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Frontiers of fundamental tribological research

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This review summarizes recent advances in the area of tribology and the challenges to achieve a molecular level understanding of friction and wear and makes specific recommendations towards attaining such a fundamental understanding. This document represents the results of a two-day workshop, sponsored by the U.S. National Science Foundation, at which participants were charged with defining the outstanding challenges in obtaining a fundamental understanding of friction and wear, thus assisting the National Science Foundation in the effective allocation of resources to address these challenges.

KEY WORDS: CAE, MEMS, AFM, Tribological systems

1. Introduction

As pointed out in the 1966 Jost report, where the term "tribology" was originally coined [1], economic losses that could be ascribed to wear and friction were equivalent to about 4% of the U.K. gross national product. While advances in lubricant technologies have undoubtedly decreased this number, our concerns are now not only economic, but also include serious environmental and security issues. While the fundamental laws describing the way in which contacting bodies move were first described at the end of the 17th century by Amontons [2], only twelve years after Newton published his laws of classical mechanics, serious research continues today seeking to understand tribological contacts on an atomistic and molecular level.

Remarkable advances have been made since the 1960s, spurred by the clear economic incentives emphasized in the Jost report. Furthermore, basic research has led to fundamental improvements in our understanding of tribological processes that have resulted in a large number of technological and scientific advances. Some key examples of such fundamental and technological advances are outlined in section 2. Many of these highlight the extent of recent progress that has been realized since the time of previous assessments of the progress of tribological developments and research [3,4].

In the future, in-depth fundamental investigations will enhance our understanding of the way in which energy is dissipated at the interface between moving solids, the atomic- and molecular-scale mechanisms of interfacial wear, and the effect of the environment on these processes, in turn leading to further technological advances. Indeed, the remarkable advances in understanding the physics, chemistry, and materials properties of tribological systems that have been achieved during the last decade promise a full understanding of many of the remaining tribological issues outlined below. Very often, these advances in understanding can be incorporated rapidly into new technologies. For example, changing lubricant formulations, altering manufacturing processes that involve tribological interfaces, or incorporating tribological processes into computer-assisted engineering (CAE) models to prevent future catastrophic failure can have an immediate and positive effect. In light of the technological advances of recent years and our increasing understanding of many fundamental tribological issues, we seek to define a number of the challenges that currently exist, and outline these in section 3. Specific recommendations as to how these challenges might be addressed are detailed in section 4.

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2. Technological and fundamental advances in tribology

This section outlines some recent examples of technological achievements and advances in our understanding of the fundamentals of tribology. It should be emphasized that this list is not meant to be comprehensive but is intended to provide a flavor of the nature of the advances that might be expected from future investments.

2.1. Hard disk drive technology

The data storage industry has been perhaps the most striking example of the way in which the solution of tribological problems has been crucial to the continued growth of a technology. The current expectation in the

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hard disk storage industry is that performance will grow exponentially (the so-called Moore's Law) in terms of speed and storage density [5,6]. This growth has hitherto been successfully achieved by the development of protective carbon overcoats, the design of lubricant systems that preserve at least a monolayer of lubricant on the disk surface, the development of air bearings, and the careful control of the disk topology [7,8]. These tribological developments have allowed for greatly reduced spacings between the recording head and the disk media as illustrated in figure 1. This reduction in magnetic spacing over time has enabled, and will continue to enable, increasing storage densities and capacities of hard disk drives. These advances have lead to routine performance of today's drives with head-disk interfaces involving relative speeds of ~10 m/s and surface separations of <10 nm.

2.2. Development of ceramic bearings

The development of ceramic bearing components has played a central and specific role in the advancement of the NASA space shuttle program by providing increased reliability and longevity of the pumps used to feed fuel and oxidizer to the main engines, where conventionally used steel bearings traditionally had to be replaced after only one or two flights [9]. The use of ceramic rolling element bearings in these pumps extended the reliable lifetime to at least seven flights. The development of these bearing systems have, in turn, also lead to improvements in machine tool spindles, ultracentrifuges, and turbomolecular pumps that must operate at high frequencies and with extremely high precision.

2.3. Thin film lubrication

Recent work entailing *in-situ* monitoring of lubricant films within the contact region [10] has provided experimental confirmation of previously proposed elastohydrodynamic (EHD) lubrication theories [11]. These methods generally rely on optical probes where one of the surfaces comprises an optically transparent material. This has allowed interferometry to be used to precisely measure film thicknesses as a function of applied load and sliding speed and to provide an experimental verification of the equations describing EHD lubrication. More recent advances have considerably improved the precision of such interferometric measurements potentially allowing much thinner boundary layers to be investigated [12–16]. In addition, optically based

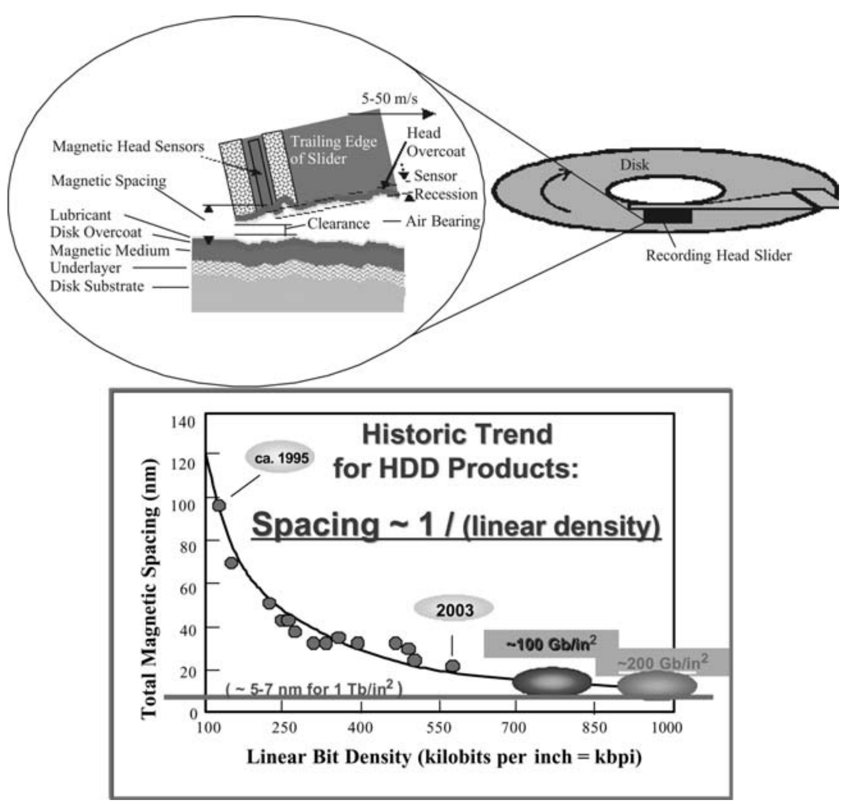

Figure 1. (Top) Right schematic shows a recording head slider flying over a rotating disk surface in hard disk drives. Left side shows an enlarged schematic of the trailing edge of the slider where the recording head is located and a cross section of the disk recording medium, overcoat, and lubricant and illustrates the contributions to the total magnetic spacing (distances from the bottom of the head sensor to the top of the magnetic medium). (Bottom) Trend of magnetic spacing as a function of linear bit density (a measure of how closely packed the bits are stored on the disk). In 2003, the magnetic spacing was ~20 nm, enabling areal densities just under 100 Gigabit/in^2. For distant future drives with Terabit/in.^{2} storage densities, the magnetic spacing is projected to be 5–7 nm (Courtesy of Mathew Mate and Peter Baumgart, Hitachi Global Storage Technologies).

spectroscopies [17], for example, laser Raman spectroscopy, have exploited this strategy to provide chemical information at the tribological interface [18]. As illustrated in figure 2, such an approach has been used to correlate the evolution of a diamond-like carbon nanocomposite with changes in the frictional properties of the interface.

2.4. Micro-electromechanical devices (MEMS)

While a number of serious tribological issues remain with respect to the successful deployment of many MEMS devices (described in a following section), the introduction of one such device, the digital light processing (DLP) micromirror, has revolutionized the way in which visual images can be projected. The principles of operation of this system are illustrated in figure 3, which demonstrates how light beams can be rapidly deflected to form images. The successful development of this technology, which involves the intermittent switching of lithographically manufactured microscopic mirrors, relied specifically on finding a tribological solution to the problem of stiction and irreversible adhesion of the micromirrors, which had caused device failure. Ultimately this solution involved the incorporation of a vapor-phase lubrication scheme based upon the gas-phase delivery of species forming molecularly thin protective films of exceedingly low surface energy [19].

2.5. Tribological investigations of single asperity contacts

In the "real" multi-asperity contact, analyzing the nature of the contact, and even computing a contact area is extremely complicated since large pressures are applied at the most prominent asperities leading to plastic deformation, while the less prominent asperities interact elastically. The development of the atomic force microscope (AFM) has provided the opportunity to obtain detailed information on surface topographies and the way in which surfaces are modified and deformed during contact on a scale that avoids many of these complexities [20]. Because the tip of the AFM provides a model for a single asperity, such experimental approaches have allowed access to simpler systems, in turn enabling theoretical predictions to be more closely compared with experiment. For example, AFM studies have been able to provide direct experimental confirmation of fundamental theories of contact mechanics, demonstrating the validity of adhesive elastic contact models described by JKR [21] and DMT [22] theories. This is illustrated in figure 4(a) where the contact area is deduced from the current passing between the tip and substrate. Such studies have emphasized the importance of including adhesion between the surfaces in order to better describe the contact properties of elastic systems. Modifications of the AFM that enable the simultaneous measurement of both normal and lateral forces also have allowed the measurement of friction on atomic and molecular scales [23,24]. Friction measurements such as these (figure 4(b)) show that the lateral force is proportional to the contact area. Again, this approach has been instrumental in reducing the complexities of contact at "real" surfaces and has begun to provide direct insight into the friction and wear properties of single asperity contacts.

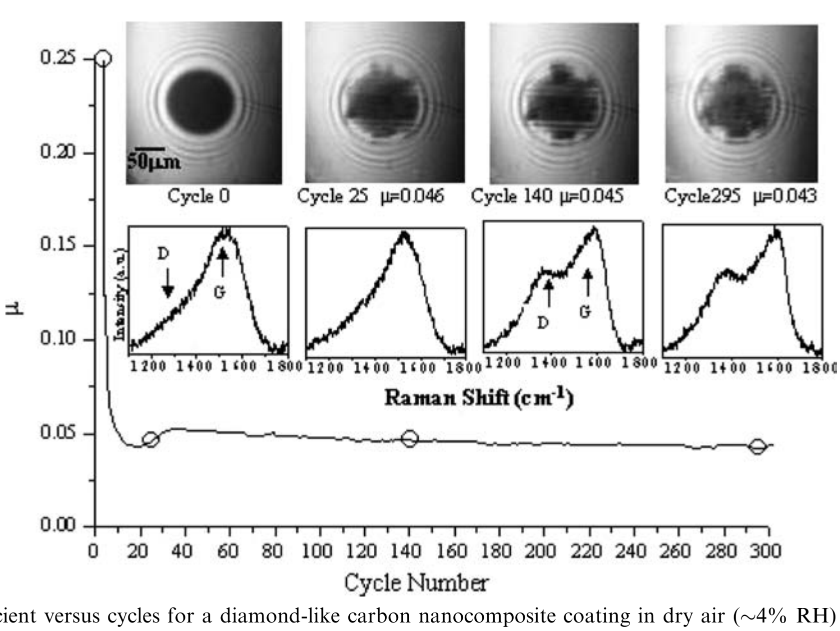

Figure 2. Friction coefficient versus cycles for a diamond-like carbon nanocomposite coating in dry air (~4% RH) at a mean Hertz stress of 0.7 GPa. Also shown are *in-situ* images and micro-Raman spectra taken at the cycles denoted by a circle on the curve (Reprinted from reference 18 with permission from AVS).

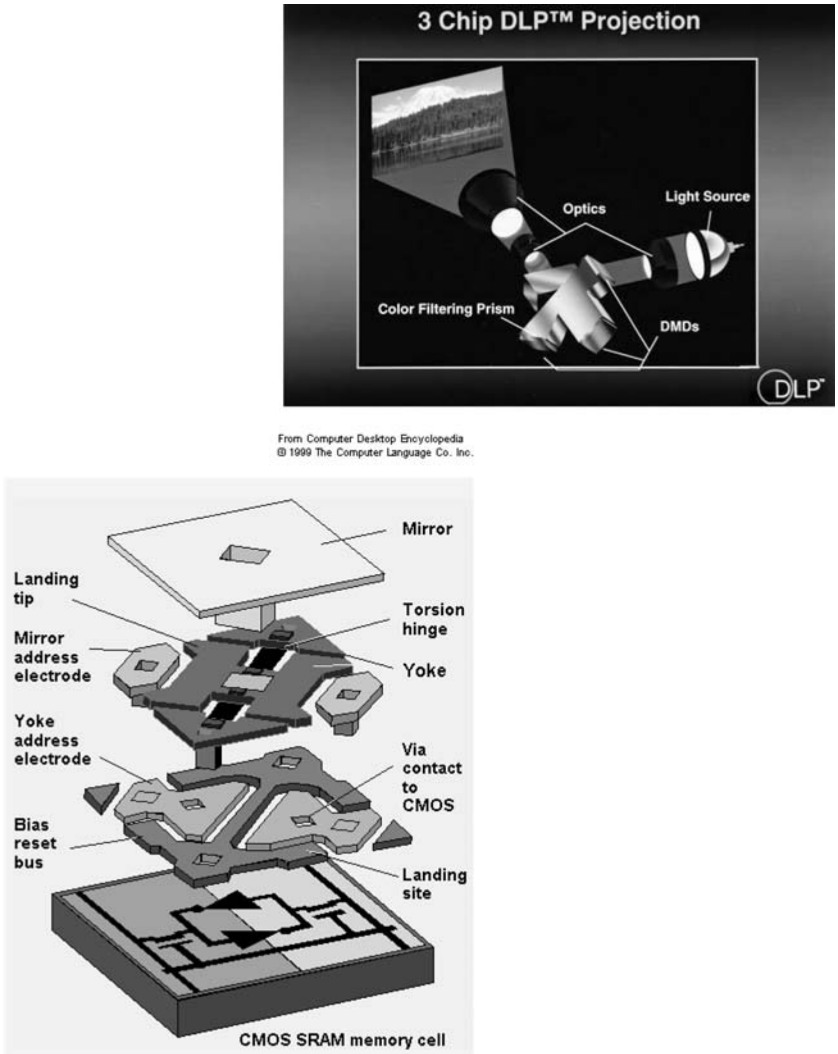

Figure 3. Schematic depiction of the construction of the digital light processing (DLP) mirror and an illustration of its use in a projection system.

2.6. *Control of tribological performance through surface modification*

The environments and operational details of many emerging technologies are requiring novel tribological solutions under conditions ranging from the vacuum of space to the physiological conditions encountered for contacts within living systems. To meet these challenges, recent studies have begun to address, at unprecedented levels, the role of surface-chemical modification in the tribological performance of different systems. Understanding how modifying surfaces affects their frictional properties places stringent requirements on surface cleanliness. The ability to carry out tribological studies under ultrahigh vacuum [25,26] or carefully controlled liquid conditions [27] has allowed the effect of surface modification on friction to be investigated. Such fundamental studies under well-controlled conditions have demonstrated the central importance of the first monolayer in friction reduction at the solid-solid interface [28–32] and have in some instances provided direct insight into the operation of tribological contacts within space environments. In a number of cases, synthetic lubricants developed to improve the lifetime and performance of space systems have also been incorporated into automotive lubricants with great success [33]. In certain aqueous environments, molecular level investigations have begun to provide insights into the fundamental tribological function and performance of naturally modified surfaces found within many living systems [34].

3. Current issues/challenges

3.1. *Technological challenges*

As emphasized above, new fundamental insights in the area of tribology are capable of producing rapid advances in technology. Some outstanding technological challenges in which advances in tribology are likely to make a significant impact are described in the following paragraphs. We note that many of these challenges

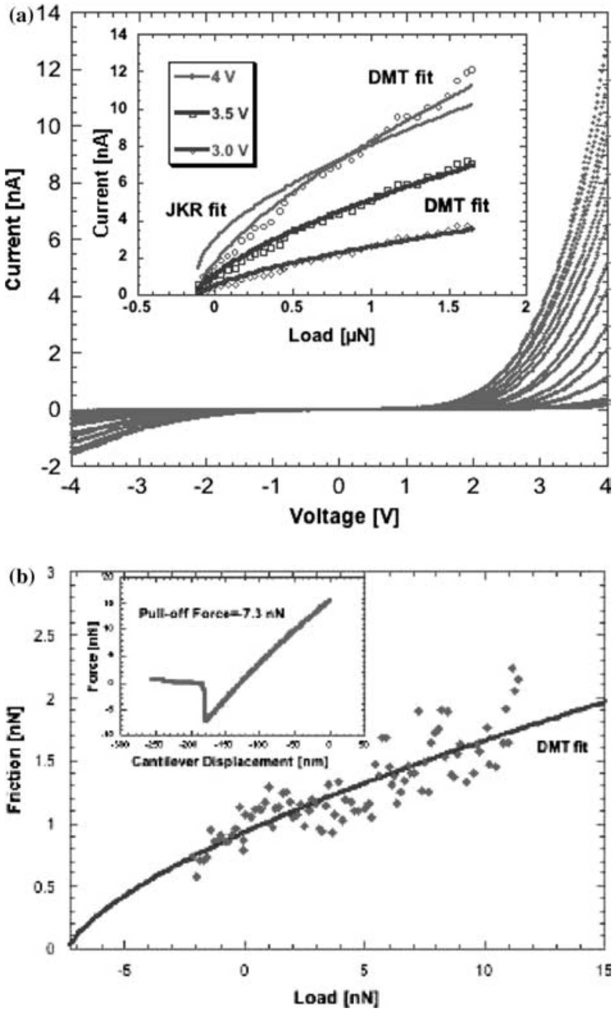

Figure 4. (a) The contact area measured from the current between the tip and substrate showing that this is well described by DMT theory. Similarly, the friction measured using AFM also varies according to DMT theory illustrating the friction is proportional to the contact area (b) (from Ref. [23], with permission).

share elements with the advances reported above and thus underscore the ongoing development in these areas.

3.1.1. Tribology under extreme environments

Lubricants and surface coatings are increasingly required to operate under extreme conditions or reactive or corrosive environments. For example, developments in re-usable launch vehicles, both by government agencies (NASA) and private companies will present tribological challenges in lubricant reliability and in developing lubricants that can operate under severe environments involving both extremely low (cryotribology) and extremely high temperatures, as well as in both air and vacuum conditions. Operation in space environments also presents the challenge of maintaining performance in hostile environments that involve the presence of atomic oxygen and high-energy radiation. In other emerging technologies, tribological problems will present, for example, a major challenge in the evolution to a hydrogen-based economy [35] requiring the development and lubrication of bearings for compressors and pumps that can operate under a highly reducing and extremely explosive, high-pressure hydrogen environment.

3.1.2. The role of tribology in energy efficiency and energy security

Tribological advances will play a central role in improving energy efficiency, reducing reliance on oil and thus improving energy security. Currently, ~15% or more of the energy lost in most combustion engines is due to frictional losses. Minimizing these losses, or increasing the thermodynamic efficiency of internal combustion engines by increasing operating temperatures, represents an important tribological challenge that will lead to significant energy savings. The challenges associated with these developments relate largely to the present inherent limitations of the materials (substrates and lubricants) employed in such applications and thus highlight the need for the development of new tribological materials and the ability to carefully control surface morphologies through, for example, laser texturing [36].

3.1.3. Tribology and micro-electromechanical devices (MEMS)

As described above, major obstacles to implementing technologies based on micro-electromechanical systems (MEMS) involve high static and kinetic friction between the surfaces of these devices and the high rates of wear associated with the forces when appropriate tribological solutions are not provided [37]. Due to the length scales involved in these devices, the vast majority of traditional tribological solutions have not proved adequate. MEMS are currently being developed as high-density memory devices (for example the IBM Millipede) and high-frequency switches. Future developments and improvements in reliability will rely on eliminating stiction, either by selection of alternative materials to silicon or by the formation of durable nanocoatings for these devices [38].

3.1.4. Environmental tribology

Lubricant disposal and environmental pollution are becoming increasingly critical areas of need. Challenges include methods for recycling industrial machining lubricants or the development of fluids that could be more easily disposed of. From an alternative perspective, the development of new lubricant systems is needed in association with increasingly restrictive emission standards. In this regard, it is being realized that, with the further purification of many fuels, the combustion products of lubricant additives are becoming a primary source of catalytic converter poisoning [39]. Some environmental issues will be partially addressed by improvements in efficiency discussed above, but many will have to be addressed through the development of environmentally benign tribological systems, which are likely to entail durable surface coatings that entirely eliminate the need for lubricants, novel lubricant additives free from elements such as P, S, and Cl, which are known to act as catalyst poisons, or water-based lubricant systems that are inherently more environmentally benign.

3.1.5. Hard disk tribology

The continuing increase in memory storage density and growth of the hard disk drive industry will require even greater tribological performance from the head-disk interface [40,41]. To achieve higher storage densities, the clearance between head and disk will have to be reduced to a few nanometers [42] or even to the point of continuous contact [43]. This will place even greater tribological demands on the few nanometers of lubricant and overcoat at this moving interface, which must provide years of wear resistance and corrosion protection. For future developments such as "thermally assisted recording" [43,44], where the disk surface is heated briefly to a few hundred degrees Celsius during the writing of data, new disk lubricants, which can withstand these elevated temperatures at ultra-high shear rates ($>10^9$ s^{-1}) will be required.

3.1.6. Biotribology

Practices within the medical community, and sliding interfaces within the body present a number of tribological challenges associated with the further advance of surgical procedures and implant technology. Procedures such as suturing of wounds, inserting catheters into veins or simple injection would benefit from the development of wear-resistant, low-friction materials. For example, the dulling of suture needles currently requires their frequent replacement within individual procedures. In the field of joint replacement, despite the improvements in the lifetimes of hip implants (currently between 10 and 15 years), many patients are facing the need for second, more traumatic replacements due to wear at the ball-socket interface [45,46]. Again, the development of new materials is needed to improve the performance of these implants, thus substantially increasing the quality of life for these patients. In all of these areas, tribological coatings will likely play a major role; however issues such as biocompatibility and biofouling compound the tribological challenges.

3.1.7. Analytical instruments utilizing nanotribology

Several variants of scanning probe microscopy (SPM) have demonstrated the ability to map material properties *via* their tribological response, including (but not limited to) sliding friction, shear compliance, phase lag under intermittent contact and pull-off forces [47]. Qualitative contrast has proven easy to achieve, particularly on organic and polymeric materials, but quantitative interpretation remains difficult. Some improvements in calibration procedures and analytical formalism have been helpful, but fundamental questions remain regarding the strongly perturbative (nonlinear) and dissipative nature of tribological processes on the nanoscale [48]. Unlike conventional electronic spectroscopies, which are both weakly perturbative and non-dissipative, a contacting and moving nanoasperity may severely modify the population of molecular conformations such that linear response theory is not valid. Theoretical developments required to further advance these analytical tribological measurements must also address the large range of interaction times and the time-dependent stress incurred by discreet molecules within the tribological contact.

3.2. Fundamental gaps

Closely related to the outstanding technological challenges described above, a number of gaps in our fundamental understanding of tribological events currently exist. Solutions to the problems described in the following paragraphs will be critical to the advancement of tribological research and the subsequent development of new technologies.

3.2.1. Contact mechanics

While substantial advances have been made in our understanding of different aspects of the tribological contact, there is still much work to be done before a full understanding has been achieved. It is clear that any serious efforts to compare the results of experiment with the predictions of theory, or to relate tribological measurements to the mechanical properties of the components, will rely on being able to accurately calculate and measure properties of the contact, an effort complicated by the time- (creep) and velocity- (junction growth) dependence of real contacts. For static, well-defined, single-asperity contacts, significant insights have been achieved using the atomic force microscope [20,23]. For rough surfaces, recent advances have been made in understanding contact properties by building on earlier multi-asperity contact models [49–54] and by incorporating a fractal description of the surface [55–59]. Based on these approaches, complete solutions are envisioned in either the completely plastic or completely elastic limit. However, extension to elasto-plastic or viscoelastic surfaces, which are more likely to resemble those occurring in real systems, still defies solution. Finally, although some headway has been made in understanding the role of adhesion [60], there are still significant gaps in our knowledge of this aspect of contact mechanics.

3.2.2. Energy dissipation mechanisms

While the friction of lubricated surfaces in now reasonably well understood [10] and has benefited from *in-situ* interferometric [12,16] and spectroscopic measurements [17,18] of the elastohydrodynamic interface, our understanding of energy dissipation within the boundary layer regime, or at the solid–solid interface is much less well developed. This is partly due to the problems outlined above in defining contact areas. While it known that the work performed during sliding of a freshly prepared interface ultimately ends up as heat (via the generation of phonons) and/or surface structural modification (plowing and wear), the details of this energy dissipation process, including the energy loss pathways and the rates with which these processes occur, are still not well understood. For example, in viscoelastic materials such as polymers, even in the glassy regime [61], the first path of energy dissipation can involve bond rotations (between isomers, e.g. gauche to trans) rather than vibrations. Identifying such dissipative mechanisms requires kinetic analysis involving rate- and temperature-dependent measurements, dynamic mechanical analysis, and dielectric spectroscopy [62]. The time evolution of tribological systems, how the interfacial structure is modified or material removed, and the role of chemistry and third bodies in these processes are also not well understood. In many senses, energy dissipation is a hierarchical problem, and as such, a full understanding of frictional processes will require a deeper understanding of contact properties and adhesion. Correspondingly, an understanding of wear, taken to include both modification of the surface structure and material removal, will require an understanding of both the nature of the contact and friction.

3.2.3. Composition/structure dependence of tribological systems

In a general sense, the current level of understanding of tribological systems offers little predictive ability. In many situations it would be desirable to anticipate the friction and wear properties of a specific interfacial contact based upon the composition, atomic/molecular structure, and topography of the individual materials [63]. Undoubtedly, quantitative predictions of friction and wear characteristics will rely upon an understanding of contact mechanics and energy dissipation as well, yet there still remains the need to understand and classify material pairs, for example, as low friction or low wear. The general principle of surface free energy can be employed to describe the adhesive characteristics of an elastic interface [60], however there is no clear relationship between the adhesion and friction/wear characteristics for most interfaces. Instead, the development of predictive abilities in terms of friction and wear characteristics will rest upon understanding these events on the level of individual chemical bonds. At this level, current gaps in our understanding include the influence of atomic and molecular order, the origin of frictional anisotropy, and the role of discreet chemical reactions in the process of atomic-scale wear.

3.2.4. State-dependent tribological properties

While it is unrealistic to expect the development of fundamental equations of state to describe the manner in which friction and wear depend on variables such as pressure, temperature, volume (size of the system) or scanning speed, many of the challenges listed above entail developing an understanding of tribological performance under conditions other than room temperature, ambient pressure, and the traditional macroscopic scale. Beyond the need to discover and implement tribological systems that will perform under such conditions, there exists the need to develop a fundamental understanding of how tribological systems respond to changes in local environment. For example, an understanding of pressure dependence is clearly needed to further the development of tribological applications intended for operation in vacuum (space) environments. The need to understand temperature dependences has been illustrated in the description of problems involving exceptionally high and low temperatures. The challenge involving tribological solutions to the problems being encountered in the development of MEMS devices is inherently related to size. Finally, a myriad of variables is known to influence tribological characteristics under aqueous environments (biological applications), yet these are not fully understood. Together, the influence of these factors in tribology represents an area in which significant gaps in our understanding currently exist.

4. Recommendations for future endeavors

4.1. Development of tribological materials

The issues of materials properties are inherent to any tribological problem/study and thus the development of new materials will lead to novel solutions and unique opportunities for operation under various and varying environments. In general, the design of tribological materials will involve the *simultaneous* understanding and control of physical (mechanical), surface chemical and topographical properties. As a result, the development of tribological materials, coatings, lubricants, and additives, as well as the control of surface topography, will likely involve interactions between groups/workers with differing skills—tribologists, materials scientists, physicists, and chemists. Advances in experiment and theory will improve our capabilities to design materials, by being able to predict structures or chemical compositions with desired properties, and target them to the tailoring of particular tribological properties. An example of this would be the design of alternative materials for MEMS fabrication. Silicon, which is currently used for these applications because all of the fabrication tools for making MEMS from this material are well established, is tribologically problematic. Replacement materials for MEMS application should possess the following properties: very low residual stress, very low stress gradient normal to the surface, machinability, low surface energy, and low friction. Candidate systems to address these needs would include both bulk materials from which the devices could be fabricated, and coatings to be incorporated during fabrication or applied following device production. Likewise, most of the other systems involving tribological interfaces discussed above would benefit from the development of new materials possessing specific properties.

4.2. Development of experimental methods

New tools are required to monitor phenomena that occur at the tribological interface and to characterize the nature of buried interfaces. Examples of issues and phenomena for which a complete understanding is currently lacking include the location of the slip plane(s) during sliding, the nature and real area of contact, the amount of strain at the interface and throughout the deformed volume, the energy density (temperature) and energy-density distribution in the contact, equilibrium versus non-equilibrium interfacial composition, damage, and morphological changes occurring in the surface and subsurface regions, and tribochemical reactivity (encompassing the topics of diffusion into and out of the interface and strain/temperature-induced reactions).

Experimental tools that will be required to address these issues include *in situ* spectroscopic, diffraction, and imaging techniques. Diffraction and imaging techniques may be based on developments in conventional electron- or photon-based methods (e.g., electron diffraction and microscopy or X-ray diffraction) or novel probes based on positrons or mesons. Spectroscopic techniques could be based on methods such as near-field scanning optical microscopies (NSOM) [64,65], incorporating fluorescence, Raman scattering or infrared absorption. Other strategies could exploit scanning–tunneling spectroscopies or use focused electron beams to probe, or emitted electrons to image, the tribological contact, potentially in the form of a spectromicroscopy making use of synchrotron radiation [66,67].

Further fundamental understanding is likely to come from improved tribometer design, both using the well-defined, single-asperity (AFM-based) tribometers as well as more conventional micro/macro-tribometers. Improvements are needed in two major areas. The first involves improving the reproducibility and reliability of tribological data coming from different laboratories/tribometers. This will involve more careful calibration of tribological measurement systems (e.g. cantilever force constants) [68], uncertainty analysis of these instruments, and identification of standard systems for comparison between laboratories. Achieving this goal will also require increased care in sample preparation, more extensive analysis of the composition and topography of the interface, and greater control of the environment. The use of ultrahigh vacuum or controlled-atmosphere environments to prepare and maintain well-characterized samples has the potential for making a significant impact in these areas. The ability to vary temperature and rate over a wide range will facilitate investigations relevant to a broader range of applications (environment, technology) while furthering fundamental understandings (thermodynamics, kinetics).

Another area entails improving the capabilities of tribometers to allow characterization over the entire range of size scales. One major issue that currently exists is the disparity between sliding speed capabilities of different tribological measurement tools. In the area of nanotribology, there is a need to improve the stability and sensitivity of current AFM designs. Conventional tribometers will require improvements in the ability to more precisely control loading and sliding cycles.

4.3. Development of theoretical methods

The availability of better quality tribological data and a wider array of results regarding the nature of tribological interfaces from spectroscopic or diffraction methods will simultaneously require substantial improvements in, and increased sophistication of, theoretical approaches. The rapid increase in computer power over the last decade presents great opportunities. However, qualitatively new algorithms and modeling approaches are needed to span the complex nature of tribological processes, which occur over a wide range of length and time scales [69,70].

Molecular dynamics (MD) simulations have been one of the primary approaches used to investigate tribological phenomena on the atomic scale [71–73]. While this approach provides full information about the role of each atom and the ability to perform ideally controlled "experiments", it is limited to length scales of micrometers and smaller, and time scales of microseconds and less. New approaches are required to provide more realistic links to experiment. For example many important tribological processes, such as the formation of a wear particle or the occurrence of a chemical reaction are, in general, too "rare" to study with MD simulations. Possible insights into these phenomena will come from being able to extend theoretical methods to longer time scales and larger size systems. Other possible strategies for accessing rare events might include biasing trajectories in the simulation to sample higher energies and potential reactions, or by applying *ad hoc* perturbations to simulate rare events. Addressing the issue of length scales might involve linking atomic-scale analyses to continuum models through simultaneous or hierarchical hybrid approaches [74–79]. Exploring chemistry and wear at the tribological interface, both of which involve bond scission, will necessitate the development of more realistic reactive potentials. Finally, little work has been done in modeling tribological processes using quantum mechanical methods. Density functional theory, for example, can now provide rather accurate energies for chemical systems [80,81], and has been applied to a wide range of phenomena, but has only begun to be applied to tribological problems [82].

At the continuum level, currently available contact mechanics models are not capable of accurately predicting contact areas for rough surfaces. This is partly due to the lack of good experimental measurements of these properties. However, any improvements in the ability to accurately measure contact properties should be matched by advances in modeling these systems. The fractal nature of many surfaces is likely to be crucial in correctly describing multi-asperity contacts and some progress has been made in this area [51–56]. These analyses are, however, only for a static contact and the problem of junction growth at the asperity contacts during sliding also needs to be addressed.

Significant improvements are also needed in computer assisted engineering (CAE) models, which will allow incorporation of tribological effects in the design at the outset. This may involve more precise experimental results being available that can be used directly as input into the CAE programs, or the development of more complex algorithms for computing the desired properties (friction coefficient or wear rates) for a particular engineering application.

4.4. Correlation of experiment and theory

A final general recommendation entails the need to forge closer links between the theoretical and experimental efforts described above. Clearly, fundamental advances can only be made if precise and reproducible experimental results are available to test theoretical models. Likewise, the complexity of tribological processes will require the development of simple, well-characterized models that define all of the parameters of the system. Such models will be crucial to the development of complete theories that in turn can be fully validated by experiment. For example, the current gap between theoretical and experimental efforts is illustrated by the disparity between molecular dynamics simulations and atomic scale measurements. Presently, simulations can only be carried out for relatively small systems and relatively short times, certainly shorter than those encountered in most tribological measurements. A specific recommendation in this direction involves working to make theoretical tools more widely available to the experimental community.

5. Conclusion

The foregoing manuscript highlights the achievements that have been made in both the fundamental understanding of tribological processes and the corresponding technological advances. With the influx of physicists, materials scientists, and chemists into the field over the last decade to supplement the more traditional engineering approaches to tribology, significant advances have been made in our insights into processes occurring at the moving solid-solid interface. The tribological community is poised to build on these first steps and the next decade promises to see the solution to many of the issues outlined above. This review makes specific suggestions for areas in which future efforts should be focused to achieve these solutions and

Table 1.
List of participants and their affiliations.

Name	Affiliation
Robert W. Carpick	Engineering Physics Department, University of Wisconsin-Madison
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Said Jahanmir	MiTiHeart Corporation
Jacqueline Krim	Department of Physics, North Carolina State University
Judith A. Harrison	Department of Chemistry, United States Naval Academy
Greg. D. Haugstad	Characterization Facility, Institute of Technology, University of Minnesota
Mathew Mate	Hitachi San Jose Research Center, Hitachi Global Storage
Scott. S. Perry	Department of Chemistry, University of Houston
Mark. O. Robbins	Department of Physics and Astronomy and Department of Mechanical Engineering, Johns Hopkins University
Miquel Salmeron	Lawrence Berkeley National Laboratory
W. Gregory Sawyer	Department of Mechanical and Aerospace Engineering, University of Florida
Wilfred T. Tysoe	Department of Chemistry and Biochemistry, University of Wisconsin-Milwaukee
Kathryn J. Wahl	Surface Chemistry Branch, U.S. Naval Research Laboratory
Martin N. Webster	Corporate Strategic Research, ExxonMobil Research and Engineering

indicates some areas in which such a fundamental understanding is likely to result in significant improvements in technology.

Acknowledgments

This review is the result of a 2-day, National Science Foundation funded workshop held on October 7 and 8, 2004 in Houston, Texas, USA. The charge to the participants was to define the outstanding challenges to obtaining a fundamental understanding of friction and wear to assist the National Science Foundation in deciding how their resources might be allocated to most effectively address these challenges. The workshop included eighteen participants from academia, industry, and national and military laboratories (see table 1), as well as from the U.S. National Science Foundation (Prof. Yip-Wah Chung), and from the U.S. Air Force Office of Scientific Research (Dr. Jennifer Gresham). We also acknowledge the input of the participants in the writing of this manuscript, both by supplying useful comments and suggestions as well as providing up-to-date and pertinent references.

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