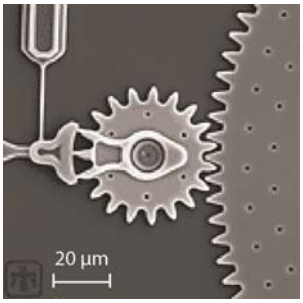
NLBB Newsletter



Nanoprobe Laboratory for Bio- & Nanotechnology and Biomimetics (NLBB)
W390 Scott Laboratory, 201 W. 19th Avenue
The Ohio State University, Columbus, Ohio 43210-1142 USA
Advancing the State-of-the-Art in Nanotribology, Nanomechanics, Nanomaterials Characterization, and Bioinspired Nanostructured Surfaces

Volume Twenty, Nov. 2014

Director's Report

by: Professor Bharat Bhushan
Ohio Eminent Scholar and
The Howard D. Winbigler Professor

Goals and Scope

NLBB's main goals are to carry out fundamental studies in the interdisciplinary areas of bio- and nanotribology, bio- and nanomechanics and bio- and nanomaterials characterization and applications to bio- and nanotechnology. The scope of the research includes the development of theoretical models, development of sophisticated instrumentation and techniques, fabrication of nanostructures, and the acquisition of research data for fundamental understanding. Measurement of mechanical and electrical properties of nanostructures is carried out. Self-assembled monolayers and perfluoropolyether lubricant and ionic liquid films are developed for micro- or nanostructures. Biomolecular films are studied for biomedical applications. In particular, bioadhesion, friction and wear issues are addressed. Another main goal is to develop bio-inspired nanostructured surfaces. There is a large activity on superhydrophobic and self-cleaning surfaces with low drag (Lotus effect) and interfaces with smart adhesion (Gecko feet). There are also research activities in nanoprobe based data recording technology and beauty care products (hair, hair conditioner, and skin cream). Instrumentation used in the lab includes atomic force microscopy /scanning tunneling microscopy (AFM/STM), micro-triboapparatus, nanoindenter, and industrial simulators.

The research activity is truly interdisciplinary, embodying materials science, physics, physical chemistry, biomedical engineering, biotribology, lubricant rheology, mechanics, applied mathematics, bio/nanomaterials characterization, biomimetics, and applications to bio/nanotechnology.

Facilities and Equipment

The Nanoprobe Laboratory is housed in Scott Laboratory. The laboratory occupies more than 4000 square feet of space. Office space includes offices for the two faculty members, an assistant, six visiting scientists/industrial fellows, and 16 graduate students. Part of the laboratory is environmentally controlled and contamination controlled to a specification of Class 100. The air tables are used to provide vibration isolation.

The laboratory is equipped with many pieces of sophisticated research equipment including a scanning tunneling microscope, five atomic force microscopes, noncontact optical profiler, stylus profiler, nanoindenter, ultra-high vacuum tribotest apparatus, microtriboapparatus, and scanning ellipsometer, and contact angle measurement apparatus. The other pieces of equipment and facilities include vapor and liquid coating-deposition facilities, pin-on-disk continuous sliding test apparatus, reciprocating sliding test apparatus, microhardness tester, optical microscope, metallurgical sample preparation and polishing facility, particle counter, microbalance, and environmental chambers.

Central facilities for micro/nanofabrication of structures are used for bio/nanotechnology and biomimetics research. An easy access exists to various physical and chemical analysis facilities such as scanning electron microscope, scanning transmission electron microscope, EDS, scanning Auger spectrometry, X-ray photon spectroscopy, time-of-flight SIMS, DTA, DSC, TMA, TGA balances, porosimeter, NMR, FTIR, mass spectrometry, laser spectroscopy, and computer controlled mechanical test equipment.

The department has extensive computer facilities. In addition, the University maintains the Ohio Supercomputer Center. All of the campus computers are connected electronically.

Technical Report

2013 has been a busy and productive year for the Nanoprobe Laboratory for Bio- & Nanotechnology and Biomimetics.

Sponsors

Industrial

Procter & Gamble
Sony

Government Sponsors

National Science Foundation
Department of Energy
ACS Petroleum Research Fund

Instrumentation Support

Hysitron
Bruker/Tribology & Mech. Testing

Following is a partial list of ongoing projects at NLBB:

Nanotribology and Nanomechanics

- Nanotribology and Nanomanipulation of Nanoobjects in Liquid Environments Using AFM
- Nanotribology of Polymers

Bio- & Nanotechnology

- Imaging of Nanobubbles and Measurement of Surface Charge and Slip on Hydrophobic Surfaces
- Electrowetting and Tunable Superhydrophobicity
- Bioadhesion of Various Proteins on Block Copolymer Films for Bone Regeneration Scaffold Applications (with Prof. S. Schricker, College of Dentistry)

Biomimetics and Green Tribology

- Lotus-inspired Durable and Transparent Superhydrophobic and Superoleophobic Surfaces for Anti-Smudge, Self-Cleaning, and Antifouling
- Shark-skin, Rice Leaf and Butterfly Wings Inspired Structured Surfaces for Low Drag and Antifouling
- Fluid Flow Modeling of Biomimetic Structures
- Other Projects: Fish and Nacre

Beauty Care Products

- Adhesion, Friction, and Wear of Skin and Skin Cream Using AFM and Development of Synthetic Skin

Batteries Aging

- Multi-scale Characterization of Aging Phenomena and In-situ Electrochemistry for Li-Ion Batteries.

NLBB Publications

Technical Papers (from 2013)

1. Nishimoto, S. and Bhushan, B., “Bioinspired Self-cleaning Surfaces with Superhydrophobicity, Superoleophobicity, and Superhydrophilicity,” (Invited), *RSC Advances* **3**, 671-690 (2013).
2. Sun, J., Bhushan, B., and Tong, J., “Structural Coloration in Nature,” (Invited), *RSC Advances* **3**, 14862-14899 (2013).
3. Bixler, G.D. and Bhushan, B., “Fluid Drag Reduction with Shark-skin Riblet Inspired Microstructured Surfaces,” (Invited), *Advanced Functional Materials*) **23**, 4507-4528 (2013); Highlighted in *Materials Views*.
4. Bixler, G.D. and Bhushan, B., “Shark Skin Inspired Low-drag Microstructured Surfaces in Closed Channel Flow,” *Journal of Colloid and Interface Science* **393**, 384-396 (2013).
5. Bixler, G.D. and Bhushan, B., “Bioinspired Micro/Nanostructured Surfaces for Oil Drag Reduction in Closed Channel Flow,” *Soft Matter* **9**, 1620-1635 (2013).
6. Bixler, G. D. and Bhushan, B., “Fluid Drag Reduction and Efficient Self-Cleaning with Rice Leaf and Butterfly Wing Bioinspired Surfaces,” (Review), *Nanoscale* **5**, 7685-7710 (2013).
7. Bhushan, B., “Bioinspired Superhydrophobic, Self-cleaning and Low Drag Surfaces,” (Invited Keynote Paper), *Nanostructured Thin Films VI*, edited by T. G. Mackay, A. Lakhtakia, Y.-J. Jen, and M. Suzuki, Proceedings of SPIE, Vol. 8818, 881802 (12 pages) (2013).

8. Bhushan, B. and Muthiah, P., "Anti-smudge Screening Apparatus for Electronic Touch Screens," *Microsystem Technologies* **19**, 1261-1263 (2013).
9. Muthiah, P., Bhushan, B., Yun, K., and Kondo, H., "Dual-layered-coated Mechanically-durable Superomniphobic Surfaces with Anti-smudge Properties," *Journal of Colloid and Interface Science* **409**, 227-236 (2013).
10. Obeso, C.G., Sousa, M.P., Song, W., Rodriguez-Perez, M.A., Bhushan, B., and Mano, J.F., "Modification of Paper Using Polyhydroxybutyrate to Obtain Biomimetic Superhydrophobic Substrates," *Colloid and Surfaces A: Physicochemical and Engineering Aspects* **416**, 51-55 (2013).
11. Perera, S., Bhushan, B., Bandara, R., Rajapakse, G., Rajapakse, S., and Bandara, C., "Morphological, Antimicrobial, Durability, and Physical Properties of Untreated and Treated Textiles Using Silver-nanoparticles," *Colloids and Surfaces A: Physicochemical and Engineering Aspects* **436**, 975-989 (2013).
12. Maali, A. and Bhushan, B., "Nanobubbles and Their Role in Slip and Drag," (Invited), *Journal of Physics: Condensed Matter* **25**, 184003 (12 pp) (2013).
13. Pan, Y. and Bhushan, B., "Role of Surface Charge on Boundary Slip in Fluid Flow," *Journal of Colloid and Interface Science* **392**, 117-121 (2013).
14. Bhushan, B., Pan, Y., and Daniels, S., "AFM Characterization of Nanobubble Formation and Slip Condition in Oxygenated and Electrokinetically Altered Fluids," *Journal of Colloid and Interface Science* **392**, 105-116 (2013).
15. Pan, Y., Bhushan, B., and Maali, A., "Slip Length Measurement of Confined Air Flow on Three Smooth Surfaces," *Langmuir* **29**, 4298-4302 (2013).
16. Jing, D. and Bhushan, B., "Effect of Boundary Slip and Surface Charge on the Pressure-Driven Flow," *Journal of Colloid and Interface Science* **392**, 15-26 (2013).
17. Jing, D. and Bhushan, B., "Quantification of surface charge density and its effect on boundary slip," *Langmuir* **29**, 6953-6963 (2013).
18. Jing, D. and Bhushan, B., "Boundary Slip of Superoleophilic, Oleophobic and Superoleophobic Surfaces Immersed in Deionized Water, Hexadecane, and Ethylene Glycol," *Langmuir* **29**, 14691-14700 (2013).
19. Bhushan, B. and Utter, J., "Nanoscale Adhesion, Friction and Wear of Proteins on Polystyrene," *Colloids and Surface B: Biointerfaces* **102**, 484-491 (2013).
20. Palacio, M.L.B., Bhushan, B., and Schricker, S.R., "Hierarchical Nanostructured Polymers for Reversible Adhesion in Biomedical Applications," *Materials Letters* **92**, 409-412 (2013).
21. Palacio, M.L. and Bhushan, B., "Depth-sensing Indentation of Nanomaterials and Nanostructures," (Invited), *Materials Characterization* **78**, 1-20 (2013).
22. Maharaj, D. and Bhushan, B., "Effect of MoS_2 and WS_2 Nanotubes on Nanofriction and Wear Reduction in Dry and Liquid Environments," *Tribology Letters* **49**, 323-339 (2013).
23. Maharaj, D., Bhushan, B., and Iijima, S., "Effect of Carbon Nanohorns on Nanofriction and Wear Reduction in Dry and Liquid Environments," (Invited Feature Article), *Journal of Colloid and Interface Science* **400**, 147-160 (2013).
24. Kumar, A. and Bhushan, B., "Effect of Nanoparticles on Nanomechanical and Nanotribological Properties of Polyethylene Blend Films," *Macromolecular Reaction Engineering* **7**, 538-548 (2013).
25. Chen, S. and Bhushan, B., "Naonomechanical and Nanotribological Characterization of Two Synthetic Skins With and Without Skin Cream Treatment Using Atomic Force Microscopy," *Journal of Colloid and Interface Science* **398**, 247-254 (2013).
26. Nagpure, S.C., Bhushan, B., and Babu, S.S., "Multi-scale Characterization Studies of Aged Li-ion Large Format Cells for Improved Performance-: An Overview," *Journal of The Electrochemical Society* **160**, A2111-A2154 (2013).
27. Bixler, G.D. and Bhushan, B., "Rice- and Butterfly-Wing Effect Inspired Self-Cleaning and Low Drag Micro/nanopatterned Surfaces in Water, Oil, and Air Flow," (Feature Article), *Nanoscale* **6**, 76-96 (2014). Cited in *Awake,* **95**, No. 4, p. 16 (April 2014), www.jw.org; The journal with the second highest worldwide monthly circulation (45 million in 99 languages).
28. Bixler, G. D., Theiss, A., Bhushan, B., and Lee, S. C., "Anti-fouling Properties of Microstructured Surfaces Bio-inspired by Rice Leaves and Butterfly Wings," (Feature Article), *Journal of Colloid and Interface Science* **419**, 114-133 (2014).
29. Sun, J., Ling, M., Wu, W., Bhushan, B., and Tong, J., "The Hydraulic Mechanism of Unfolding of Hind Wings in *Dorcus titanus platymelus* (Order: Coleoptera)," *International Journal of Molecular Sciences,* 15, 6009-6018 (2014) doi:10.3390/ijms15046009.
30. Ye, X., Bhushan, B., Zhou, M., and Lei, W., "The Surface Microstructure of Cusps and Leaflets in Rabbit and Mouse Heart Valves," *Beilstein Journal of Nanotechnology* **5**, 622-629 (2014).

31. Martin, S. and Bhushan, B., "Fluid Flow Analysis of a Shark-Inspired Microstructure," *Journal of Fluid Mechanics* **756**, 5-29 (2014).
32. Pan, Y., Bhushan, B., and Zhao, X., "The Study of Surface Wetting, Nanobubbles and Boundary Slip With an Applied Voltage: A Review," *Beilstein Journal of Nanotechnology* **5**, 1042-1065 (2014).
33. Bhushan, B. and Schricker, S.R., "A Review of Block Copolymer-Based Biomaterials that Control Protein and Cell Interactions," (Invited), *Journal of Biomedical Materials Research: Part A* **102A**, 2467-2480. (2014).
34. Maharaj, D. and Bhushan, B., "Scale Effects of Nanomechanical Properties and Deformation Behavior of Au Nanoparticles and Thin Film Using Depth Sensing Nanoindentation," *Beilstein Journal of Nanotechnology* 5, 822-836 (2014).
35. Maharaj, D. and Bhushan, B., "Nanomanipulation, Nanotribology and Nanomechanics of Au Nanorods in Dry and Liquid Environments Using an AFM and Depth Sensing Nanoindenter," *Nanoscale* **6**, 5838-5852 2014).
36. Yilbas, B.S. and Bhushan, B., "Laser Treatment of Sintered Silicon Nitride Surface for Enhanced Hydrophobicity," (Invited), *JOM* **66**, 87-94 (2014).
37. Yilbas, B. S., Kumar, A., and Bhushan, B., "Single- and Two-layer Coatings of Metal Blends onto Carbon Steel: Mechanical, Wear, and Friction Characterizations," (Invited), *JOM* **66**, 37-45 (2014).
38. Yilbas, B. S., Kumar, A., Bhushan, B., and Abdul Aleem, B. J., "Material, Mechanical, and Tribological Characterization of Laser-Treated Surfaces," (Invited), *Journal of Thermal Spray Technology* **23**, 1210-1224 (2014).
39. Yilbas, B. S., Bhushan, B., Abdul Aleem, B. J., and Gaseem, Z., "Tribology and Superhydrophobicity of Laser-Controlled-Melted Alumina Surfaces with Hard Particles," (Invited), *JOM* **66**, 1068-1079 (2014).
40. Ramdon, S. and Bhushan, B., "Nanomechanical Characterization and Mechanical Integrity of Unaged and Aged Li-ion Battery Cathodes," *Journal of Power Sources* **246**, 219-224 (2014).
41. Ramdon, S., Bhushan, B., and Nagpure, S. C., "In Situ Electrochemical Studies of Lithium-ion Battery Cathodes using Atomic Force Microscopy," *Journal of Power Sources* **249**, 373-384 (2014).
42. Demirocak, D. E. and Bhushan, B., "In situ Atomic Force Microscopy Analysis of Morphology and Particle Size Changes in Lithium Iron Phosphate Cathode During Discharge," *Journal of Colloid and Interface Science* **423**, 151-157 (2014).
43. Bhushan, B. "Science and Technology Policy: What is at Stake and Why Should Scientists Participate?: A Fellow's Perspective", submitted for publication.
44. Bixler, G. D. and Bhushan, B., "Rice- and Butterfly-Wing Effect Inspired Low Drag and Antifouling Surfaces: A Review," (Invited), *Critical Reviews in Solid State and Materials Sciences* (in press).
45. Wang, Y. and Bhushan, B., "Wear-Resistant and Anti-Smudge Superoleophobic Coating on Polyethylene Terephthalate (PET) Substrate Using SiO_2 Nanoparticles," submitted for publication.
46. Brown, P. S. and Bhushan, B, "Mechanically Durable, Superoleophobic Coatings Prepared by Layer-by-Layer Technique for Anti-smudge and Oil–water separation," submitted.
47. Maharaj, D. and Bhushan, B., "Nanomechanical Behavior of MoS_2 and WS_2 Nanotubes and Carbon Nanohorns," submitted for publication.
48. Maharaj, D. and Bhushan, B., "Characterization of Nanofriction of MoS_2 and WS_2 Nanotubes," submitted.
49. Kumar, A. and Bhushan, B., "Nanomechanical, Nanotribological and Macrotribological Characterization of Hard Coatings and Surface Treatment of H-13 Steel," *Tribology International* **81**, 149-158 (2015).
50. Yilbas, B. S., Bhushan, B., Abdul Aleem, B. J. and Askandarani, A. A., "Analysis of Arc Sprayed Coatings of Nano-crystalline Metallic Wires on Carbon Steel Surface: Microhardness, Residual Stresses, Surface hydrophobicity, Friction and Wear," submitted for publication.

Book Chapters

1. Bhushan, B., "Tribology of Magnetic Head-Medium Interface," *High Density Digital* Recording, edited by K. H .J. Buschow, G .J. Long and F. Grandjean, NATO ASI Series E: Applied Sciences-Vol. 229, Kluwer Academic Publishers, Dordrecht, Netherlands, 1993, pp. 281-314.
2. Bhushan, B., "Magnetic Recording Surfaces," *Characterization of Tribological Materials*, edited by W. A. Glaeser, Butterworth - Heinemann, Stoneham, Massachusetts and Manning Publications Co., Greenwich, Connecticut, 1993, pp. 116-133.
3. Bhushan, B., "Tribology of Magnetic Storage Systems," *CRC Handbook of Lubrication and Tribology*, Vol. 3: Monitoring, Materials, Synthetic Lubricants and Applications, edited by E. R. Booser, CRC Press, Boca Raton, Florida, 1994, pp. 325-374.
4. Chandrasekar, S., Farris, T. N., and Bhushan, B., "Ceramics for Magnetic Recording Applications," *Friction and Wear of Ceramics*, edited by S. Jahanmir, Marcel Dekker Inc., New York, 1994, pp. 383-424.

5. Bhushan, B., “Nanotribology and its Applications to Magnetic Storage Devices and MEMS,” *Forces in Scanning Probe Methods, edited by H. J. Guntherodt, D. Anselmetti, and E. Meyer,* NATO ASI Series E: *Applied Sciences* - Vol. 286, Kluwer Academic Publishers, Dordrecht, Netherlands, 1995, pp. 367-395.
6. Bhushan B., "Introduction," *Handbook of Micro/Nanotribology*, edited by B. Bhushan, CRC Press Inc., Boca Raton, Florida, 1995, pp. 3-79.
7. Majumdar, A. and Bhushan, B., “Characterization and Modelling of Surface Roughness and Contact Mechanics,” *Handbook of Micro/Nanotribology*, edited by B. Bhushan, CRC Press Inc., Boca Raton, Florida, 1995, pp. 109-165.
8. Bhushan, B., “Nanomechanical Properties of Solid Surfaces and Thin Films,” *Handbook of Micro/Nanotribology*, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 1995, pp. 321-396.
9. Bhushan, B., “Micro/nanotribology and Micro/nanomechanics of Magnetic Storage Devices and MEMS,” *Handbook of Micro/Nanotribology*, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 1995 pp. 443-503.
10. Bhushan, B., “Tribology-Friction, Wear and Lubrication,” *The Engineering Handbook,* edited by R. C. Dorf, CRC Press, Boca Raton, Florida, 1996, pp. 210-229.
11. Bhushan, B., “Tribology of the Head-Medium Interface,” *Magnetic Recording Technology*, second edition, edited by C. D. Mee and E. D. Daniel, McGraw-Hill, New York, 1996, pp 7.1-7.66.
12. Bhushan, B., “History of Tribology and Micro/Nanotribology,” *Micro/Nanotribology and its Applications,* edited by B. Bhushan, NATO ASI Series E: Applied Sciences, Vol. 330, Kluwer Academic Publishers, Dordrecht, Netherlands, 1997, pp. 1-16.
13. Bhushan, B., “Friction, Scratching/Wear, Indentation and Lubrication on Micro- to Nanoscales,” *Micro/Nanotribology and its Applications,* edited by B. Bhushan, NATO ASI Series E: Applied Sciences-Vol. 330, Kluwer Academic Publishers, Dordrecht, Netherlands, 1997, pp. 169-191.
14. Bhushan, B., “Micro/Nanotribology,” *The CRC Handbook of Mechanical Engineering,* edited by F. Kreith, CRC Press, Boca Raton, Florida, 1998, pp. 3-197-3-208.
15. Bhushan, B., “Introduction – Measurement Techniques and Applications,” *Handbook of Micro/Nanotribology*, second edition, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 1999, pp. 3-80.
16. Majumdar, A. and Bhushan, B., “Characterization and Modelling of Surface Roughness and Contact Mechanics,” *Handbook of Micro/Nanotribology*, second edition, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 1999, pp. 187-245.
17. Bhushan, B., “Microscratching/Microwear, Nanofabrication/Nanomachining and Nano/Picoindentation Using Atomic Force Microscopy,” *Handbook of Micro/Nanotribology*, second edition, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 1999, pp. 335-355.
18. Bhushan, B., “Boundary Lubrication Studies Using Atomic Force/Friction Force Microscopy,” *Handbook of Micro/Nanotribology*, second edition, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 1999, pp. 357-370.
19. Bhushan, B., “Nanomechanical Properties of Solid Surfaces and Thin Films,” *Handbook of Micro/Nanotribology,* second edition, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 1999, pp. 433-524.
20. Bhushan, B., “Micro/Nanotribology and Micro/Nanomechanics of Magnetic Studies Devices,” *Handbook of Micro/Nanotribology*, second edition, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 1999, pp. 691-762.
21. Bhushan, B., “Micro/Nanotribology and Micro/Nanomechanics of MEMS Devices,” *Handbook of Micro/Nanotribology*, second edition, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 1999, 797-831.
22. Weick, B. L. and Bhushan, B., “Magnetic Tapes,” *Wiley Encyclopedia of Electrical and Electronics Engineering*, Vol. 12, edited by J. G. Webster, John Wiley, New York, 1999, pp. 226-242.
23. Bhushan, B. and Gupta, B. K., “Macro- and Micromechanical and Tribological Properties,” *Handbook of Hard Coatings - Deposition Technologies, Properties and Applications,* edited by R. F. Bunshah, Noyes Publications, Park Ridge, New Jersey, 2001, pp. 229-369.
24. Bhushan, B., “Surface Roughness Analysis and Measurement Techniques,” *Modern Tribology Handbook, Vol. 1 - Principles of Tribology*, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 2001, pp. 49-119.
25. Bhushan, B., “Friction, Scratching/Wear, Indentation, and Lubrication Using Scanning Probe Microscopy,” *Modern Tribology Handbook*, *Vol. 1 - Principles of* Tribology, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 2001, pp. 667-716.
26. Bhushan, B., “Self-Assembled Monolayers for Controlling Hydrophobicity and/or Friction and Wear,” *Modern Tribology Handbook*, *Vol. 2 - Materials, Coatings, and Industrial Applications*, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 2001, pp. 909-929.

27. Bhushan, B., "Macro- and Microtribology of Magnetic Storage Devices," *Modern Tribology Handbook*, *Vol. 2 - Materials, Coatings, and Industrial Applications*, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 2001, pp. 1413-1513.
28. Bhushan, B., "Macro- and Microtribology of MEMS Materials," *Modern Tribology Handbook*, *Vol. 2 - Materials, Coatings, and Industrial Applications*, edited by B. Bhushan, CRC Press, Boca Raton, Florida, 2001, pp. 1515-1548.
29. Bhushan, B., "Macro- and Microtribology of Magnetic Rigid Disk Drives," *Magnetic Storage Systems Beyond 2000*, edited by G. C. Hadjipanayis, NATO Science series II: Mathematics, Physics and Chemistry - Vol. 41, Kluwer Academic Publishers, Dordrecht, Netherlands, 2001, pp. 487-495.
30. Bhushan, B., "Friction, Wear, Lubrication, and Materials Characterization Studies Using Scanning Probe Microscopy," *Fundamentals of Tribology and Bridging the Gap Between the Macro- and Micro/ Nanoscales*, edited by B. Bhushan, NATO Science Series II: Mathematics, Physics and Chemistry - Vol. 10, Kluwer Academic Publishers, Dordrecht, Netherlands, 2001, pp. 13-39.
31. Bhushan, B., "Macro- and Microtribology of Information Storage and Retrieval Devices," *Fundamentals of Tribology and Bridging the Gap Between the Macro- and Micro/ Nanoscales*, edited by B. Bhushan, NATO Science Series II: Mathematics, Physics and Chemistry - Vol. 10, Kluwer Academic Publishers, Dordrecht, Netherlands, 2001, pp. 851-868.
32. Sundararajan, S. and Bhushan, B., "Micro/Nanoscale Tribology of MEMS Materials, Lubricants and Devices," *Fundamentals of Tribology and Bridging the Gap Between the Macro- and Micro/ Nanoscales*, edited by B. Bhushan, NATO Science Series II: Mathematics, Physics and Chemistry - Vol. 10, Kluwer Academic Publishers, Dordrecht, Netherlands, 2001, pp. 821-850
33. Weick, B. L. and Bhushan, B., "The Anisotropic Friction Characteristics of Crystalline Materials: A Review," *Fundamentals of Tribology and Bridging the Gap Between the Macro- and Micro/ Nanoscales*, edited by B. Bhushan, NATO Science Series II: Mathematics, Physics and Chemistry - Vol. 10, Kluwer Academic Publishers, Dordrecht, Netherlands, 2001, pp. 279-297.
34. Bhushan, B. and Kajdas, C., "The Present State-of-the-Art on Degradation Models of Perfluoropolyethers with DLC Coatings in Thin-Film Magnetic Rigid Disks," *Fundamentals of Tribology and Bridging the Gap Between the Macro- and Micro/ Nanoscales*, edited by B. Bhushan, NATO Science Series II: Mathematics, Physics and Chemistry - Vol. 10, Kluwer Academic Publishers, Dordrecht, Netherlands, 2001, pp. 735-745.
35. Bhushan, B., "Magnetic Recording Devices: Head/Medium Interface," *The Encyclopedia of Materials: Science and Technology*, Vol. 5, edited by K. H. J. Buschow, R. W. Cahn, M. C. Flemings, B. Ilschner, E. J. Kramer, and S. Mahajan, Elsevier, Amsterdam, 2001, pp. 4856-4868.
36. Bhushan, B. and Li, X., "Nanomechanical Characterization of Ceramic Materials," *High Pressure Surface Science and Engineering,* edited by Y. Gogotsi and V. Domnich, Institute of Physics Publishing, Bristol, U. K., 2004, pp. 321-348.
37. Bhushan, B., "Micro/Nanotribology Studies Using Scanning Probe Microscopy," *Applied Scanning Probe Methods*, edited by B. Bhushan, H. Fuchs, and S. Hosaka, Springer, Heidelberg, Germany, 2004, pp. 171-205.
38. Bhushan, B., "Introduction to Nanotechnology," *Springer Handbook of Nanotechnology*, first edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2004, pp. 1-6.
39. Bhushan, B. and Marti, O., "Scanning Probe Microscopy - Principle of Operation, Instrumentation, and Probes," *Springer Handbook of Nanotechnology*, edited by B. Bhushan, Springer, Heidelberg, Germany, first edition, 2004, pp. 325-369; second edition, 2007, pp. 591-635; third edition, 2009, pp. 573-617; *Nanotribology and Nanomechanics – An Introduction,* edited by B. Bhushan, Springer, Heidelberg, Germany, first edition, 2005, pp. 41-115; second edition, 2008, pp. 37-110; third edition, Vol. 1 - Measurement Techniques and Nanomechanics, 2011, pp. 37-110.
40. Bhushan, B., "Micro/Nanotribology and Materials Characterization Studies Using Scanning Probe Microscopy," *Springer Handbook of Nanotechnology*, first edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2004, pp. 497-541; *Nanotribology and Nanomechanics – An Introduction,* edited by B. Bhushan, Springer, Heidelberg, Germany, 2005, pp. 315-387.
41. Bhushan, B., "Mechanical Properties of Nanostructures," *Springer Handbook of Nanotechnology*, first edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2004, pp. 763-787; *Nanotribology and Nanomechanics – An Introduction,* edited by B. Bhushan, Springer, Heidelberg, Germany, 2005, pp. 731-771.
42. Bhushan, B., "Nanotribology of Ultrathin and Hard Amorphous Carbon Films," *Springer Handbook of Nanotechnology*, edited by B. Bhushan, Springer, Heidelberg, Germany, first edition, 2004, pp. 791-830; second edition, 2007, pp. 1339-1378; third edition, 2010, pp. 1269-1308; *Nanotribology and Nanomechanics – An Introduction,* edited by B. Bhushan, Springer, Heidelberg, Germany, first edition, 2005, pp. 827-884; second edition, 2008, pp. 843-899; third edition, Vol. 2 - Nanotribology, Biomimetics, and Industrial Applications, 2011, pp. 347-402.

43. Bhushan, B. and Liu, H., "Self-Assembled Monolayers for Controlling Adhesion, Friction, and Wear," *Springer Handbook of Nanotechnology*, first edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2004, pp. 831-860; *Nanotribology and Nanomechanics – An Introduction,* edited by B. Bhushan, Springer, Heidelberg, Germany, 2005, pp. 885-928.
44. Bhushan, B. and Liu, H., "Nanoscale Boundary Lubrication Studies," *Springer Handbook of Nanotechnology*, edited by B. Bhushan, Springer, Heidelberg, Germany, first edition, 2004, pp. 861-882; second edition, 2007, pp. 1417-1438; *Nanotribology and Nanomechanics – An Introduction,* edited by B. Bhushan, Springer, Heidelberg, Germany, first edition, 2005, pp. 929-962; second edition, 2008, pp. 959-991.
45. Bhushan, B., "Micro/Nanotribology of MEMS/NEMS Materials and Devices," *Springer Handbook of Nanotechnology*, first edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2004, pp. 983-1021; *Nanotribology and Nanomechanics – An Introduction,* edited by B. Bhushan, Springer, Heidelberg, Germany, 2005, pp. 1031-1089.
46. Bhushan, B., "Tribology: Friction, Wear, and Lubrication," *The Engineering Handbook*, second edition, edited by R.C. Dorf, CRC Press, Boca Raton, Florida, 2004, pp. 21-1 to 21-19.
47. Bhushan, B., "Micro/Nanotribology," *The CRC Handbook of Mechanical Engineering*, second edition, edited by F. Kreith and D. Y. Goswami, CRC Press, Boca Raton, Florida, 2005, pp. 3-222 to 3-231.
48. Bhushan, B., "Introduction – Measurement Techniques and Applications," *Nanotribology and Nanomechanics – An Introduction,* edited by B. Bhushan, Springer, Heidelberg, Germany, first edition, 2005, pp. 1-37; second edition, 2008, pp. 1-34; third edition, Vol. 1 - Measurement Techniques and Nanomechanics, 2011, pp. 1-34.
49. Bhushan, B. and Nosonovsky, M., "Scale Effects in Mechanical Properties and Tribology," *Nanotribology and Nanomechanics – An Introduction,* edited by B. Bhushan, Springer, Heidelberg, Germany, first edition, 2005, pp. 773-834; second edition, 2008, pp. 791-840; third edition, Vol. 2 – Nanotribology, Biomimetics, and Industrial Applications, 2011, pp. 293-344; *Springer Handbook of Nanotechnology*, edited by B. Bhushan, Springer, Heidelberg, Germany, second edition, 2007, pp. 1167-1197; third edition, 2010, pp. 1023-1054.
50. Bhushan, B., "Micro/Nanotribology and Micro/Nanomechanics of Magnetic Storage Devices," *Nanotribology and Nanomechanics – An Introduction,* edited by B. Bhushan, Springer, Heidelberg, Germany, first edition, 2005, pp. 965-1029; second edition, 2008, pp. 1137-1197; third edition, Vol. 2 – Nanotribology, Biomimetics, and Industrial Applications, 2011, pp. 771-831.
51. Castillo, J. and Bhushan, B., "Tribology of Hard Disk Drives – Magnetic Data Storage Technology," *Handbook of Lubrication and Tribology*: *Vol. 1 – Application and Maintenance*, second edition, edited by G. E. Totten, CRC Press, Taylor & Francis Group, Boca Raton, Florida, 2006, pp. 16-1 to 16-44.
52. Burton, Z. and Bhushan, B., "Surface Characterization and Adhesion and Friction Properties of Hydrophobic Leaf Surfaces and Nanopatterned Polymers For Superhydrophobic Surfaces," *Applied Scanning Probe Methods III – Characterization*, edited by B. Bhushan and H. Fuchs, Springer, Heidelberg, Germany, 2006, pp. 55-81.
53. Bhushan, B. and LaTorre, C., "Nanotribological Characterization of Human Hair and Skin Using Atomic Force Microscopy (AFM)," *Applied Scanning Probe Methods IV – Industrial Applications*, edited by B. Bhushan and H. Fuchs, Springer, Heidelberg, Germany, 2006, pp. 35-103; *Biosystems – Investigated by Scanning Probe Microscopy*, edited by H. Fuchs and B. Bhushan, Springer, Heidelberg, Germany, 2010, pp. 621-689.
54. Bhushan, B., "Introduction to Nanotechnology," *Springer Handbook of Nanotechnology*, second edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2007, pp. 1-10.
55. Bhushan, B., "Nanotribology, Nanomechanics and Materials Characterization," *Springer Handbook of Nanotechnology*, second edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2007, pp. 791-857; *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, second edition, 2008, pp. 311-416.
56. Bhushan, B., "Mechanical Properties of Nanostructures," *Springer Handbook of Nanotechnology*, second edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2007, 1305-1336; *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, second edition, 2008, pp. 741-789.
57. Bhushan, B., "Self-Assembled Monolayers (SAMs) for Controlling Adhesion, Friction, and Wear," *Springer Handbook of Nanotechnology*, second edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2007, pp. 1379-1415; *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, second edition, 2008, pp. 901-991.
58. Bhushan, B., "Nanotribology and Materials Characterization of MEMS/NEMS and BioMEMS/BioNEMS Materials and Devices," *Springer Handbook of Nanotechnology*, second edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2007, pp. 1575-1638; *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, second edition, 2008, pp. 1199-1295.

59. Tambe, N. and Bhushan, B., "Velocity Dependence of Nanoscale Friction, Adhesion, and Wear," *Springer Handbook of Nanotechnology*, second edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2007, pp. 1011-1049.
60. Bhushan, B., LaTorre, C., Wei, G., and Chen, N., "Structural, Nanomechanical and Nanotribological Characterization of Human Hair Using Atomic Force Microscopy and Nanoindentation," *Springer Handbook of Nanotechnology*, second edition, edited by B. Bhushan, Springer, Heidelberg, Germany, 2007, pp. 1223-1304.
61. Song, Y. and Bhushan, B., "Modeling of Tip-Cantilever Systems in Dynamic Atomic Force Microscopy," *Applied Scanning Probe Methods Vol. V – Scanning Probe Microscopy Techniques*, edited by B. Bhushan, H. Fuchs, and S. Kawata, Springer, Heidelberg, Germany, 2007, pp. 113-148.
62. Su, C., Huang, L., Prater, C. B., and Bhushan, B., "Torsional Resonance Microscopy and its Applications," *Applied Scanning Probe Methods Vol. V – Scanning Probe Microscopy Techniques*, edited by B. Bhushan, H. Fuchs, and S. Kawata, Springer, Heidelberg, Germany, 2007, pp. 149-223.
63. Nosonovsky, M. and Bhushan, B., "Lotus Effect: Roughness-Induced Superhydrophobicity," *Applied Scanning Probe Methods Vol. VII – Biomimetics and Industrial Applications*, edited by B. Bhushan and H. Fuchs, Springer, Heidelberg, Germany, 2007, pp. 1-40; *Biosystems – Investigated by Scanning Probe Microscopy*, edited by H. Fuchs and B. Bhushan, Springer, Heidelberg, Germany, 2010, pp. 741-780.
64. Bhushan, B. and Sayer, R., "Gecko Feet: Natural Attachment Systems for Smart Adhesion," *Applied Scanning Probe Methods Vol. VII – Biomimetics and Industrial Applications*, edited by B. Bhushan and H. Fuchs, Springer, Heidelberg, Germany, 2007, pp. 41-76; *Biosystems – Investigated by Scanning Probe Microscopy*, edited by H. Fuchs and B. Bhushan, Springer, Heidelberg, Germany, 2010, pp. 781-841.
65. Bhushan, B. and Liu, H., "Development of MOEMS Devices and Their Reliability Issues," *Applied Scanning Probe Methods Vol. VII – Biomimetics and Industrial Applications*, edited by B. Bhushan and H. Fuchs, Springer, Heidelberg, Germany, 2007, pp. 349-366.
66. Bhushan, B., Nosonovsky, M., and Jung, Y. C., "Lotus Effect: Roughness-Induced Superhydrophobic Surfaces," *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, second edition, 2008, pp. 995-1072.
67. Bhushan, B., "Gecko Feet: Natural Hairy Attachment Systems for Smart Adhesion – Mechanism, Modeling and Development of Bio-Inspired Materials," *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, second edition, 2008, pp. 1073-1134.
68. Bhushan, B. and LaTorre, C., "Structural, Nanomechanical and Nanotribological Characterization of Human Hair Using Atomic Force Microscopy and Nanoindentation," *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, second edition, 2008, pp. 1325-1485.
69. Bhushan, B., "Nanotribology of Ultrathin and Hard Amorphous Carbon Films," *Tribology of Diamond-like Carbon Films: Fundamentals and Applications*, edited by C. Donnet and A. Erdemir, Springer, Berlin, Germany, 2008, pp. 510-570.
70. Kasai, T. and Bhushan, B., "Applications of Scanning Probe Methods in Chemical Mechanical Planarization," *Applied Scanning Probe Methods Vol. X – Biomimetics and Industrial Applications*, edited by B. Bhushan, H. Fuchs, and M. Tomitori, Springer, Heidelberg, Germany, 2008, pp. 131-151.
71. Bhushan, B. and Sayer, R., "Gecko Feet: Natural Attachment Systems for Smart Adhesion – Mechanism, Modeling, and Development of Bio-Inspired Materials," *Applied Scanning Probe Methods Vol. X – Biomimetics and Industrial Applications*, edited by B. Bhushan, H. Fuchs, and M. Tomitori, Springer, Heidelberg, Germany, 2008, pp. 1-61.
72. Tambe, N. S. and Bhushan, B., "High Sliding Velocity Nanotribological Investigations of Materials for Nanotechnology Applications," *Applied Scanning Probe Methods Vol. IX – Characterization*, edited by B. Bhushan, H. Fuchs, and M. Tomitori, Springer, Heidelberg, Germany, 2008, pp. 283-310.
73. Hoque, E., DeRose, J.A., Bhushan, B., and Mathieu, H. J., "Self-Assembled Monolayers on Aluminum and Copper Oxide Surfaces: Surface and Interface Characteristics, Nanotribological Properties, and Chemical Stability," *Applied Scanning Probe Methods Vol. IX – Characterization*, edited by B. Bhushan, H. Fuchs, and M. Tomitori, Springer, Heidelberg, Germany, 2008, pp. 235-281.
74. Nagpure, S. C. and Bhushan, B., "Atomic Force Microscopy Studies of Aging Mechanisms in Lithium-Ion Batteries," *Applied Scanning Probe Methods XIII*, edited by B. Bhushan and H. Fuchs, Springer, Heidelberg, Germany , 2009, pp. 203-233.
75. Bhushan, B., "Introduction to Nanotechnology," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, pp. 1-13.
76. Bhushan, B., "Nanotribology, Nanomechanics, and Materials Characterization Studies Using Scanning Probe Microscopy," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, pp. 789-856; *Nanotribology and Nanomechanics – An Introduction*, edited by B.

Bhushan, Springer, Heidelberg, Germany, third edition, Vol. 2 – Nanotribology, Biomimetics, and Industrial Applications, 2011, pp. 3-106.

77. Bhushan, B. and LaTorre, C., "Structural, Nanomechanical, and Nanotribological Characterization of Human Hair Using Atomic Force Microscopy and Nanoindentation," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, pp. 1055-1170; *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany.
78. Bhushan, B., "Mechanical Properties of Nanostructures," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, pp. 1227-1265; *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, third edition, Vol. 1, Measurement Techniques and Nanomechanics, 2011, pp. 527-584.
79. Bhushan, B., "Self-Assembled Monolayers for Nanotribology and Surface protection," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, pp. 1309-1346; *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, third edition, Vol. 2 – Nanotribology, Biomimetics, and Industrial Applications, 2011, pp. 403-460.
80. Bhushan, B., "Nanoscale Boundary Lubrication Studies," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, pp. 1347-1396; *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, third edition, Vol. 2 – Nanotribology, Biomimetics, and Industrial Applications, 2011, pp. 461-530.
81. Koch, K., Bhushan, B., and Barthlott, W., "Multifunctional Plant Surfaces and Smart Materials," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, pp. 1399-1436.
82. Bhushan, B., Jung, Y. C., and Nosonovsky, M., "Lotus Effect: Surfaces with Roughness-Induced Superhydrophobicity, Self-Cleaning, and Low Adhesion," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, pp. 1437-1524.
83. Lee, S. C. and Bhushan, B., "Biological Molecules in Therapeutic Nanodevices," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, pp. 453-484.
84. Bhushan, B., "Gecko Feet: Natural Hairy Attachment Systems for Smart Adhesion – Mechanism, Modeling and Development of Bio-Inspired Materials," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, pp. 1553-1597; *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, third edition, Vol. 2 – Nanotribology, Biomimetics, and Industrial Applications, 2011, pp. 701-767.
85. Bhushan, B., "MEMS/NEMS and BioMEMS/NEMS Materials and Devices and Biomimetics," *Springer Handbook of Nanotechnology,* edited by B. Bhushan, third edition, Springer, Heidelberg, Germany, 2010, 1663-1740; *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, third edition, Vol. 2 – Nanotribology, Biomimetics, and Industrial Applications, 2011, pp. 833-945.
86. Bhushan, B. and Jung, Y. C., "Biomimetics Inspired Surfaces for Superhydrophobicity, Self-Cleaning, Low Adhesion, and Drag Reduction," *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, third edition, Vol. 2 – Nanotribology, Biomimetics, and Industrial Applications, 2011, pp. 533-699.
87. Palacio, M. and Bhushan, B., "Calibration of Normal and Lateral Forces in Cantilevers used in Atomic Force Microscopy," *Nanotribology and Nanomechanics – An Introduction*, edited by B. Bhushan, Springer, Heidelberg, Germany, third edition, Vol. 1, Measurement Techniques and Nanomechanics, 2011, pp. 135-193.
88. Nosonovsky, M. and Bhushan, B., "Capillary Adhesion and Nanoscale Properties of Water," *Scanning Probe Microscopy in Nanoscience and Nanotechnology Vol. 2*, edited by B. Bhushan, Springer, Heidelberg, Germany, 2011, pp. 551-571.
89. Nosonovsky, M. and Bhushan, B., "Green Tribology, Its History, Challenges and Perspectives," *Green Tribology: Biomimetics, Energy Conservation and Substainability*, edited by M. Nosonovsky and B. Bhushan, Springer, Heidelberg, Germany, 2012, pp. 3-22.
90. Nosonovsky, M. and Bhushan, B., "Lotus Versus Rose: Biomimetic Surface Effects," *Green Tribology: Biomimetics, Energy Conservation and Substainability*, edited by M. Nosonovsky and B. Bhushan, Springer, Heidelberg, Germany, 2012, pp. 25-40.
91. Sixteen entries: Bhushan, B., "Nanotechnology," pp. 1841-1850; Bhushan, B., "Biomimetics," pp. 290-298; Bhushan, B. and Palacio, M.L.B., "Atomic Force Microscopy," pp. 146-160; Bhushan, B. and Palacio, M.L.B., "Kelvin Probe Force Microscopy," pp. 1173-1179; Bhushan, B. and Palacio, M.L.B., "Nanoindentation," pp. 1576-1596; Nagpure, S.C. and Bhushan, B., "Nanomaterials for Electrical Energy Storage Devices," pp. 1597-1608; Bhushan, B., "Nanotribology," pp. 1859-1869; Bhushan, B., "Nanomechanical Properties of Nanostructures," pp. 1620-1630; Bhushan, B. and Palacio, M.L.B., "Bioadhesion," pp. 186-193; Nosonovsky, M. and Bhushan, B., "Green Tribology and Nanoscience," pp. 978-981; Bhushan, B., "Self-Assembled

Monolayers for Nanotribology," pp. 2344-2354; Bhushan, B., "Boundary Lubrication," pp. 354-362; Bhushan, B. and Nosonovsky, M., "Lotus Effect," pp. 1224-1233; Bhushan, B. and Nosonovsky, M., "Rose Petal Effect," pp. 2265-2272; Bhushan, B., "Gecko Effect," pp. 943-951; Bhushan, B., "Shark Skin Effect," pp. 2401-2412; *Encyclopedia of Nanotechnology*, edited by B. Bhushan, Springer, Heidelberg, Germany, 2012.

92. Maharaj, D. and Bhushan, B., "Nanomanipulation and Nanotribology of Nanoparticles and Nanotubes Using Atomic Force Microscopy," *Handbook of Nanomaterials Properties Volume 1*, edited by B. Bhushan, D. Luo, S. Schricker, W. Sigmund and S. Zauscher, Springer, Heidelberg, Germany, 2014, pp. 299-315.
93. Schricker, S.R., Palacio, M. and Bhushan, B., "Modulating Protein Adhesion and Conformation with Block Copolymer Surfaces," *Handbook of Nanomaterials Properties Volume 2,* edited by B. Bhushan, D. Luo, S. Schricker, W. Sigmund and S. Zauscher, Springer, Heidelberg, Germany, 2014, pp. 1343-1376.

Dedicated Journal Issues

1. Macro- and Micro-Tribology and Mechanics of Magnetic Storage Systems, in Wear, Vol. 190, No. 1, 1995.
2. Macro- and Micro-Tribology and Mechanics of Magnetic Storage Systems, in Wear, Vol. 202, No. 1, 1996.
3. Macro- and Micro-Tribology and Mechanics of Magnetic Storage Systems, in Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, Vol. 211, No. 4, 1997.

Editorship of Journal Issues

1. Nanotribology, Nanomechanics and Applications to Nanotechnology I and II, Philosophical Transactions of the Royal Society A, Vol. 366, No. 1869 & 1870, 2008.
2. Biomimetics I: Functional Biosurfaces and II: Fabrication and Applications, Philosophical Transactions of the Royal Society A, Vol. 367, No. 1893 & 1894, 2009.
3. Green Tribology, Philosophical Transactions of the Royal Society A, Vol. 368, No. 1929, 2010.
4. Biosensors – Surface Structures and Materials, Philosophical Transactions of the Royal Society A, Vol. 370, No. 1967, 2012.

Technical Books

1. Bhushan, B., Tribology and Mechanics of Magnetic Storage Devices, Springer, New York, 1990 (first edition) and 1996 (second edition).
2. Bhushan, B. and Gupta, B. K., Handbook of Tribology: Materials, Coatings, and Surface Treatments, McGraw-Hill Book Company, New York, 1991; Reprint w/corrections, Krieger Publishing Company, Malabar, Florida, 1997.
3. Bhushan, B., Mechanics and Reliability of Flexible Magnetic Media, Springer, New York, first edition, 1992 and second edition, 2000.
4. Bhushan, B., Principles and Applications of Tribology, John Wiley, New York, 1999; Second edition, 2013; eBook: http://onlinelibrary.wiley.com/book/10.1002/9781118403020.
5. Bhushan, B., Introduction to Tribology, John Wiley, New York, 2002; Translated into Chinese by China Machine Press, 2006 (Translated by S. Ge); Second edition, 2013; eBook: http://onlinelibrary.wiley.com/book/10.1002/9781118403259.
6. Nosonovsky, M. and Bhushan, B., Multiscale Dissipative Mechanisms and Hierarchical Surfaces: Friction, Superhydrophobicity, and Biomimetics, Springer, Heidelberg, Germany, 2008; eBook: http://dx.doi.org/10.1007/978-3-540-78425-8.
7. Bhushan, B., Biophysics of Human Hair: Structural, Nanomechanical and Nanotribological Studies, Springer, Heidelberg, Germany, 2010; eBook: http://dx.doi.org/10.1007/978-3-642-15901-5.
8. Bhushan, B., Biomimetics: Bioinspired Hierarchical-Structured Surfaces for Green Science and Technology, Springer, Heidelberg, Germany, 2012; eBook: http://dx.doi.org/10.1007/978-3-642-25408-6.

Edited Reference Books

1. Bhushan, B., Micro/Nanotribology and its Applications, NATO ASI Series E: Applied Sciences-Vol. 330, Kluwer Academic Publishers, Dordrecht, Netherlands, 1997.
2. Bhushan, B., *Tribology Issues and Opportunities in MEMS*, Kluwer Academic Publishers, Dordrecht, Netherlands, 1998.
3. Bhushan, B., *Tribology of Magnetic Storage Systems,* The Institution of Mechanical Engineers, Professional Engineering Publishing Limited, London, U.K., 1998.
4. Bhushan, B., *Handbook of Micro/Nanotribology*, CRC Press, Boca Raton, Florida, First ed., 1995; Translated into Korean by Korea Economic Daily & Business Publications, 2000; Second ed., 1999; ebook: http://dx.doi.org/10.1201/9781420050493.
5. Bhushan, B., *Modern Tribology Handbook, Vol. 1 - Principles of Tribology; Vol. 2 - Materials, Coatings, and Industrial Applications*, CRC Press, Boca Raton, Florida, 2001.

6. Bhushan, B., *Fundamentals of Tribology and Bridging the Gap Between the Macro- and Micro/ Nanoscales,* NATO Science Series II: Mathematics, Physics and Chemistry - Vol. 10, Kluwer Academic Publishers, Dordrecht, Netherlands, 2001.
7. Bhushan, B., *Springer Handbook of Nanotechnology*, Springer, Heidelberg, Germany, first edition, 2004; second edition, 2007; Translated into Chinese by Science Press, 2009; Translated into Russian by Technosphera, 2010; third edition, 2010; Translated into Chinese by HIT Press, 2013; eBook: http://www.springerlink.com/content/978-3-642-02524-2#section=691520&page=1.
8. Bhushan, B., *Nanotribology and Nanomechanics – An Introduction*, Springer, Heidelberg, Germany, first edition, 2005; second edition, 2008; third edition - *Nanotribology and Nanomechanics I - Measurement Techniques and Nanomechanics*, *II - Nanotribology, Biomimetics, and Industrial Applications*, 2011; eBook Part I: http://dx.doi.org/10.1007/978-3-642-15283-2; eBook Part II: http://dx.doi.org/10.1007/978-3-642-15263-4.
9. Nosonovsky, M. and Bhushan, B., *Green Tribology: Biomimetics, Energy Conservation and Sustainability*, Springer, Heidelberg, Germany, 2012; eBook: http://dx.doi.org/10.1007/978-3-642-23681-5.
10. Bhushan, B., *Encyclopedia of Nanotechnology*, Volumes 1-4, 2868 pages, 2012 (first edition), second edition (in progress), Springer, Heidelberg, Germany.
11. Bhushan, B., Luo, D. Schricker, S. R. and Sigmund, W, . and Zauscher, S., *Handbook of Nanomaterials Properties*, Volumes 1-2, 1464 pages, Springer, Heidelberg, Germany, 2014; eBook: http://link.springer.com/book/10.1007/978-3-642-31107-9

Edited Scanning Probe Book Series

1. Bhushan, B., Fuchs, H., and Hosaka, S., Applied Scanning Probe Methods, Springer, Heidelberg, Germany, 2004.
2. Bhushan, B. and Fuchs, H., Applied Scanning Probe Methods II – Scanning Probe Microscopy Techniques, Springer, Heidelberg, Germany, 2006; eBook: http://dx.doi.org/10.1007/b139097.
3. Bhushan, B. and Fuchs, H., Applied Scanning Probe Methods III – Characterization, Springer, Heidelberg, Germany, 2006; eBook: http://dx.doi.org/10.1007/b138285.
4. Bhushan, B. and Fuchs, H., Applied Scanning Probe Methods IV – Industrial Applications, Springer, Heidelberg, Germany, 2006; eBook: http://dx.doi.org/10.1007/b138289.
5. Bhushan, B., Fuchs, H., and Kawata, S., Applied Scanning Probe Methods V – Scanning Probe Microscopy Techniques, Springer, Heidelberg, Germany, 2007; eBook: http://dx.doi.org/10.1007/978-3-540-37316-2.
6. Bhushan, B. and Kawata, S., Applied Scanning Probe Methods VI – Characterization, Springer, Heidelberg, Germany, 2007; eBook: http://dx.doi.org/10.1007/11776314.
7. Bhushan, B. and Fuchs, H., Applied Scanning Probe Methods VII – Biomimetics and Industrial Applications, Springer, Heidelberg, Germany, 2007; eBook: http://dx.doi.org/10.1007/11785705.
8. Bhushan, B., Fuchs, H., and Tomitori, M., Applied Scanning Probe Methods VIII – Scanning Probe Microscopy Techniques, Springer, Heidelberg, Germany, 2008; eBook: http://dx.doi.org/10.1007/978-3-540-74080-3.
9. Bhushan, B., Fuchs, H., and Tomitori, M., Applied Scanning Probe Methods IX - Characterization, Springer, Heidelberg, Germany, 2008; eBook: http://dx.doi.org/10.1007/978-3-540-74083-4.
10. Bhushan, B., Fuchs, H., and Tomitori, M., Applied Scanning Probe Methods X - Biomimetics and Industrial Applications, Springer, Heidelberg, Germany, 2008; eBook: http://dx.doi.org/10.1007/978-3-540-74085-8.
11. Bhushan, B. and Fuchs, H., Applied Scanning Probe Methods XI – Scanning Probe Microscopy Techniques, Springer, Heidelberg, Germany, 2009; eBook: http://dx.doi.org/10.1007/978-3-540-85037-3.
12. Bhushan, B. and Fuchs, H., Applied Scanning Probe Methods XII - Characterization, Springer, Heidelberg, Germany, 2009; eBook: http://dx.doi.org/10.1007/978-3-540-85039-7.
13. Bhushan, B. and Fuchs, H., Applied Scanning Probe Methods XIII - Biomimetics and Industrial Applications, Springer, Heidelberg, Germany, 2009; eBook: http://dx.doi.org/10.1007/978-3-540-85049-6.
14. Fuchs, H. and Bhushan, B., Biosystems – Investigated by Scanning Probe Microscopy, Springer, Heidelberg, Germany, 2010.
15. Bhushan, B., Scanning Probe Microscopy in Nanoscience and Nanotechnology, Springer, Heidelberg, Germany, 2010; eBook: http://dx.doi.org/10.1007/978-3-642-03535-7.
16. Bhushan, B., Scanning Probe Microscopy in Nanoscience and Nanotechnology Vol. 2, Springer, Heidelberg, Germany, 2011; eBook: http://dx.doi.org/10.1007/978-3-642-10497-8.
17. Bhushan, B., Scanning Probe Microscopy in Nanoscience and Nanotechnology Vol. 3, Springer, Heidelberg, Germany, 2013; eBook: http://dx.doi.org/10.1007/978-3-642-25414-7.

Edited Information Storage Book Series

1. Bhushan, B., Bogy, D., Eiss, N. S. and Talke, F. E., Tribology and Mechanics of Magnetic Storage Systems, Special Publication SP-16, American Society of Lubrication Engineers, Park Ridge, Illinois, 1984.

2. Bhushan, B. and Eiss, N. S., Tribology and Mechanics of Magnetic Storage Systems, Vol. 2, Special Publication SP-19, American Society of Lubrication Engineers, Park Ridge, Illinois, 1985.
3. Bhushan, B. and Eiss, N. S., Tribology and Mechanics of Magnetic Storage Systems, Vol. 3, Special Publication SP-21, American Society of Lubrication Engineers, Park Ridge, Illinois, 1986.
4. Bhushan, B. and Eiss, N. S., Tribology and Mechanics of Magnetic Storage Systems, Vol. 4, Special Publication SP-22, Society of Tribologists and Lubrication Engineers, Park Ridge, Illinois, 1987.
5. Bhushan, B. and Eiss, N. S., Tribology and Mechanics of Magnetic Storage Systems, Vol. 5, Special Publication SP-25, Society of Tribologists and Lubrication Engineers, Park Ridge, Illinois, 1988.
6. Bhushan, B. and Eiss, N. S., Tribology and Mechanics of Magnetic Storage Systems, Vol. 6, Special Publication SP-26, Society of Tribologists and Lubrication Engineers, Park Ridge, Illinois, 1989.
7. Bhushan, B., Tribology and Mechanics of Magnetic Storage Systems, Vol. 7, Special Publication SP-29, Society of Tribologists and Lubrication Engineers, Park Ridge, Illinois, 1990.
8. Bhushan, B., Advances in Information Storage Systems, Vol. 1, American Society of Mechanical Engineers, New York, 1991.
9. Bhushan, B., Advances in Information Storage Systems, Vol. 2, American Society of Mechanical Engineers, New York, 1991.
10. Bhushan, B., Advances in Information Storage Systems, Vol. 3, American Society of Mechanical Engineers, New York, 1991.
11. Bhushan, B., Advances in Information Storage Systems, Vol. 4, American Society of Mechanical Engineers, New York, 1992.
12. Bhushan, B., Advances in Information Storage Systems, Vol. 5, American Society of Mechanical Engineers, New York, 1993.
13. Bhushan, B., Advances in Information Storage Systems, Vol. 6, World Scientific Publishing Co. Inc., River Edge, New Jersey, 1995.
14. Adams, G. G., Bhushan, B., Miu, D. and Wickert, J., Advances in Information Storage and Processing Systems, ISPS - Vol. 1, ASME, New York, 1995.
15. Bhushan, B., Advances in Information Storage Systems, Vol. 7, World Scientific Publishing Co. Inc., River Edge, New Jersey, 1996.
16. Adams, G. G., Bhushan, B., Connolly, D. and Wickert, J., Proceedings of the 7th Annual Information Storage and Processing Systems Symposium, ISPS - Vol. 2, ASME, New York, N.Y., 1996.
17. Adams, G. G., Bhushan, B., Connolly, D., Messner, W. and Wickert, J., Proceedings of the 8th International Symposium on Information Storage and Processing Systems, ISPS - Vol. 3, ASME, New York, 1997.
18. Bhushan, B., Advances in Information Storage Systems, Vol. 8, World Scientific Publishing Co. Inc., River Edge, New Jersey, 1998.
19. Adams, G. G., Bhushan, B., Connolly, D. and Wickert, J., Proceedings of the 9th International Symposium on Information Storage and Processing Systems, ISPS – Vol. 4, ASME, New York, 1998.
20. Bhushan, B., Advances in Information Storage Systems, Vol. 9, World Scientific Publishing Co. Inc., River Edge, New Jersey, 1998.
21. Bhushan, B., Advances in Information Storage Systems, Vol. 10, World Scientific Publishing Co. Inc., River Edge, New Jersey, 1999.

U.S. Patents

1. Bhushan, B., “High Temperature Low Friction Surface Coatings,” U.S. Patent No. 4,227,756, October 14, 1980.
2. Bhushan, B., “High Temperature Low Friction Surface Coatings and Method of Application,” U.S. Patent No. 4,253,714, March 3, 1981.
3. Bhushan, B., “Tractor/Trailer Safety Device,” U.S. Patent No. 4,269, 426, May 6, 1981.
4. Bhushan, B. and Gray, S., “Support Element for Compliant Hydrodynamic Journal Bearings,” U.S. Patent No. 4,274,683, June 23, 1981.
5. Bhushan, B., Coe, J. V., and Gupta, B. K., “Method for Coating Fullerene Materials for Tribology,” U.S. Patent No. 5,558,903, September 24, 1996.
6. Bhushan, B., “Method of Texturing a Magnetic Recording Medium for Optimum Skewness and Kurtosis to Reduce Friction with a Magnetic Head,” U.S. Patent No. 5,737,229, April 7, 1998.
7. Bhushan, B., “Surfaces Having Optimized Skewness and Kurtosis Parameters for Reduced Static and Kinetic Friction,” U.S. Patent No. 6,007,896, Dec. 28, 1999.
8. Bhushan, B., “Scanning Capacitance Device for Film Thickness Mapping Featuring Enhanced Resolution, Measurement Methods Using Same,” U.S. Patent No. 6,404,207, June 11, 2002.
9. Bhushan, B. and Hahm, C. D., “Capacitance Devices for Film Thickness Mapping, Measurement Methods Using Same,” U.S. Patent No. 6,459,280, Oct. 1, 2002.

10. Bhushan, B. and Hahm, C. D., "Liquid Dielectric Capacitor for Film Thickness Mapping, Measurement Methods Using the Same," U.S. Patent No. 6,504,386, Jan. 7, 2003.
11. Bhushan, B. and Hahm, C. D., "Liquid Dielectric Capacitor for Film Thickness Mapping," U.S. Patent No. 6,717,419 B1, April 6, 2004.
12. Bhushan, B. and Hahm, C. D., "Pin and Cup Devices for Measuring Film Thickness," U.S. Patent No. 6, 724, 199 B1, April 20, 2004.
13. Bhushan, B. and Hahm, C. D., "Method for Measuring Film Thickness Using Capacitance Technique," U.S. Patent No. 6,756,791 B1, June 29, 2004.
14. Pelz, J. P., Lee, D. T., and Bhushan, B., "Direct, Low Frequency Capacitance Measurement for Scanning Capacitance Microscopy," U.S. Patent No. 6,856,145 B2, Feb 15, 2005; World Intellectual Property Org., Int. Bureau, Dec. 11, 2003; Japanese Patent No. 4,331,104, June 26, 2009.
15. Pelz, J. P., Lee, D. T., and Bhushan, B., "Method for Measuring NM-Scale Tip-Sample Capacitance," U.S. Patent No. 7,023,220 B2, April 4, 2006.
16. Bhushan, B., Jung, Y. C., and Nosonovsky, M., "Hierarchical Structures for Superhydrophobic Surfaces and Methods of Making," U. S. Patent No. 8,137,751 B2, March 20, 2012.
17. Bhushan, B., Jung, Y. C., and Nosonovsky, M., "Hierarchical Structures for Superhydrophobic Surfaces and Self-Cleaning and Methods of Making," U. S. Patent Pending.
18. Ebert, D.R. and Bhushan, B., "Methods of Fabricating Superhydrophobic, Optically Transparent Surfaces," U.S. Patent Pending.
19. Bixler, G. D. and Bhushan, B., "Fluid Conveying Apparatus with Low Drag, Anti-fouling Flow Surface and Methods of Making Same," U.S. Patent Pending.
20. **Published:** Bhushan, B. and Nosonovsky, M., "Hydrophobic Surface with Geometric Roughness Pattern," U.S. Patent Application Publication No. US 2006/0078724 A1, April 13, 2006.

Editor of Book Series

1. Avoris, P., Bhushan, B., Bimberg, D., von Klitzing, K., Sasaki, H., and Wiesendanger, R., NanoScience and Technology Series, Springer, Heidelberg, Germany, 2004-.
2. Bhushan, B., Mechanics and Materials Science Series, CRC Press Inc., Boca Raton, Florida, 1993-2002.
3. Bhushan, B., Advances in Information Storage Systems Series, ASME Press, New York, 1991-1993; World Scientific, Singapore, 1994-1999.

Editor-In-Chief of a Journal

1. *Editor-in-Chief - Microsystem Technologies* (with B. Michel), Springer Berlin-Heidelberg, Vol. 8, 2002-; formerly, *Journal of Information Storage and Processing Systems*, Birkhauser Boston (A Division of Springer), Vol. 1-3, 1999-2001.

Editorial Advisory Board

1. Honorary Member, The Research Board of Advisors, *The American Biographical Institute*, Raleigh, North Carolina (1996-).
2. *Journal of Friction and Wear*, The National Academy of Sciences, Belarus (1998-).
3. *International Journal of Surface Science and Engineering*, Inderscience Publishers (2006-).
4. *International Journal of Materials and Structural Integrity,* Inderscience Publishers (2006-).
5. *International Journal of Nanosystems*, Inderscience Publishers (2006-).
6. *Advances in Tribology*, Hindawi Publishing Corporation (2007-).
7. *Research Letters in Nanotechnology*, Hindawi Publishing Corporation (2008-).
8. *Journal of Nanotechnology*, Hindawi Publishing Corporation (2008-).
9. *The Open Mechanical Engineering Journal*, Bentham Science Publishers (2007-).
10. *The Open Ceramic Science Journal*, Bentham Science Publishers (2008-).
11. *The Open Polymer Science Journal*, Bentham Science Publishers (2008-).
12. *The Open Surface Science Journal*, Bentham Science Publishers (2008-).
13. *The Open Condensed Matter Physics Journal*, Bentham Science Publishers (2008-).
14. *The Open Colloid Science Journal*, Bentham Science Publishers (2008-).
15. *The Journal of Biotechnology & Biomaterials–Open Access*, OMICS Publishing Group (2010-).
16. *The Journal of Petroleum & Environmental Biotechnology–Open Access*, OMICS Publishing Group (2010-).
17. *Journal of Nanomedicine and Biotherapeutic Delivery-Open Access*, OMICS Publishing Group (2010-).
18. *The Journal of Biotechnology Applications*, Bioinfo Publications, Mumbai, India (2010-).
19. *Tribology in Industry*, Serbian Tribology Society (2011-).
20. *Open Journal of Organic Polymer Materials*, Scientific Research Publishing, USA (2011-).
21. *The Open Nanoscience Journal*, Bentham Science Publishers (2011-).

22. *Lubricants*, MDPI (2011-).
23. *Surface Innovations*, Ice Publishing (2012-).

Annual Research Meeting

The next Annual Research Meeting will be held soon.

Short Courses Taught

1. "Tribology Graduate Course (Guest Lectures)," Mechanical Engineering Department, King Fahd University of Petroleum & Minerals, Dec. 2013.
2. "Principles and Applications of Tribology (Accelerated 4 days (16 hours) course)," School of Mechatronics Engineering, Harbin Institute of Technology, Harbin, China, Aug. 2014.

Students Updates

We presently have five postdoctoral fellows/visiting senior scientists, and five Ph.D. graduate students. The following students graduated in 2013-14:

Ph.D.

1. Gregory D. Bixler, "Bioinspired Surface for Low Drag, Self-Cleaning, and Antifouling: Shark Skin, Butterfly and Rice Leaf Effects," Ph.D. Thesis, Dept. of Mech. and Aerospace Eng., Dec. 2013.
2. Yunlu Pan, "Study of the Relation Between Electric Field and the Drag of Liquid Flow on a Solid Surface in Micro/Nanoscale," Ph.D. Thesis, Dept. of Mechatronics, Harbin Institute of Technology, China (co-advised with Prof. X. Zhao), June, 2014. Abstract available at www.mecheng.osu.edu/nlbb/content/theses.

M.S.

1. Sanjay Ramdon, "Nanoscale Characterization of Aged Li-ion Battery Cathodes," M.S. Thesis, Dept. of Mech. and Aero. Eng., Aug. 2013.

Student Ph.D. Theses Abstracts

Full theses can be found on the web at http://www.mecheng.osu.edu/nlbb

Gregory Bixler, "Bioinspired Surface for Low Drag, Self-Cleaning, and Antifouling: Shark Skin, Butterfly and Rice Leaf Effects."

Researchers are continually inspired by living nature to solve complex challenges through the field of biomimetics. Nature thrives on effective designs while optimizing the use of precious resources, which is something that inspires engineers worldwide. Gaining a deeper understanding of nature can lead to bioinspired products that save time, money, and lives. Examples include "low drag" boat hulls inspired by shark skin as well as "self-cleaning" windows and "antifouling" medical devices inspired by the superhydrophobic and low adhesion lotus leaf. Common engineering challenges solved in nature but hindering many industries are fluid drag reduction and antifouling. Nature holds clues to these challenges, including the unique surface characteristics of rice leaves and butterfly wings that combine the shark skin (anisotropic flow leading to low drag) and lotus leaf (superhydrophobic and self-cleaning) effects, producing the so-called rice and butterfly wing effect.

In this thesis, first presented is a chapter on biofouling and inorganic-fouling which is generally undesirable for many medical, marine, and industrial applications. A survey of promising flora and fauna are studied in order to discover new antifouling methods that could be mimicked for engineering applications. New antifouling methods will presumably incorporate a combination of physical and chemical controls. Mechanisms and experimental results are presented focusing on my new drag reducing shark skin inspired surfaces. This includes my new laser etched and microtextured film samples for closed channel drag using water, oil, and air as well as in wind tunnel. Finally mechanisms and experimental results are presented focusing on my newly discovered rice and butterfly wing effect surfaces. I collected and present morphology, drag, antifouling, contact angle, and contact angle hysteresis results to understand the role of sample geometrical dimensions, wettability, viscosity, and velocity. Hierarchical liquid repellent coatings combining nano- and micro-sized features and particles are utilized to recreate or combine various effects. I fabricated such samples with photolithography, soft lithography, hot embossing, and coating techniques. Discussion is provided along with new conceptual models describing the role of surface structures related to low drag and antifouling properties. Modeling provides design guidance when developing novel low drag and antifouling surfaces for medical, marine, and industrial applications.

Student M.S. Theses Abstracts

Sanjay Ramdon, Nanoscale Characterization of Aged Li-Ion Battery Cathodes

Lithium-ion (Li-ion) batteries have become very prominent as a form of energy storage for numerous applications due to its high energy and power densities. They are used for numerous portable devices and more recent electric vehicles (EVs). It is important to increase the cycle life of Li-ion batteries in order for them to be more viable for the automotive industry. With use, these batteries undergo an aging process which reduces the battery storage capacity and increases internal resistance. To reduce the aging process it is essential to first understand the degradation mechanisms on the electrodes of the battery.

A multi-scaled approach has been previously applied to the study of the degradation of the LiFePO4 cathodes. It has been shown that nanoparticles in cathodes coarsen as a result of aging. Coarsening of nanoparticles has been shown to lead to an increase in surface resistance and decrease in surface conductivity, which is responsible for reduced lithium retaining capacity. It is therefore important to study the cause of these aging mechanisms in order to increase the life of the battery. An in depth study of cathode on the nanometer scale is necessary using atomic force microscope (AFM) related techniques. In this work, both ex-situ and in-situ studies were conducted to understand the aging phenomenon in LiFePO4 battery cathodes. High resolution AFM imaging and current measurements were conducted to study the difference of the unaged cathode from the aged. This was done to quantify the coarsening process. Particle agglomeration was observed in the aged cathode, which is believed to reduce surface conductivity.

Nanomechanical characterization and mechanical integrity studies were then conducted on unaged and aged cathodes using AFM equipped with nanoindentor. This was done to determine the effect of increased internal stress within the cathode created during aging on the nanomechanical and mechanical integrity properties. Properties of hardness, elastic modulus, creep, nanowear, nanoscratch and nanofriction were examined and significant differences were observed between unaged and aged cathodes. The aged cathodes showed higher hardness, creep depth and critical load in scratch and lower wear depth and coefficient of friction.

In order to further understand aging mechanisms, real time examination of battery cathodes were done during operation of the cell using in-situ techniques. AFM in-situ techniques allow direct observation of cathodes during cycling of the cell on the nanometer scale. Morphology data showed increase in particle size from FePO4 phase to LiFePO4 phase during discharge of the cell due to lithiation. In-situ AFM electrochemical characterization has been shown to be a useful technique to study Li-ion battery aging mechanisms.

These studies further the understanding of the degradation mechanisms of Li-ion battery cathodes. The in situ electrochemistry approach advanced in this work is believed to be useful for fundamental understanding of aging mechanisms.

Technical Seminars

We invite industrial members to visit the NLBB and present seminars. If you would like to give a seminar, please contact Professor B. Bhushan.

Honors and Awards (B. Bhushan)

2014 **STLE - International Award for Outstanding Contribution to Tribology and/or its Related Sciences**; It is Society's highest honor for lifetime achievement and bestows lifetime honorary membership.

Sept. 2013-Aug. 2014 ASME/AAAS Science & Technology Policy Fellow, House Committee on Science, Space, and Technology; detailed to House Committee on Energy and Commerce and House Committee on Oversight and Government Reform, United States Congress, Washington, D.C.

Nov. 12- 14 2014 How Butterfly Wings Can Inspire New High-Tech Surfaces, **NSF Science Now** (11/16/12); Covered by **NSF Discoveries News**, **Columbus Dispatch** (12/2/12); **sciencenewsline.com** (11/7/12); **gizman.com** (11/8/12); **qmed.com** (11/12); **eetimes.com** (11/8/12); **redorbit.com** (11/8/12); **scilifestyle.com** (11/12/12); **microscopy-analysis.com** (11/12/12); **eetasia.com** (11/12/12); **sciencebusiness.technewslit.com** (11/12/12); **silobreaker.com** (12/2/12); **MRS Materials 360 online** (12/18/12); **NSF Livescience and Discovery Page** (1/23/13); **ISTV & American Institute of Physics** (11/13); **Awake** (4/14), www.jw.org; The journal with the second highest worldwide monthly circulation (45 million in 99 languages).etc.

Oct. 19, 2014 "Biomimetics: Bioinspired Superomniphobic, Self-cleaning/Antifouling and Low Drag Surfaces," **Lunch with a Scientist**, **ScienceWriters 2014**, The Annual Joint Meeting of the National Association of Science Writers (NASW) and the Council for the Advancement of Science Writing (CASW), Columbus, Ohio, 10/17-21, 2014.

Professor Bharat Bhushan
Director, Nanoprobe Laboratory
for Bio- & Nanotechnology
and Biomimetics
The Ohio State University
201 W. 19th Avenue
W390 Scott Laboratory
Columbus, OH 43210-1142
614-292-0651, -0171 (office)
bhushan.2@osu.edu (email)
http://www.mecheng.osu.edu/nlbb

First Class Mail