip oscillates at specific distances where sharp local slips occur [137], providing an interesting and exotic mechanism for mechanical dissipation. Similarly, dissipation may arise by modifications of magnetic order parameters. It is then natural to consider a possible spin-dependence of frictional forces in the case of magnetic materials [138]. To investigate such an influence, single Co adatoms are moved over a magnetic template by means of a spin-polarized scanning tunneling microscopy tip [139]. It is found that the spin degree of freedom modifies the amount of dissipated energy, the threshold force needed to move the magnetic atom and the tip position at which the jump to the next site occurs. It may look surprising that the spin degree of freedom can play such a significant role in atom manipulation processes, given the different orders of magnitude of chemical and magnetic coupling energies. The reason is that the exchange energy does not have to compete with the adatom binding energy, but only with the energy barriers between adjacent adsorption sites, which can be of similar magnitude as the exchange interaction, especially in manipulation experiments. Because of this similarity, magnetic adatoms can be used as local probes to enhance the magnetic signal of atomic-scale spin structures [140]. Single-spin magnetic dissipation phenomena are observed with magnetic tips on, e.g., antiferromagnetic NiO [141] and are explained theoretically as caused by quantum mechanical spin-flip events [142].

There are, at least in principle, more quantum effects in nanoscale frictional and mechanical dissipation than we can describe. Here we mention just two. Phonon dissipation is entirely quantum at very low temperatures but not readily simulated in that regime. Vacuum friction, due to retardation of electromagnetic waves, and taking place because the speed of relative motion between two sliders reduces their generalized Casimir attraction, has also been outlined theoretically [143–145].

7. **Trapped optical systems: ions and colloids**

The fundamental understanding of the multifaceted nature of microscopic friction, going hand in hand with the possibility of fully testing theoretical predictions, is often hampered by both the impossibility of tuning physical properties of real materials and the lack of well-designed experiments at well-characterized buried interfaces. The field of nanotribology can now benefit from the opportunities offered by handling nano/micro particles with artificial optical potentials,
opening the possibility to change parameters almost freely and to visualize directly the intimate mechanisms of sliding friction in simple controlled cases.

Despite the firm theoretical background of simplified approaches such as the Prandtl-Tomlinson and the Frenkel-Kontorova models [90], describing how properties such as substrate corrugation, temperature, driving velocity and lattice mismatch may influence the tribological response, from intermittent stick-slip dynamics to superlubric regimes of motion, neither of these models has been directly tested experimentally.

Thanks to a highly innovative experimental apparatus [50], a brand new light is cast on elemental tribological processes by exploiting the versatility of charged colloidal systems driven across interfering laser-generated potentials, whose geometry can be tuned at will. While AFM, SFA and QCM yield, a system response in terms of crucial, but averaged, physical quantities, colloidal friction provides an unprecedented real-time insight into the basic dynamical mechanisms at play, excitingly observing what each individual particle is directly doing at the sliding interface.

Specifically, by driving highly charged polystyrene spheres, naturally forming in water a 2D triangular crystal [146,147], across both a commensurate and incommensurate laser-generated substrate geometry, the colloid approach [50] highlights the crucial tribological role played by localized superstructures (such as kinks and antikinks), which emerge as shadow-like density modulations in crystalline overlayers that are out of registry with their substrates. According to theory and numerical simulations [52,148–150], the experiment shows the dramatic change of the static-friction threshold from a strongly pinned colloidal regime to an almost superlubric frictional sliding as a function of the over-layer/substrate lattice mismatch (see Figure 6).

While nucleation dynamics rules the depinning mechanism of a stiff commensurate colloidal monolayer [148], for an incommensurate interface the presence/absence of pinning depends upon the system parameters; when an increasing substrate corrugation turns an initially free-sliding network of solitons into a colloid pinned state, the static friction force crosses a well-defined, Aubry-like, dynamical phase transition, from zero to finite [51,151]. The transition value for the critical corrugation depends significantly upon the relative colloid/substrate orientation, which, energetically, is always slightly misaligned, as shown in recent work [152]. By further considering an optical substrate with quasiperiodic symmetry [153], which lacks translational invariance, the colloidal approach shows how the peculiar phenomenon of directional locking may also occur on overlayers driven on quasicrystalline potentials [154].

From colloidal mesoscale suspensions down to the nanoworld of cold ions, the use of artificial tribology emulators has recently taken us to the ultimate limit of atomic friction. Inspired by earlier theoretical suggestions [155–157], and as predicted by many-particle models [90,158,159], the experimental setup of a laser-cooled Coulomb crystal of ions moving over a periodic light-field potential
Figure 6. Zoom-in (front) of a MD simulated frictional interface between a colloid monolayer and an optical corrugated substrate potential. The overlayer/substrate lattice mismatch, tunable experimental parameter, realizes a network of solitonic structures (back), ruling the system tribological response.

Figure 7. A sketch of the synthetic nanofriction interface between a Coulomb crystal of $^{174}$Yb$^+$ ions and an optical corrugated lattice, with imaging realized through a microscope with single-ion resolution. From Ref. [160], copyright 2015, The American Association for the Advancement of Science.

highlights the practical feasibility to control friction, from strongly dissipative stick-slip to almost free sliding, by tuning the interface structural mismatch [160] and the optical corrugation [161] at the level of just a few interacting atom systems (see Figure 7).
Compared to standard experimental tribology techniques, another outstanding achievement within the framework of such ion-crystal system in a optical lattice relies on the possibility to span almost five orders of magnitude in velocity, while controlling temperature and dissipation [162], emulating the PT model to near perfection.

8. Conclusions

The physics of tribology from the atomic, to the nano and micro scale is alive and well. In this bird’s eye review there is of course neither space nor scope for dozens of exciting ongoing research lines. Yet, we hope to have given at least the flavor of some new and interesting problems that are being discovered and studied, with the interplay of experiments, theory and simulations that are making this area currently hot and rich. Last but not least, the efforts that are being made to develop the physical understanding will undoubtedly contribute in due course to novel methodologies in applied tribology.

Acknowledgements

Discussion and collaboration with A. Benassi, P.P. Baruselli, A.R. Bishop, O.M. Braun, O. Brovko, R. Capozza, Y. Crespo, L. Gigli, R. Guerra, A. Laio, F.P. Landes, D. Mandelli, E. Panizon, F. Pellegrini, B.N.J. Persson, M. Peyrard, S. Prestipino, G.E. Santoro, J. Scheibert, M. Teruzzi, M. Urbakh, T. Zanca, S. Zapperi is gratefully acknowledged.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work is partly funded by the ERC Advanced [grant number 320796-MODPHYSFRICT], and by COSTction MP1303. G.P. also acknowledges Regione Emilia Romagna, Project INTERMECH MO.RE.

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