Center for Materials Processing and Tribology Distinguished Seminar

Nanoscale Factors Controlling Friction and Lubrication: From 2D Materials to Engine Oil

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Abstract: Although tribological processes — friction, adhesion, lubrication, and wear are common and important phenomena, we lack well-grounded scientific theories to explain or predict them. Such understanding would allow the development of rational strategies for reducing energy dissipation and increasing reliability at all length scales, enabling applications, such as micro-/nano-electromechanical systems (MEMS/NEMS), where friction and wear are primary limitations. I will discuss recent studies of nanoscale friction/ lubrication that reveal surprising new behavior and insights obtained using AFM.

First, the behavior of nanoscale contacts with 2-dimensional materials will be discussed. For nanoscale contacts to graphene, the friction force exhibits a significant dependence on the number of 2-D layers, which we attribute to a puckering mechanism arising from the increased tendency of thinner materials to adhere to the sliding tip [1]. An even stronger effect occurs when graphene is fluorinated, where experiments and molecular dynamics simulations consistently show that friction between nanoscale tips and fluorinated graphene (FGr) monolayers exceeds that for pristine graphene by an order of magnitude. The results can be interpreted in the context of the Prandtl-Tomlinson model of stick-slip friction, where static friction arises from the high electronic roughness of fluorinated graphene [2]. This demonstrates how corrugation of potential energy is key to controlling atomic-scale friction.

Second, I will discuss very recent results where AFM is used to develop new insights into practical lubrication mechanisms. We study zinc dialkyldithiophosphates (ZDDPs), which are highly effective anti-wear additive molecules used nearly universally in engine oils. ZDDPs function by breaking down under the combination of contact stress and temperature to form wear-resistant protective films on the steel surfaces. However, the generation of phosphorous- and sulphur-containing compounds reduces the working life of the catalytic converter, motivating studies to understand how ZDDPs work so that its use can be reduced or eliminated. We developed a novel AFM-based approach for visualizing and quantifying the formation of ZDDP anti-wear films *in situ* at the nanoscale. Film growth depends exponentially on temperature and stress, which can explain the known graded-structure of the films. Our findings provide new insights into the mechanisms of formation of ZDDP derived anti-wear films and the control of lubrication in automotive applications [3].

Bio-sketch: Robert Carpick is John Henry Towne Professor, Dept. of Mech. Engg. & Applied Mechanics, University of Pennsylvania, where he has served as Department Chair since 2011. Previously, he was a faculty member at the University of Wisconsin-Madison (2000-2007). He received his B.Sc. from the University of Toronto (1991), and his Ph.D. from the University of California at Berkeley (1997), both in Physics, and was a postdoc at Sandia National Laboratory (1998-1999). He studies nanotribology, nanomechanics, and scanning probes. He is the recipient of a NSF CAREER award (2001), the ASEE Outstanding New Mechanics Educator award (2003), the ASME Newkirk award (2009), an *R&D* 100 Award (2009), and is a Fellow of the American Physical Society, the American Vacuum Society, and the Society of Tribologists and Lubrication Engineers. He holds 4 patents and has authored over 140 peer-reviewed journal publications.

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[1] C. Lee, Q. Li, W. Kalb, X-Z. Liu, H. Berger, R. W. Carpick, and J. Hone. Frictional characteristics of atomically thin sheets. *Science*, 328(5974):76–80, 2010.

[2] Q. Li, X-Z. Liu, S-P. Kim, V. B. Shenoy, P. E. Sheehan, J. T. Robinson, and R. W. Carpick. Fluorination of graphene enhances friction due to increased corrugation. *Nano Letters*, 14(9):5212–5217, 2014.

[3] N. N. Gosvami, J. A. Bares, F. Mangolini, A. R. Konicek, D. G. Yablon, and R. W. Carpick. Mechanisms of antiwear tribofilm growth revealed in situ by single-asperity sliding contacts. *Science*, 348(6230):102–106, 2015.

Additional information, contact S. Chandrasekar (`chandy@purdue.edu`). Refreshments at 10:50 AM.