NON-LINEAR DYNAMICAL EFFECTS IN FRICTIONAL ENERGY DISSIPATION

M. Hirano*, K. Kimura, and S. Hasebe
*hirano@hosei.ac.jp
Department of Mechanical Engineering, Faculty of Science and Engineering,
Hosei University
3-7-2 Kajino-cho, Koganei, Tokyo 184-8584, Japan

KEYWORDS

Keyword: Nano Tribology; Modelling in Tribology; Friction; Non-linear Dynamics, Chaos in Friction

ABSTRACT

Dynamics in friction is studied from an atomistic point of view. Friction is formulated as a problem of whether or not a given kinetic energy for the translational motion dissipates into the kinetic energies for the internal motions during sliding. From the study of the Frenkel-Kontorova model (FK model) with kinetic energy terms, it is found that two different regimes appear in a parameter space specifying the FK model: the superlubricity and the friction regimes. We have also found the peculiar frictional behavior at the specific frictional parameters, showing the abrupt decrease in the sliding velocity at unexpected time while superlubricity appears for a while, i.e. the upper body slides at constant velocity for a while after it has been pushed along sliding direction at initial sliding velocity. It has been observed that the state of superlubricity has collapsed and the catastrophic reduction of the sliding speed has occurred. This paper discusses to elucidate how the catastrophic transition for the appearance of friction occurs from the viewpoint of non-linear dynamics and chaos.

The atomistic origin of friction forces stemming from atomic interactions has been investigated from both of theoretical and experimental viewpoints [1-5]. We have for the first time defined the atomistic origins of static/dynamic friction and superlubricity for clean surfaces and potentially offers a rigorous solution to this problem [2]. Graphitic nano-structured materials have been recently explored to test this idea [3-5]. The ultralow friction forces have been identified at scales from a few micrometers [5] to large macro scale [6].

This study has examined the one-dimensional Frenkel-Kontorova atomistic friction model, given by

$$H = \sum_{i}^{N} \frac{p_i^2}{2} + \sum_{i}^{N} \left\{ \frac{1}{2} k(x_{i+1} - x_i - \ell)^2 + \frac{f}{2\pi} \sin(2\pi x_i) \right\}, \quad (1)$$

where, $p_i, x_i\ k, \ell$, and f stand for the momentum of atoms, the atomic position, the inter-atomic interaction, the mean distance between two adjacent atoms, and the amplitude of friction energy. This is one-dimensional dynamic Frenkel-Kontorova model with kinetic energy terms. The periodicity length of the sinusoidal potential in Eq. (1) is taken as a unit, while ℓ is assumed to be equal to the golden mean number $\ell = (1+\sqrt{5})/2$. To examine the frictional properties including superlubricity, the dynamics has been studied after the upper solid surface at the ground state is pushed with initial sliding velocity $P(0)$ with the Hamiltonian dynamics conserving the energy. The friction dynamics is studied by examining the quantities such as mass center velocity $P(t)$, mass center position $Q(t)$, and the sliding distance defined as the distance over which the upper solid surface slides during time. These quantities are obtained by numerically solving Eq. (1) by using the velocity Verlet algorithm. The high-resolution friction phase diagram, where friction and superlubricity regimes is described in a parameter space specified by the two parameters such as the initial sliding velocity and the magnitude of friction energy determining friction forces, has been presented. The two distinct regimes representing the appearance of friction and superlubricity, and their boundary have been determined in the friction phase diagram. We have discucussed the spectral analysis and the Poincaré mapping in phase space for the atomic oscillation appeared in the FK model in sliding motion and proposed the role of the non-linear dynamics appeared in the friction and superlubricity.

REFERENCES

[1] K. Shinjo and M. Hirano, Dynamics of Friction: Superlubric State, Surf. Sci. 283 (1993) 473.
[2] M. Hirano, Friction at the Atomic Level: Atomistic Approaches in Tribology (Wiley-VCH, Weinheim, Germany, 2018).
[3] M. Dienwiebel et al., Superlubricity of Graphite, Phys. Rev. Lett., 92 (2004) 126101.
[4] John Cumings and A. Zettl, Low-Friction Nanoscale Linear Bearing Realized from Multiwall, Science 289 (2000) 602.
[5] Z. Liu, et al., Observation of microscale superlubricity in graphite. Phys. Rev. Lett., 108 (2012) 205503.
[6] J. M. Martin and Ali Erdemir, Superlubricity: Friction's vanishing act, Physics Today 71, 4, (2018) 40.