Elements of Friction Theory and Nanotribology

Combining the classical theories of contact mechanics and lubrication with the study of friction on the nanometer range, this multi-scale book for researchers and students alike guides the reader deftly through the mechanisms governing friction processes, based on state-of-the-art models and experimental results.

The first book in the field to incorporate recent research on nanotribology with classical theories of contact mechanics, this unique text explores atomic scale scratches, non-contact friction and fishing of molecular nanowires as observed in the laboratory. Beginning with simple key concepts, the reader is guided through progressively more complex topics, such as contact of self-affine surfaces and nanomanipulation, in a consistent style, encompassing both macroscopic and atomistic descriptions of friction, and using unified notations to enable use by physicists and engineers across the scientific community.

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CAMBRIDGE
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University Printing House, Cambridge CB2 8BS, United Kingdom

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It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107006232

First published 2015

Printing in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

Gnecco, Enrico.
Elements of friction theory and nanotribology / Enrico Gnecco and Ernst Meyer.
pages cm
Includes bibliographical references and index.
ISBN 978-1-107-00623-2
1. Tribology. 2. Friction. 3. Elasticity. I. Meyer, E. (Ernst), 1962– II. Title.
TJ1075.G58 2015
621.8′9–dc23
2014043415

ISBN 978-1-107-00623-2 Hardback

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Preface

Friction permeates every aspect of our life. It accompanies us when we walk and our fingers when they slide on the display of a tablet. Friction produces very annoying results when a chalk is rubbed against a blackboard and may cause tremendous damage when it fails to hold two tectonic plates together and a powerful earthquake is suddenly generated. Friction can also be very useful, when a cat suddenly jumps in front of our car and the brake pedal avoids serious consequences; and even pleasant, when a talented violinist takes up a bow and starts playing his Stradivarius. In any case, friction is certainly not a boring subject, and writing a book about friction is definitely not an easy task.

In spite of an immense amount of experimental data, a general theory of sliding friction between two solid surfaces is still missing. The simple Amontons' law, stating that the friction is proportional to the normal force, has been found to work exceptionally well in a variety of situations. Based on this law, theoretical models with different degrees of complexity have been derived and successfully applied to reproduce real situations. Even if Amontons' law is universally accepted as empirical evidence rather than as a consequence of first principles, the attitude is rapidly changing and it is now possible to prove by analytical means that the friction between two rough elastic surfaces has to be almost proportional to the loading force. A different situation is encountered when studying the drag force accompanying the motion of a solid object in a viscous liquid. Here, the Navier–Stokes law works usually quite well, which made hydrodynamic lubrication an established subject a long time ago. Still, problems arise when the lubricants are confined and the friction can only be investigated, theoretically, using atomic-scale models.

In the past 25 years, significant progress has been achieved in the understanding of the basic principles of sliding friction. This progress was essentially caused by the invention of the atomic force microscope (AFM) and the tremendous growth of computational power. The AFM has allowed us to investigate the motion of nano-asperities driven on solid surfaces with unprecedented space and force resolution. The atomic-scale friction features so measured are found to be in good agreement with a model developed by Ludwig Prandtl sixty years before the AFM was developed. On the other hand, molecular dynamics simulations involving a few hundred thousand atoms can be run nowadays in a reasonable time scale, although the duration of the processes reproduced by these virtual experiments is too short compared to the real measurements. Much more difficult is to explain the different wear processes which usually accompany the sliding. A detailed atomistic description of these phenomena is not feasible even with the fastest supercomputers. At the same time, it is not possible to visualize the structure of a wear scar on the atomic scale, although good progress is being made using transmission electron microscopy and, again, AFM.

Having this in mind, we believe that a ‘modern’ approach needs to be adopted to explain the fundamental friction theories, as we understand them nowadays, to undergraduate and graduate students in physics or engineering, and to anyone interested in this multidisciplinary and fascinating subject. In this book we have made a rather simple choice, and limited the discussion to theoretical results based on well-posed analytical derivations and numerical calculations, and to experiments aimed to shed light on nanoscale friction and performed in well-defined environmental conditions such as ultra-high vacuum. It was in no way our intention to present long tables of friction coefficients or to introduce purely phenomenological models. For this reason, no attempts to discuss abrasive, adhesive and other forms of wear have been made, with the exception of a few focused investigations on the nanoscale. Similarly, we have not included technical details regarding the chemical composition of contacting surfaces or lubricants, which would have led us too far from our goal.

Classifying and ordering the material is also not easy. A problem that we had to face was unifying the notation, since the same physical quantities are often addressed in different ways by physicists and engineers. Having in mind the various backgrounds of our readers, we have divided the book into four parts. In the first part, the basic theory of elastic contacts is discussed. The influence of friction on normal contacts, partial slips, sliding and rolling of elastic objects with simple geometric shapes is introduced with the minimal assumption that Amontons’ law is applicable. The second part of the book focuses on more advanced and not always independent topics such as rough, viscoelastic, adhesive and plastic contacts, thermal and electric effects at the interface between two surfaces, fracture and macroscopic stick–slip. In all these frames, the connection to friction is rather obvious. A particular emphasis is given to the theory recently developed by Bo Persson, which, in our opinion, can explain several phenomena more elegantly than any alternative finite element model. In the third part theoretical models and representative experiments at the basis of modern nanotribology are presented in more detail. Besides atomic-scale sliding friction, we will also discuss manipulation, wear and non-contact friction experiments and the Prandtl–Tomlinson model for atomic-scale stick–slip. The last part of the book is dedicated to the dynamics of viscous fluids and its application to lubrication. This part ends with an overview of important phenomena observed in tiny 'spots' such as capillary condensation, fluid flow between rough surfaces and spreading of liquid droplets on a solid surface. Friction force microscopy, gas viscosity and slip boundary conditions in the Navier–Stokes equation are briefly discussed in separated appendices. In this way, we hope that the main message conveyed by our book is that investigating friction is not a messy task but a rather elegant exercise.

Before starting, we would like to thank all the people who accompanied us in the study of friction and related phenomena. Even if it is not possible to cite all of them, special acknowledgment goes to Hans-Joachim Güntherodt, Alexis Baratoff, Roland Bennewitz, Shigeki Kawai, Marcin Kisiel, Anisoara Socoliuc, Sabine Maier, Karine Mougin, Raphael Roth, Pascal Steiner, Thilo Glatzel, Tibor Gyalog, Martin Bammerlin, Rodolfo Miranda, Carlos Pina, Johannes Gierschner, Reinhold Wannemacher, Pawel Nita, Santiago Casado, Patricia Pedraz, Carlos Pimentel, Robert Szoszkiewicz, Pasqualantonio Pingue, Ruben Perez, Juanjo Mazo, Renato Buzio, Ugo Vibusa and Stefano Brizzolari. We also thank Karyn Bailey, Emily Trebilcock, Roisin Munnelly, Bronte Rawlings and Simon Capelin from Cambridge University Press for assisting us in the publishing process, and Frances Lex for critical comments and improvements to the manuscript. Last but not least, E.G. is immensely grateful to his wife Tatiana and his son Valerio. Without their infinite patience in the uncountable hours spent in front of the screen, this book would have never reached its conclusion.