Fundamentals of Friction: Macroscopic and Microscopic Processes

Edited by

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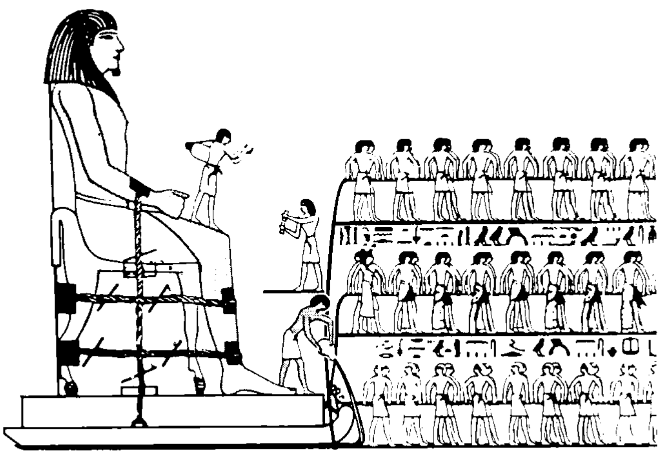

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PREFACE AND ACKNOWLEDGEMENTS: THE BRAUNLAGE MEETING

The NATO Advanced Study Institute on the fundamentals of friction, held in July/August 1991 at Braunlage in the Harz mountains of Germany, was set up in order to take advantage of a particular opportunity - the convergence of two hitherto separate disciplines. Classical tribologists have used concepts of surface contact, adhesion, deformation and fracture with increasing success in recent decades in order to model macroscopic friction behaviour. However, gaps in understanding remain, in part because surface-mechanical behaviour (including friction) has only recently attracted the full attention of experts within a second discipline, that of modern surface science. These include theorists, molecular dynamicists, and users of surface proximity devices (surface force apparatus, single-asperity probes, atomic force/scanning tunnelling microscopes) who now have the tools to carry out fundamental studies of sliding interfaces at the atomic level.

The objective of the ASI was to bring together experts in these two fields, in order to improve their understanding of friction processes and to pass on this knowledge to the ASI students and to the scientific/engineering community in general. We hope that this book will show that friction has come of age as an interdisciplinary subject involving theoretical physics and chemistry as well as engineering.

We organised the ASI by inviting outstanding investigators from the two fields, conferring with them on the "burning issues" needing to be addressed, and then structuring lectures, discussions and workshops accordingly. Sixty-five students, mainly from NATO countries, joined the twenty-one lecturers for ten days of morning and evening sessions (the participants are listed in section 8). Lengthy question-and-answer sessions followed the lectures, and many lecturers posted copies of their presentations after their talks as an aid to informal discussion. Students had the opportunity to present their work at either of two poster sessions, beginning with a three-minute overview from each contributor. In response to individual requests, lecturers and students gave afternoon tutorials on special topics. Workshops on "Computer simulations and modelling" and on "Friction: machines and measurements" included short contributions and video presentations by students. Finally the penultimate morning was devoted to topical discussion groups of five to fifteen participants or "wandering scholars", and this resulted in a typed collection of important issues. These served as focal items for the final day's overview on "Future issues in microscopic and macroscopic friction".

The directors are very grateful for the hard and time-consuming oral and written work which lecturers and discussion contributors devoted to this meeting, and which led to its quite special atmosphere and success. We hope that this book reflects some of this atmosphere; that it will contribute to the integration of the two disciplines; and that tribologists will gain new insights into friction processes, while proximity-probe scientists will recognise the challenges (and rewards) of solving tribological problems.

The major support for the Institute was provided by NATO Scientific Affairs Division. We thank also the home institutions of the directors for support, both direct and indirect: the U S Naval Research Laboratory and the School of Physics and Materials of Lancaster University, in particular Miss H Coates for her secretarial work. Additional co-sponsors were:

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We are especially grateful to the ASI Administrator, Mr M G de St V Atkins, who was largely responsible for the smooth running of the months of preparation, the meeting itself and the follow-up period. We warmly thank also the following: Mr Jonathan Singer for recording over fifty hours of lectures, discussions, workshops and panels on videotape and transcribing them to audiotape; Mrs Barbara Kester of International Transfer of Science and Technology, Overijse, for helpful advice and assistance with planning; Frau Silke Harling and the staff of the Maritim Hotel Braunlage, whose facilities, food, comfort and friendly atmosphere were outstanding; members of the organising committee, especially Dr B J Briscoe for help with the planning of the scientific programme; Professor D Dowson, for his evening presentation on "Friction in everyday life", which informed and entertained a mixed scientific and non-technical audience; and Prof Dr-Ing J Holland, Dipl-Ing A Linnenbrügger and Dipl-Ing M Tychsen of the Clausthal Technical University's Institut für Reibungstechnik und Maschinenkinetik, who organised transport, arranged highly successful excursions, provided a computer and made arrangements for the use of electronic mail. We are also grateful to Longman Group (UK) Ltd. for permission to reproduce seven figures, shown here on pages 2, 136, 236, 324, 404, 522, and 568, from *History of Tribology* by D Dowson (1979).

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INTRODUCTION AND SUMMARY

This book describes what is known about friction from models and experiments on a macroscopic scale, and what is being learned at the microscopic level. It has been 40 years since the last comparable publication appeared,[1] and it is unusual for tribology conference proceedings to focus on this specific topic. The 1952 publication followed a gathering of scientists in London at the Royal Society in April 1951. At that time, questions were raised about fundamental mechanisms of friction, such as energy dissipation, but the techniques needed to probe friction at microscopic scales (of both space and time) did not evolve until the 1980s. By 1991 the time was ripe for presenting and discussing the "burning issues" of friction with new insights gained with the help of these techniques, and the NATO advanced study institute, whose aims are spelled out in the Preface, was the chosen forum.

The book is a synthesis of the material from lectures, discussions and workshops that took place at Braunlage. The texts of most of the lectures are included. Although other relevant aspects of tribology, such as contact mechanics, surface treatments, and wear behavior, are reported, the emphasis here is on defining the state of knowledge and the gaps in understanding of friction processes. It will be for the reader to judge how successfully the various issues have been clarified. In this respect, we hope that the transcribed discussions following many of the chapters will prove useful. In addition, an *epilogue* found in the Appendix (section 8) summarizes issues and recommendations for scientists and engineers seeking to contribute to future understanding of the fundamentals of friction. The rest of the book is divided into seven sections:

1. SCIENTIFIC AND ENGINEERING PERSPECTIVES. Current understanding of friction involves concepts of adhesion, elastic and plastic deformation, boundary lubrication by surface films, and surface forces. In addition to reviewing some of the general ideas that emerged during his fifty-five years of the study of friction, D. Tabor treats the question: how is energy dissipated when friction occurs? In many cases the mechanism is clear, but recently, there has been increasing interest in the intriguing physical problem of energy dissipation for interfacial sliding under elastic or near-elastic conditions.[2]

On the engineering side, E. Rabinowicz documents the fallacy that friction coefficients of materials are constant. Many of the parameters that contribute to friction fluctuations (as distinct from variations) are described, and the size and nature of surface asperities and junctions are suggested as especially important

[1] Proc. Royal Soc. A 212 (1952) pp. 439-520

[2] This question is especially relevant to the sliding of diamond and other hard ceramics - a topic that has always proved difficult to model, hence the absence of a specific chapter on the friction of such materials. However, it will be clear from discussions transcribed here that to some extent this question is being answered through an understanding of atomic-scale processes.

factors.

Sections 2 - 6 address the more scientific aspects of friction, and section 7, the engineering issues:

2. CONTACT MECHANICS, SURFACES AND ADHESION. This section contains background material needed for an understanding of models that have been used with increasing success to model macroscopic friction behaviour. (For those needing a review of the fundamentals of contact mechanics, K.L.Johnson's summary of the principal formulae is presented in an appendix). Of particular interest are the topics where gaps in understanding remain. Current theories of roughness are reasonable as regards the number and size of the micro-contacts between surfaces, but as one of the originators of models of surface roughness, J.A. Greenwood, sees it, we know little more now of how to describe it than we did in 1933 when the profilometer was invented. Will the fractal approach prove more effective than the spectral density approach? Surface forces can be measured by means of various types of "adhesion" experiment - but, as H.M. Pollock points out, the influence of surface forces on "adhesive friction", or on any other variety of friction, is complex. Here, as described by A. R. Thölén, electron microscopy is proving to be a powerful tool, being able to reveal adhesion stress fields, with elastic and plastic deformation as well as material transfer, at the asperity scale. The usual pragmatic approach to friction regards the friction coefficient as an intrinsic material constant: one consequence of shirking the question of the physical aspects is that predictability is largely lost when we are outside empirically tested limits. The fracture mechanics approach, presented by A.R. Savkoor, can explain why an interface is much weaker in the normal than in the tangential direction, and promises to clarify the differences between peeling and slipping. At last, it is becoming possible to say to what extent kinetic friction (an energy-dissipative process) may be considered as a series of sequential processes of static friction (a conservative process!)

3. FRACTURE, DEFORMATION AND INTERFACE SHEAR. While fracture processes may play an important role in friction, B.R. Lawn illustrates the converse part played by friction in the fracture of brittle ceramics. This can be deleterious, as regards strength, abrasion and wear, or beneficial, by helping to dissipate energy and thus to increase toughness. Recent development of the two-term, non-interaction model of friction, with adhesion and ploughing components, owes much to studies of the friction of organic polymers, thanks partly to their wide spectrum of mechanical response. According to B.J. Briscoe, the model's predicative capability is good, and there is confidence in the validity of concepts such as intrinsic interface shear stress. The friction of flowing powders, according to M.J. Adams, can also be understood in terms of the same two-term model. While the friction of powders against smooth walls requires only relatively simple multi-asperity contact models, the bulk deformation of compacted powders

involves mechanical interlocking (Coulombic friction), and computer simulation is required to model friction at the shear planes. The two-term model of friction also provides an intuitive starting point for a more detailed description of the deformation of rough, elasto-plastic surfaces in the presence of adhesion. From continuum models for elastic and plastic deformation, T.H.C. Childs develops flow maps that delineate regions of elastic contact from wave, wedge, or chip-forming flow as a function of surface roughness and interfacial shear strength. The section concludes with a "speculative argument" by K.L. Johnson that one may include the possibility of mode II fracture and take the relevant critical stress intensity factor into account when constructing a friction map. This approach promises to be valuable in attempts to establish the conditions for bulk shearing, intrinsic stick-slip, or elastic contact with steady sliding in metals, polymers and ceramics.

4. LUBRICATION BY SOLIDS AND TRIBOCHEMICAL FILMS. Lubrication "cheats" Mother Nature of the damage to which sliding surfaces are predisposed. The mechanisms by which thin solid films reduce friction are reviewed by I.L. Singer from both a macroscopic and a microscopic viewpoint. Interfacial films that form during sliding contact are investigated, and models of film generation and the chemistry of formation are proposed. Boundary lubrication, when successful, produces a thin film responsible for reduced friction. J-M. Georges et al. analyze the different physicochemical processes induced by a boundary lubricant and describe mechanical properties of boundary films developed over a wide range of pressures, from 1 kPa to 10 GPa. Boundary lubricants must also react with the solid surface if they are to lubricate effectively. R.S. Timsit demonstrates that the shear strength and other tribological properties of molecular layers of stearic acid on glass, aluminum and gold surfaces correlate with the chemical reactivity of stearic acid to the solid surface. Chemical reactivity often controls both the friction and wear behavior of tribomaterials in many practical situations. Tribochemical reactions that affect a variety of engineering materials, from oxidative wear of steels to embrittlement of ceramics, are described by T.E. Fischer. Interactions of sliding solid surfaces with gases or liquids lead to surface modification and enhance reaction rates. Tribochemical reactions involved in extreme pressure (EP) lubrication of steel motivate J.T. Yates et al. to investigate surface chemical reactions between Fe(100) surfaces and CCl_4 in UHV. The influence of surface defects, chemisorbed oxygen and temperature on the stability of $FeCl_2$ EP layers is described.

5. LUBRICATION BY LIQUIDS AND MOLECULARLY-THIN LAYERS. Liquid lubrication can provide the most effective means of separating surfaces in relative motion. Presenting the subject from an historical perspective, D. Dowson reviews the past century's developments in our understanding of bearing lubrication, from fluid films through elasto-hydrodynamic contacts to suggestions of fluid solidification. An instrument that has enabled scientists to observe

directly the behavior of liquids confined to molecularly-thin volumes, the Surface Force Apparatus (SFA), has provided much of the material for the next two chapters. The principal developer of the SFA, J.N. Israelachvili, begins by reviewing recent advances in experimental and theoretical techniques for probing adhesion, interfacial friction and lubrication at the Ångstrom level. His very comprehensive chapter describes experiments that have evaluated a range of theories, from contact mechanics (e.g., JKR vs Hertz) to friction mechanisms (e.g., Amontons vs. Bowden-Tabor), and presents results of computer simulations that account for "quantized jumps" that occur during shear of molecularly-thin fluids. S. Granick also examines the rheological behavior of fluids a few molecular diameters thick, and provides further evidence that the properties of fluids at interfaces differ considerably from those in the bulk. Exotic fluid behaviors such as shear-rate dependent viscosity and time-dependent yield strength of confined ultrathin liquid films are presented, and some of the engineering implications of liquids behaving like solids are discussed.

6. NEW APPROACHES AT THE NANO- AND ATOMIC SCALE. This section introduces a variety of proximal probe and computational techniques for studying the fundamental behavior of contacting and sliding interfaces at the atomic level. Two experimental techniques, the atomic force and scanning tunnelling microscopes (AFM/STM), offer the potential to investigate adhesion and friction at a scale of single-atom contact. G.M. McClelland and J.N.Glosli review simple theoretical models and recent experimental advances concerned with frictional processes at the atomic scale. Models for wearless (*and even frictionless*!) interfacial sliding are discussed and compared with molecular dynamics calculations of frictional forces and energy dissipation between close-packed alkane monolayers. AFM measurements of atomic-scale friction are but one of many applications of "proximal probes" techniques in the field of nanotribology. E. Meyer et al. demonstrate that another technique, friction force microscopy (FFM), enhances the capability of depicting surface topographical features from the atomic to the micron scale. FFM images reveal features such as monolayer steps in 2-layer LB films and periodic track spacing of 1.6 μm in magneto-optical discs. Mechanisms of failure of boundary lubricant layers are also investigated by intentionally damaging LB films by overloading them, then imaging the damage sites.

The final three chapters present several tools of surface physics theory that have recently been introduced into tribology. J. Ferrante and G. Bozzolo describe a variety of computational techniques, ranging from first-principles to semi-empirical methods, that are available for studying tribology at the atomic level. In addition to discussing the techniques, their accuracy and their limitations, they show that surface energy calculations using semi-empirical techniques can be relatively simple to perform, and then apply these methods to solve problems of adhesion and friction. Molecular dynamics provides not only the computational techniques to simulate contacts between solid-solid and solid-liquid interfaces, but also visually exciting portrayals of these interactions. U. Landman et al. give a comprehensive review of their molecular dynamics investigations of atomistic mechanisms involved in adhesive contact formation, friction, and wear processes. Results are presented for several tip and substrate materials (metallic, ionic and covalent), and thin alkane films. Visual presentations are replete with stress and strain contour plots and stunning photo-sequences of atomic configurations during jump-to-contact, elastic and plastic deformation, neck formation and surface reconstruction, wetting, molecular re-ordering, material transfer and atomic-scale stick-slip. J. Belak and I.F. Stowers take a similar approach in their study of the indentation and scraping of a clean metal surface by a hard diamond tool. While calculated stress fields give excellent agreement with continuum models during the initial elastic indentation, the onset of plastic deformation occurs at a much higher yield stress in the atomistic simulations. This enhanced hardness at shallow indentations is discussed in terms of the theoretical yield stress required to create dislocations a few lattice spacings deep.

7. MACHINES AND MEASUREMENTS. This section elaborates on the theme introduced in the second chapter by E. Rabinowicz, the engineering concerns about friction fluctuations and variations. P.J. Blau describes a set of sliding friction experiments designed to address the issue of whether friction is a fundamental property of two contacting materials or a property of the larger tribosystem. The studies show that frictional behavior (steady state plus variations) depends on the tribosystem and confirm, therefore, that a single friction coefficient cannot adequately characterize the behavior of laboratory or engineering tribosystems. Fluctuations in friction associated with vibrations is the topic of the last two papers. Beginning with a tutorial overview of dynamical friction during continuous sliding, D.P. Hess and A. Soom predict the contact and surface roughness conditions that lead to unsteady friction in dry sliding. Although many of the results still await experimental verification, the models warn us that while vibrations may not always change the average friction coefficient, complex nonlinear dynamic behavior can lead to unstable and even chaotic behavior in seemingly simple sliding systems. One of the undesirable by-products of friction between sliding surfaces is friction-induced vibrations (stick-slip). M.T. Bengisu and A.Akay present a stability analysis of friction-induced stick-slip vibrations to demonstrate the significance of the number of degrees of freedom. Finally, systems with multiple degrees of freedom are shown to exhibit bifurcations in their response characteristics, and may respond chaotically.

CONTENTS

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VII. MACHINES AND MEASUREMENTS

VIII. APPENDIX

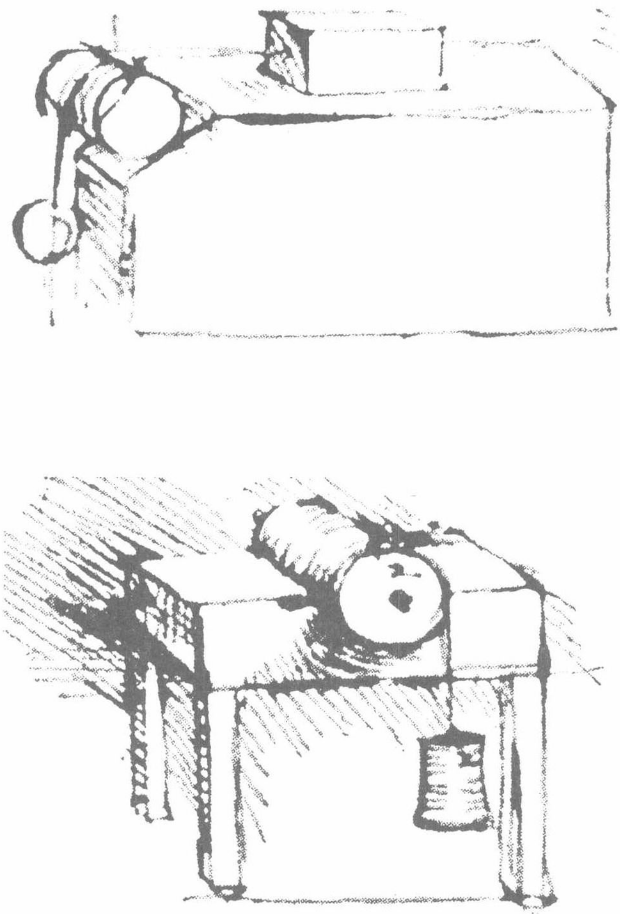
SCIENTIFIC AND ENGINEERING PERSPECTIVES

..... **What is happening at the interface between solids during sliding? Nowadays, when so many physicists are devoting their time to studying the complexities of nuclear disintegration, this may seem a humdrum topic, but there are times when it is well to remember that the world in which we live is not entirely made up of disintegrating nuclei .....**

F P BOWDEN, in "A discussion on friction", Proc. Roy. Soc. **A 212**, 439 (1952).

..... **If an understanding of the nature of surfaces calls for such sophisticated physical, chemical, mathematical, materials and engineering studies in both macro- and molecular terms, how much more challenging is the subject of ".... interacting surfaces in relative motion"?**

D DOWSON, "History of Tribology", Longman 1979, p 3.



Leonardo da Vinci's studies of friction. Sketches showing experiments to determine: (top) the force of friction on a horizontal plane by means of a pulley; (bottom) the friction torque on a roller and half bearing. [From D. Dowson, History of Tribology (Longman, London, 1979) p. 98, with permission.]