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 17\textsuperscript{th} 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. 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.

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
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 \( \sim 10 \text{ m/s} \) and surface separations of \(< 10 \text{ nm}\).

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 \textit{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](image1.png)

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 \( \sim 20 \text{ nm} \), enabling areal densities just under 100 Gigabit/in. For distant future drives with Terabit/in. storage densities, the magnetic spacing is projected to be 5–7 nm (Courtesy of Mathew Mate and Peter Baumgurt, Hitachi Global Storage Technologies).