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References

Annis, B. K., and Pedraza, D. F., 1993, "Effect of Friction on Atomic Force Microscopy of Ion Implanted Highly Oriented Pyrolytic Graphite," *Journal of Vacuum Science and Technology, B*, Vol. 11, No. 5, pp. 1759–1765.

Binnig, G., Quate, C. F., and Gerber, Ch., 1986, "Atomic Force Microscope," *Physics Review Letters*, Vol. 56, No. 9, pp. 930–933.

Bogy, D., Yun, X., and Knapp, B. J., 1994, "Enhancement of Head-Disk Interface Durability by Use of Diamond-Like Carbon Overcoats on the Slider's Rail," *IEEE Transactions on Magnetics*, Vol. 30, No. 2, pp. 2148–2153.

Grafstrom, S., Neitzert, M., Hagen, T. Ackermann, J. Neumann, R., Probst, O. and Wortge, M., 1993, "The Role of Topography and Friction for the Image Contrast in Lateral Force Microscopy," *Nanotechnology*, Vol. 4, No. 3, pp. 143–151.

Kaneko, R., Nonaka, N., and Yasuda, K., 1988, "Atomic Force Microscope for Microtribology, *Journal of Vacuum Science and Technology*, Series A, 6(2), pp. 291–292.

Kaneko, R., Miyamoto, T., and Hamada, E., 1991, "Development of a Controlled Frictional Force Microscope and Imaging of Recording Disk Surfaces," *Advanced Information Storage System*, Vol. 1, pp. 267–277.

Kohno, T., Ozawa, N., Miyamoto, K., and Musha, T., 1988, "High Precision Optical Surface Sensor," *Applied Optics*, Vol. 27, No. 1, pp. 103–108.

Marti, O., Colchero, J., and Mlynek, J., 1990, "Combined Scanning Force and Friction Microscopy of Mica," *Nanotechnology*, Vol. 1, No. 2, pp. 145–151.

Marti, O., Colchero, J., and Mlynek, J., 1993, "Friction and Forces on an Atomic Scale," *Nanosources and Manipulation of Atoms under High Fields and Temperature: Application*, Vu Thien Binh, N. Garcia, and K. Dransfeld, eds., Kluwer Academic Publishers, London, UK.

Mate, C. M., McClelland, G. M., Erlandsson R., and Chiang, S., 1987, "Atomical-Scale Friction of a Tungsten Tip on a Graphite Surface," *Physical Review Letters*, Vol. 59, No. 17, pp. 1942–1945.

Mate, C. M., 1992, "Atomic-Force-Microscope Study of Polymer Lubricants on Silicon Surfaces," *Physical Review Letters*, Vol. 68, No. 22, pp. 3323—3326.

Meyer, G., and Amer, N., 1990, "Simultaneous Measurement of Lateral and Normal Forces with an Optical-Beam-Deflection Atomic Force Microscope," *Applied Physics Letters*, Vol. 57, No. 20, pp. 2089–2091.

Miyamoto, T., Kaneko, R., and Andoh, Y., 1991, "Microscopic Adhesion and Friction between a Sharp Diamond Tip and Al_2O_3-TiC", ASME *Advances in Information and Storage Systems*, Vol. 2, pp. 11–21.

Miyamoto, T., Miyake, S., and Kaneko, R., 1993, "Wear Resistance of C^+-implanted Silicon Investigated by Scanning Probe Microscopy," *Wear*, Apr. 13, Vol. 162, pp. 733–738.

Neubauer, G., Cohen, S., McClelland, G., Horne, D., and Mate, C., 1990, "Force Microscopy With Bidirectional Capacitance Sensor," *Review of Scientific Instruments*, Vol. 61, No. 9, pp. 2296–2308.

O'Shea, S. J., Welland, M. E., and Rayment, T., 1992, "Atomic Force Microscope Study of Boundary Layer Lubrication," *Applied Physics Letters*, Vol. 61, No.18, pp. 2240–2242.

Overney, R., and Meyer, E., 1993, "Tribological Investigations Using Friction Force Microscopy," *MRS Bulletin*, May, pp. 26–34.

Ruan, J.-A., and Bhushan, B., 1994, "Atomic-Scale Friction Measurements Using Friction Force Microscopy: Part I-General Principles and New Measurement Techniques," ASME Journal of Tribology, to appear.

Thundat, T., Warmack, R. J., Allison, D. P., Bottomley, L. A., Lourenco, A. J., and Ferrel, T. L., 1992, "Atomic Force Microscopy of Deoxyrbonuoleic Acid Strands Adsorbed on Mica: The Effect of Humidity on Apparent Width and Image Contrast," *Journal of Vacuum Science and Technology*, Series A, Vol. 10, No. 4, pp. 630–635.

Yanagisawa, M., and Motomura, Y., 1987, "An Ultramicro Identation Hardness Tester and Its Application to Thin Films," *Lubrication Engineering*, Vol. 43, No. 1, pp. 52–56.

DISCUSSION

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I would like to congratulate authors for a well written paper. This discusser agrees with authors that most commercial AFM/FFM instruments measure vertical motion and twisting of the tip to measure the normal and friction forces, respectively. This is done to simplify the design and to reduce cost. However, number of lab designs have been published in which lateral and normal forces are independently measured (Erlandsson et al., 1988; Fujisawa et al., 1994).

Authors state that independent measurements of normal and friction force facilitate the calibration and provide more accurate friction data. It is comforting to note that coefficient of friction values reported in this paper are comparable to that obtained using the commercial instruments in which twisting of the tip is used to measure friction forces (Bhushan et al., 1994a, 1994b, 1994c; Bhushan, 1995). Friction response to stepped surfaces and surface slope can also be obtained with a commercial instrument (Overney and Meyer, 1993; Bhushan, 1994, 1995; Bhushan et al., 1994a, 1994b, 1994c). Thus the commercial instruments appear to have no limitations in the friction measurements.

Additional References

Bhushan, B., 1995, "Micro/nanotribological and Its Applications to Magnetic Storage Devices and MEMS," *Tribol. International* (in press).

Bhushan, B., 1995, *Handbook of Micro/Nanotribology*, CRC Press, Boca Raton, FL.

Bhushan, B., Koinkar, V. N., and Ruan, J., 1994a, "Microtribology of Magnetic Media," *Proc. Instn. Mech. Engrs., Part J: J. Eng. Tribol.*, Vol. 208, pp. 17–29.

Bhushan, B., and Ruan, J., 1994b, "Atomic-Scale Friction Measurements Using Friction Force Microscopy: Part II—Application to Magnetic Media," ASME Journal of Tribology, Vol. 116, pp. 389–396.

Bhushan, B., and Koinkar, V. N., 1994c, "Tribological Studies of Silicon for Magnetic Recording Applications," *J. Appl. Phys.*, Vol. 75, pp. 5741–5746.

Erlandsson, R., Hadzioannou, G., Mate, C. M., McClelland, G. M., and Chiang, S., 1988, "Atomic-Scale Friction Between the Muscovite Mica Cleavage Plane and a Tungsten Tip," *J. Chem. Phys.*, Vol. 69, pp. 5190–5193.

Fujisawa, S., Ohta, M., Konishi, T., Sugawara, Y., and Morita, S., 1994, "Difference Between the Forces Measured by an Optical Lever Deflection and by an Optical Interferometer in an Atomic Force Microscope," *Rev. Sci. Instrum.*, Vol. 65, pp. 644–647.

Overney, R., and Meyer, E., 1993, "Tribological Investigations Using Friction Force Microscopy," *MRS Bulletin*, May, pp. 26–34.

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Authors' Comments

The discusser's interest in our paper is appreciated.

The authors would like to point out that research in Nanotribology should go far beyond measurements of the nano-friction coefficient. Investigations of nano-indentation hardness, nano-wear, and nano-fatigue wear, together with nano-friction compose the complete world of Nanotribology. The Scanning Probe Microscope (SPM) [including Scanning Tunneling Microscope (STM), Atomic Force Microscope (AFM), Point Contact Microscope (PCM), Friction Force Microscope (FFM), and Lateral Force Microscope (LFM)] provides a practical and reliable tool for these investigations. However, when we studied nano-indentation, nano-wear, and nano-fatigue wear, limitations of many laboratory and commercially designed scanning probe microscopes were exposed: (1) convenient yet reliable experimental calibrations of tip spring constants were not available for sufficiently accurate normal load and lateral friction data, (2) the normal load could not reach a sufficiently large value (typically, the load range from 2 μN to 2 mN is desirable, depending on the tested materials) to damage the tested sample surfaces for nano-indentation, nano-wear and nano-fatigue wear on various films and materials such as Si, ion implanted Si, SiO_2, SiN, SiC, diamond like carbon, Al_2O_3, TiC and Mn-Zn ferrite, and (3) the friction force for such large normal loads with both no-wear and wear was not measurable.