Review Article: Open Access

DOI: 10.35840/2631-5076/9269

International Journal of
Metallurgy and Metal Physics

ISSN: 2631-5076

Advances in Atomic-Scale Frictions with Stick-Slip and Super-Lubricity

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Abstract

With the development of Micro-/Nanoelectromechanical systems (MEMS/NEMS), the friction problems at micro/nanoscale induced the failure of many devices in MEMS. The basic model of atomic-scale friction and associated advancement of experimental research were reviewed in this paper. Two common atomic-friction behaviors, i.e. stick-slip and super-lubricity friction were also discussed here. Challenges and promising points for future research in atomic-scale friction were enumerated.

Keywords

MEMS, Atomic-scale friction, Stick-slip, Super-lubricity

Introduction

Micro-/nanoelectromechanical systems (MEMS/NEMS) are an important part of the integrated circuit industry and MEMS/NEMS devices like accelerators and resonators have been extendedly applied from the aerospace, automobile industry to the biomedical industry [1]. Due to the miniaturization of these devices, numerous tribological phenomena also happen at micro/nanoscale. For instance, as shown in Figure 1, the continuous friction and wear would induce surface damage in MEMS devices. The surface roughness was enhanced by the friction between the silicon sidewall of MEMS device and the on-chip actuator under oscillation, indicated by the circle in Figure 1a [2]. And the friction and wear reduce the lifetime of the microactuators and make the device fail in less than 10^4 cycles [3]. Stiction also could induce the fracture of the freestanding cantilever in a comb drive (Figure 1b) [4]. Besides, the friction and wear problems are easy to be induced due to the mechanical contact in micro-gears with high-rate rotation [5] and between the rotor and the stator in electrostatic motors [6]. High stiction at the rotor-stator interface limits the operation repeatability in the electrostatic micromotors [7]. The contact-type MEMS switches also require low surface resistance and low friction [8,9]. The strong adhesion or the contact damage directly deteriorate the reliability of the microcontact in MEMS switches [10]. Stiction and wear issues between the yoke and electrode directly influence the operation reliability of micromirror devices [11]. Thus, investigating the friction mechanism is critical to control the damage of devices and improve the feasibility and reliability of MEMS/NEMS like polysilicon microactuators in the magic disk [12], silicon accelerometer in the sensory system [13], polysilicon micro-motors

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Accepted: August 07, 2021; **Published:** August 09, 2021

Wang and Mao. Int J Metall Met Phys 2021, 6:069

Citation: Wang X, Mao SX (2021) Advances in Atomic-Scale Frictions with Stick-Slip and Super-Lubricity. Int J Metall Met Phys 6:069

[7], micromirror in the display device [14], and polysilicon micro-gears in the microturbine [15].

Friction between asperities without the participation of any lubricant is called dry friction [16]. In many practical contacts in MEMS devices, no extra lubricant is added and most of the friction problems belong to the dry friction. So, atomic friction research mainly focuses on the dry contact of two asperities. Here, the theoretical model about single-asperity atomic friction was introduced, and then related experimental research about two typical friction behaviors including the stick-slip and superlubricity were reviewed. Finally, some potential points about future research on atomic-scale friction are listed. Investigating atomic friction is expected to provide significant insights to control the friction damage of micro-devices and their feasibility.

The theoretical model of atomic-scale friction

Friction behaviors could be simply classified into two types, stick-slip and super-lubricity in atomic friction [17]. The stick-slip friction behavior could be interpreted well by the classical Prandtl-Tomlinson model proposed in 1920s [18]. The simplest model is for the one-dimensional case and the friction occurs between one tip dragged by a spring and the materials' surface, as shown in Figure 2. The total energy stored in the system could be simplified into [19].

$$U_{tot}(r,t)=U_{eff}(x)+\frac{1}{2}k(x-vt)^2 \quad (1)$$

Where the right first part is an interaction partial between the tip and surface and the second part is the elastic energy stored in the spring. And the tip located the position x of the minimum U_{tot} and the lateral force could be expressed by [19].

$$F_L=k(x_{tip}-vt)=-\frac{2\pi U_0}{a}\sin\frac{2\pi x_{tip}}{a} \quad (2)$$

and *a* is the lattice distance between two atoms and *k* is the effective spring constant [20-22]. Later, the one-dimensional PT model was extended and developed further. The thermal effect and the scanning velocity [23] or the tip shape [24] also could influence the friction force vibration and the PT model was required to be modified.

For example, the atomic friction was simplified as one suspended atom of the tip head sliding on the substrate in the traditional Pt model and thus the needle tip was applied in experiments to investigate the atomic friction [18]. However, in general, the contact surface in real crystal materials has a two-dimension periodicity and the interaction potential between the tip-substrate should be considered into a two-dimension model [25,26].

When loading conditions and friction configuration change, the friction behavior is expected to transit from the stick-slip to smooth sliding with ultralow friction [27-32]. The ultralow friction also is referred to as super-lubricity which was firstly proposed by Hirano, et al. [33] and the friction coefficient of superlubricity is normally in the order of ~0.001 [34]. The theory to explain the super-lubricity was known as the "Mechanical Instability" [21,35]. The relation of the interaction potential between the tip-surface and the spring

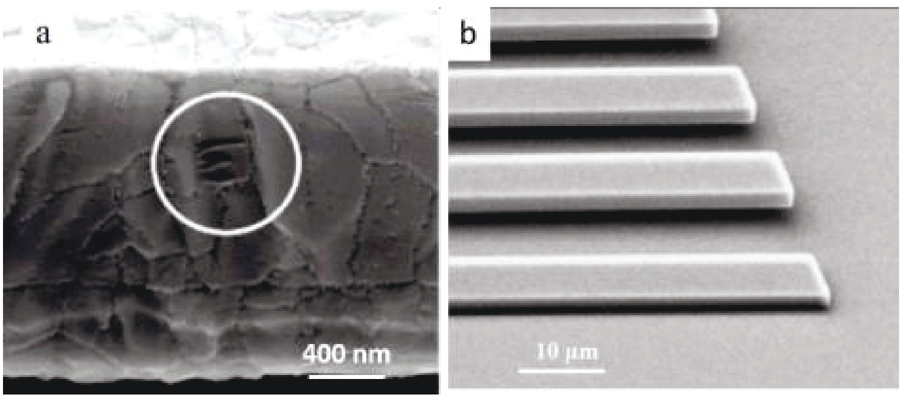

Figure 1: Tribology problems in MEMS/NEMS: a) Damaged surface induced by friction and wear in MEMS devices. The damaged region was marked by the circle. Source: Reprinted with the permission from [2] ©2008 American Chemical Society; b) Stiction-induced fracture of the freestanding cantilever in a comb drive. Source: Reprinted with the permission from [4] ©2002 IOP Publishing.

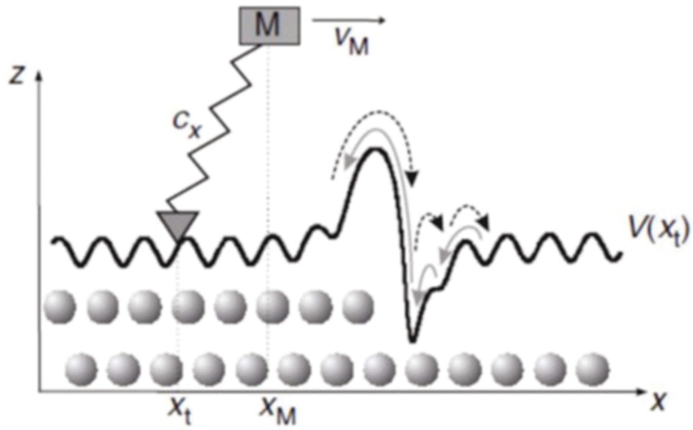

Figure 2: Illustration of The Prandtl-Tomlinson Model. Source: Reprinted with the permission from [22] ©2008 American Physical Society.

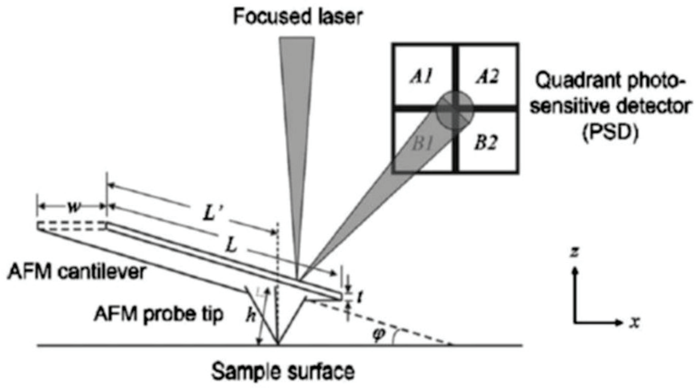

Figure 3: Friction Force Microscopy. Source: Reprinted with the permission from [39] ©2006 AIP Publishing.

stiffness is expressed by a parameter [21,22].

$$\eta = \frac{2\pi^2 U_0}{ka^2} \tag{3}$$

When η > 1, the model is fitted with stick-slip friction behavior. And for *η* > 1, the model could be matched with super-lubricity. The parameter *η* can be adjusted by changing the normal force [36] and the cantilever stiffness [37] to achieve the reduction of the friction force in experimental observation. Predicted friction behaviors and the transition between stick-slip and superlubricity have been revealed by efforts on the experimental observation.

Atomic-scale friction investigated by AFM-based technology

Generally, the friction coefficient-the ratio of the normal force and the friction force at the dynamic friction stage is used to evaluate the friction between two asperities. The critical issue for friction problems is to measure the magnitude of the friction force. However, the friction force is very small at micro/nanoscale contact and the force-sensitive tool is required to detect this small force. Based on the concept of atomic force microscopy (AFM), friction force microscopy or lateral force microscopy (Figure 3) has been invented to determine the friction force between a rigid tip and the contact surface [38,39]. The principle to measure the force is to measure the vertical deflection and torsion of the cantilever using sensitive photosensors. With the aid of friction force microscopy, the friction behavior at atomic scale could be revealed and abundant friction researches have been carried out in previous decades [40]. Numerous MEMS devices are fabricated from silicon (Si)-based materials [41]. Zhang, et al. [42] found that the nanoscale friction behaviors are dominated by the nano-sliding with a low friction coefficient between two-body silicon contact when the surface deformation is within the adhering regime. Using friction force microscopy,

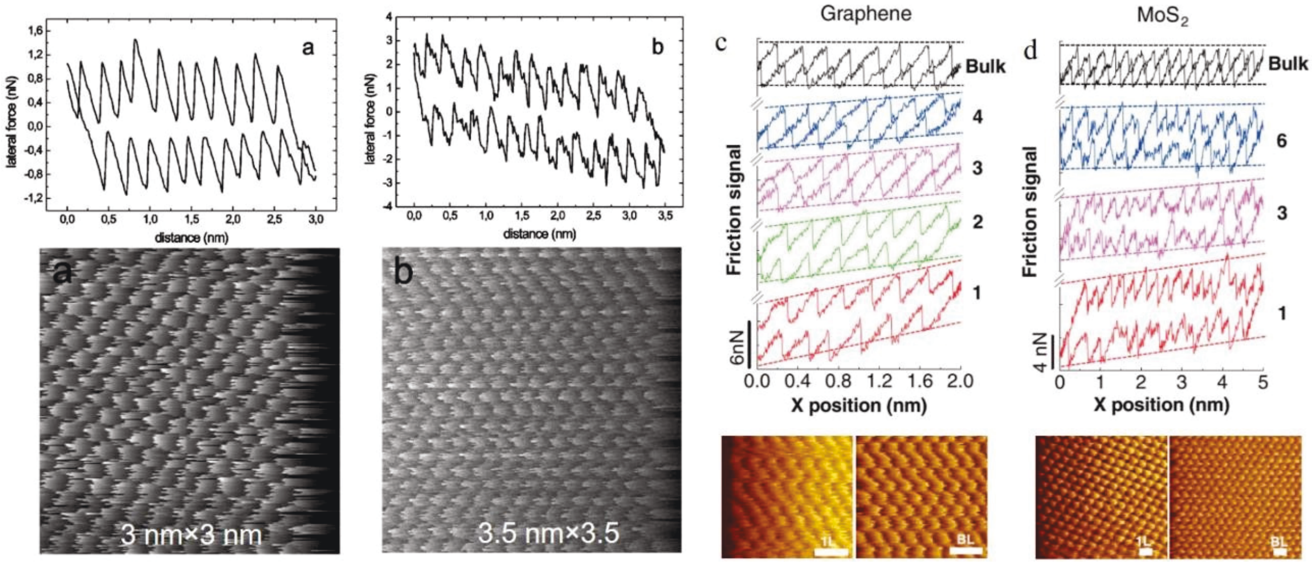

Figure 4: Stick-Slip Friction on Metal Surface and in 2D materials: a,b) The stick-slip friction on the copper (111) surface. Source: Reprinted with the permission from [68] ©1999 American Physical Society; c,d) The stick-slip friction behaviors in Graphene and MoS_2. Source: Reprinted with the permission from [53] ©2006 The American Association for the Advancement of Science.

Schirmeisen, et al. investigated the temperature-related point contact frictional behaviors on silicon wafer and found that the friction exhibits a logarithmic sliding velocity-dependence below 150 K but keeps nearly-constant above 150 K [43]. Later, Marchetto, et al. [44] found that the nano-pattern on silicon surface can effectively lower the friction coefficient and avoid wear in the two-dimensional flat contact of silicon by AFM-based friction tests. Silicon carbide (SiC) is an important substitute material for silicon to be applied in MEMS devices. Zum Gahr, et al. [45] found that the friction coefficient in nanoscale SiC friction is independent of the humidity [46]. Compared to Si, SiC with high hardness exhibits low friction and less wear under low normal loads [47]. But the plastic deformation and wear are supposed to be induced on SiC surface when the normal load increases to the load regime applied in MEMS devices (> 100 nN) [48].

Using friction force microscopy, the atomic-scale stick-slip behavior in the vacuum has been observed in many materials. As shown in Figure 4a and Figure 4b, the lateral force along the (110) direction on Cu (111) surface showed a typical zigzag change with the sliding distance [49]. The probing tip was covered by the native oxide layer to reduce the adhesion effect and chemical reaction between the tip and substrate in the friction experiments [49]. Some Cu atoms were expected to transfer to the silicon tip and the friction transited to the contact between copper and copper. However, there lacks of a deep understanding of the diffusion phenomenon on the interface. The morphology of copper (111) surface was captured during the scanning of the silicon, which was based on the imaging of AFM. The wavelength (2.5 angstroms) of the stick-slip friction was consistent with the lattice period of the copper along (110) direction on (111) plane (Figure 4a and Figure 4b). Diamond, as a superior wide-bandgap semiconductor material with excellent mechanical properties, has been widely applied in MEMS sensors [50]. The stick-slip was also reported in the friction on diamond surface and the researchers found that the hydrogen-termination treat could effectively reduce the friction magnitude [51]. This stick-slip friction behavior also has been discovered in many two-dimensional (2D) materials [52]. For example, graphene and molybdenum disulfide (MoS_2) exhibited lattice stick-slip friction and friction singles increased with the thinning of 2D material sheets (Figure 4c and Figure 4d) [53]. The number marked in the figure showed the change of the layer number of the sheet. The intrinsic mechanism of the friction-thickness dependence is contributed to the surface deformation of 2D materials. When the thickness decreased, the interaction between the tip and the top raised which induced the buckling of the top surface.

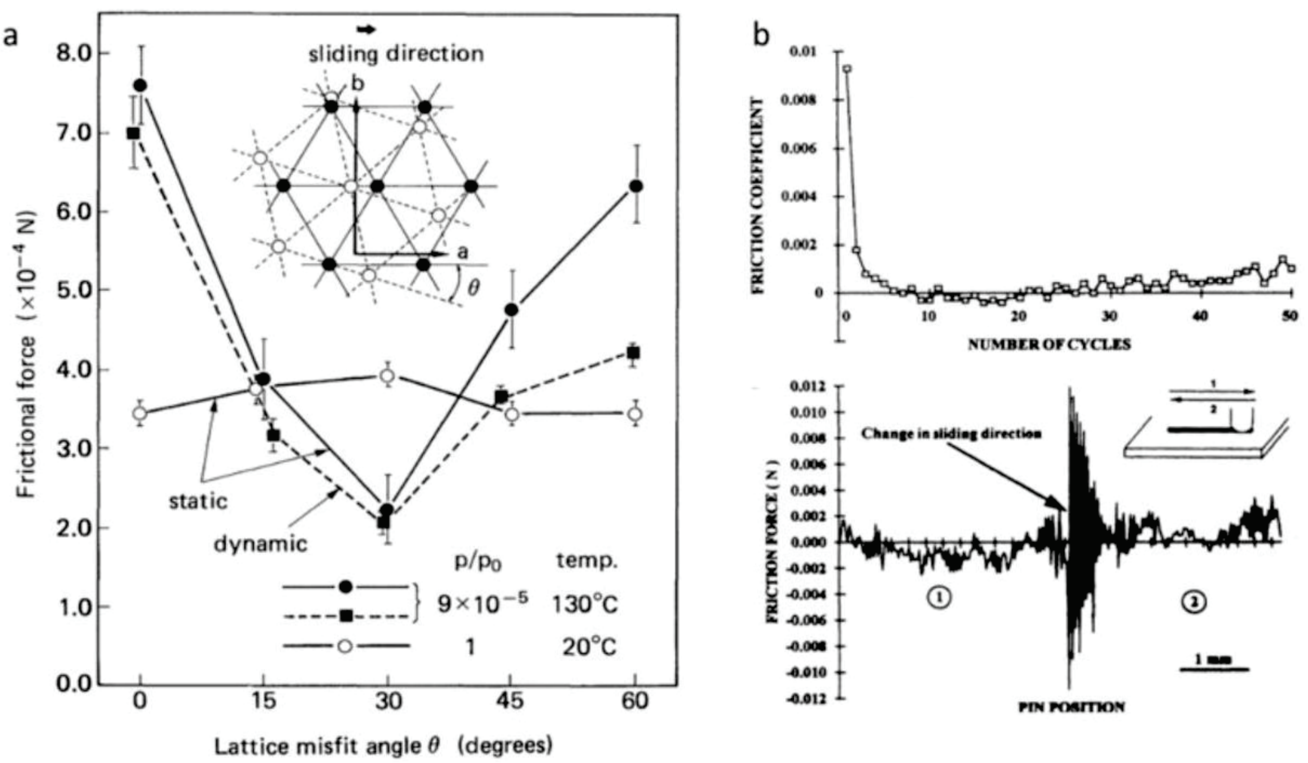

Figure 5: Super-lubricity Friction: a) The orientation-dependence friction behavior between two mica sheets. Source: Reprinted with the permission from [54] ©1991 American Physical Society; b) The super-lubricity in MoS_2. Source: Reprinted with the permission from [55] ©1993 American Physical Society.

And the sliding of the tip became harder and the energy dissipation increased. The presence of ultralow friction is related to the orientation between two asperities. Hirano, et al. [54] found the orientation-dependence friction behavior between two atomistically-flat mica sheets. The change period of the friction force matched with the lattice symmetry and the ultralow friction force exited when the lattice misorientation was about 30 degrees, as shown in Figure 5a [54]. The super-lubricity also was found in many 2D materials, as shown in Figure 5b [55]. The interaction between the scanning tip and surface is expected to be very weak when the contact occurred at a certain orientation or scanning direction [33]. The superlubricity with friction coefficient ~0.003 has been reported in contact between graphene-coated silica nanoparticles and graphene and hexagonal boron nitride substrates [56,57]. Besides, surface-termination/passivation to change the surface properties of materials is a significant approach to lower the friction and achieve superlubricity. Diamond-like carbon (DLC) film with high hardness, as an excellent coating, was applied to improve the frictional properties of devices [58]. Later, researchers found that the hydrogen termination treatment leading to form the hydrogenated-DLC films could passivate the dangling bonds of carbon atoms and give rise to superlubricity [59,60]. DLC films synthesized from the hydrogenated plasmas vapor deposition could also effectively reduce the friction and lead to superlubricity [61]. The ultralow friction coefficients can be obtained through the passivation of dangling covalent bonds of diamond films favored by oxygen or humid air [62]. If there exists a strong thermal effect during the friction process, the thermal excitations significantly benefit the contact between asperities to overcome the energy barrier of sliding, contributing to a reduction of the friction forces of contacts [63]. The thermal jump rate of the tip could move on the surface with a very low energy barrier. But for strong interaction potential between the tip and surface, the thermal effect becomes weak and the tip motion exhibited the stick-slip behavior again [64]. To achieve super-lubricity is imperative to lower the energy dissipation and extend the service life of devices. Superlubricity with ultralow friction has been realized in potential devices of nanoelectromechanical systems (NEMS) by experimental research such as ultralow-friction

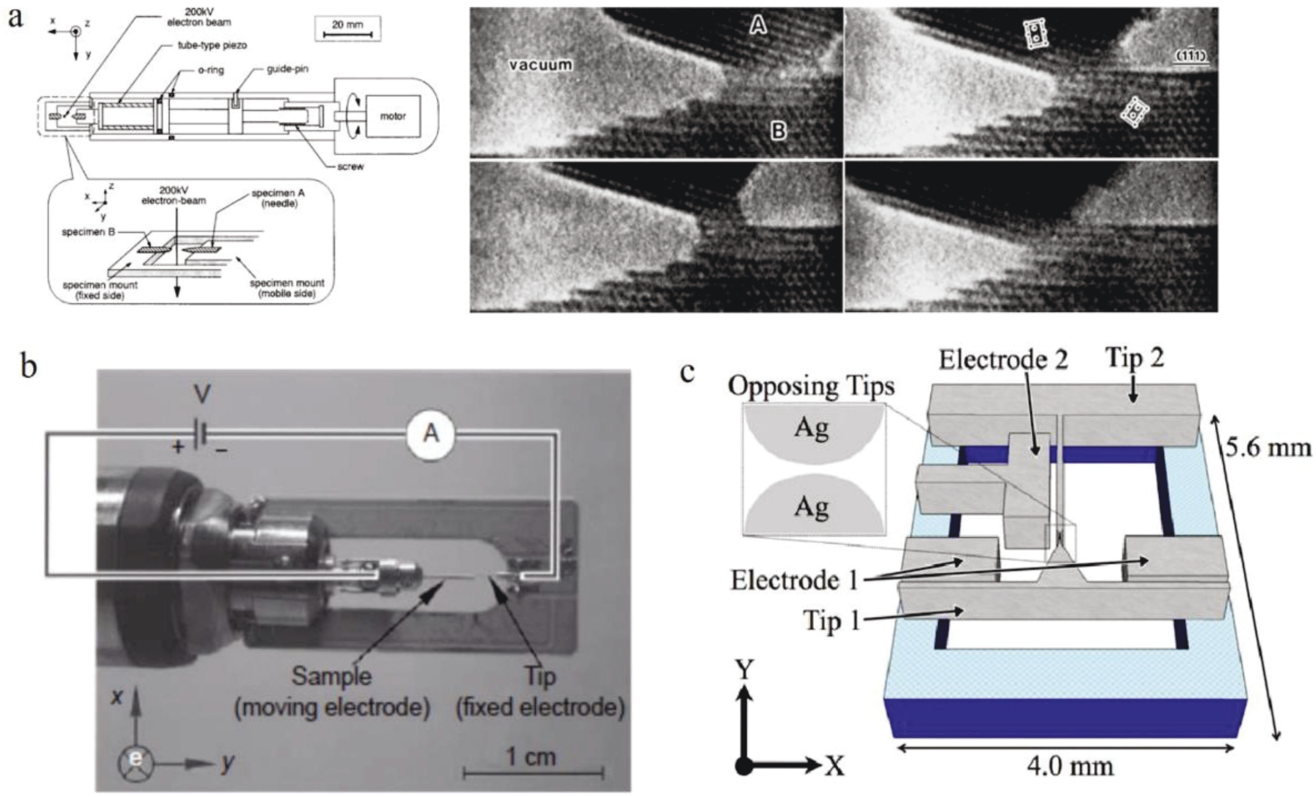

Figure 6: Design of the in-situ platform for the nanofriction *In-Situ* Nanofriction by Transmission Electron Microscopy: a) Illustration of a specimen holder for atomic-scale surface scanning and serial images of the motion of the gold tip. Source: Reprinted with the permission from [69] ©1997 American Physical Society; b) The mobile probe design-STM-TEM holder. Adapted permission from [71] under a Creative Commons license; c) Schematic of the MEMS device for force measurement. Source: Reprinted with the permission from [75] ©2012 IOP Publishing.

nanoscale linear bearings formed by multiwall carbon nanotubes [65], tunable nanoresonators constructed by telescoping nanotubes [66], and nanoscale rotational actuator incorporating a metal plate with carbon nanotubes [67].

In-situ TEM observation on atomic-scale friction

However, the structure characteristic of the friction surface could only be captured by AFM imaging and the real structure evolution of two asperities cannot be revealed by friction force microscopy. Transmission electron microscopy (TEM) provides a window to capture the structure change of friction asperities and record the real-time friction process. How to achieve investing the friction under TEM observation is still a challenge for atomic-friction research, which depends on the development of in-situ TEM techniques. For example, a movable probe was successfully designed in the TEM holder and the motion of the probe was controlled by a low-velocity motor (Figure 6a) [68]. The minimum step of the probe's motion along the sliding direction is 0.16 nm and the time resolution of the video is 1/60 s [68]. The real-time evolution of the cross-section of Au junction could be recorded by this technique [68]. However, the motion of the probe is confined in one direction and the relative motion between two asperities is hard to carry out. Based on the similar principle of scanning tunneling microscopy, a more flexible control [69] was designed to activate the probe movable (Figure 6b) [70] in three dimensions and the friction between two asperities could be realized [69,71].

Although the friction phenomenon has been recorded by in-situ TEM imaging, the force evolution is still required to be measured by an extra force detection system. AFM is a powerful tool to measure the small force and implanting AFM cantilever into TEM [72] provides an ideal method to evaluate the force at atomic-scale (Figure 6c) [73]. A similar system with two force sensors was

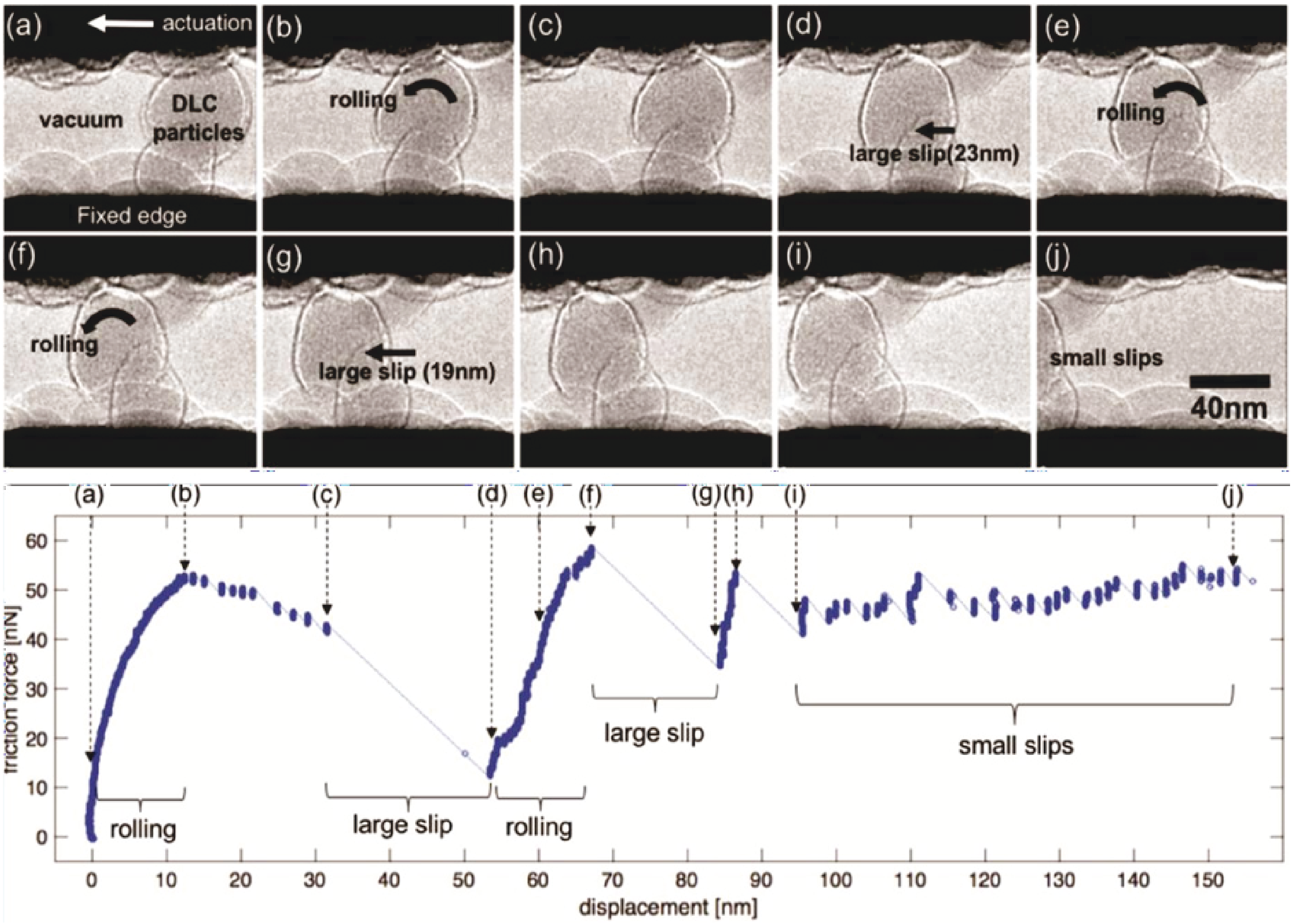

Figure 7: Observing the motion of DLC wear particles and recording the friction force evolution under *in-situ* TEM. Source: Reprinted with the permission from [74] ©2018 IOP Publishing.

invented to measure the friction and normal force at the same time during the TEM observation [74]. The speed of the probe is about 10 nm min^{-1} [74]. For example, the simultaneous change of the friction force between two silicon surfaces covered with diamond-like carbon (DLC) (Figure 7) was captured by the developed MEMS devices under in-situ TEM [74]. There exited three main mechanical behaviors including the rolling, the slipping, and the sticking of particles between the contacting surfaces were successfully captured and the movement of the wear particle mediated the friction process [73]. The detection precision about the force reaches the level of nN and the movement velocity of the probe can be adjusted within 1-500 nm s^{-1} [73]. These *in-situ* researches under TEM observation focus on the plastic deformation of asperity like the formation and fracture of the neck between asperities [74,75] or wear [76]. However, the atomic- scale observation about the well-defined interface structure, directly affecting the frictional behaviors has not been acquired. Some pioneer experiments have revealed the surface defects like the step has significant effects on friction [22] but the real-time evolution on the interface and the dynamic interaction between the sliding probe and the surface step has not been visualized.

Summary and Outlook

The P-T model provides a simple theory to understand the atomic friction and the developed model can be applied to explain two typical atomic-friction behaviors, i.e. the stick-slip and superlubricity. They have been reported by much experimental research through AFM-based technology. The transition between these two behaviors can be explained by the parameter η which can be adjusted by changing the friction configuration and loading conditions. Furthermore, advanced *in-situ* TEM provides new opportunities to investigate the contact evolution during friction and the relations between the interface and friction force evolutions can be built up by combining the force-measurement system under

TEM observation. However, some challenges and key points, which are of potential interest for future research in atomic-scale friction, are required with much attention to be overcome.

- The real-time atomic-scale observation on the interface between asperities is still a challenge for friction research, and smart methods especially for in-situ high-resolution TEM technologies, are expected to be proposed.
- Lowering the drift effect [77] and improving the accuracy of force measurement [78] are significant to extend the in-situ technologies for future atomic-scale friction research.
- It is well-known that the materials' properties may experience huge transition when the size of the asperities reduces to nanoscale or even smaller [79,80]. Multiple technologies will be required to characterize the complex interface phenomenon such as sliding-induced diffusion or segregation [81] in alloy systems in atomic-scale friction.
- Extending the revealed friction mechanism at atomic-scale to macroscopic application demands the future advancement of the theoretical model and experimental designs considering the practical environment in friction systems.

Acknowledgments

S. X. M. acknowledges support from National Science Foundation (NSF CMMI 1824816) through University of Pittsburgh.

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DOI: 10.35840/2631-5076/9269