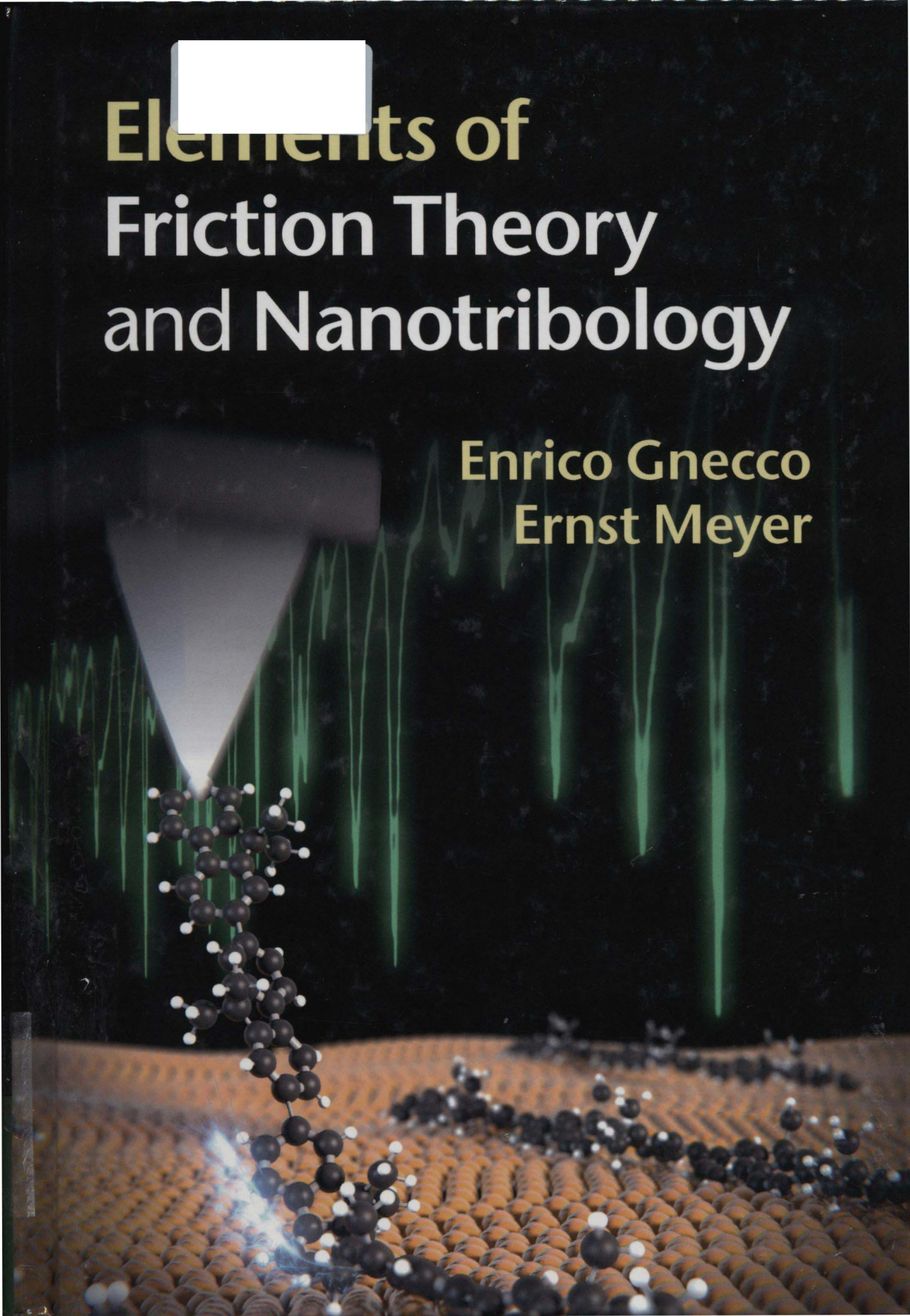


The background of the cover is a dark, textured surface. In the lower half, there is a detailed illustration of a molecular structure, possibly a polymer chain, with black and white spheres representing atoms. This structure is positioned over a surface that looks like a textured, orange-brown material, possibly a substrate or a surface being studied. A bright blue and white light source is visible at the point of contact between the molecular structure and the surface. In the upper left, there is a white rectangular box, likely a placeholder for a logo or a small image.

Elements of Friction Theory and Nanotribology

Enrico Gnecco
Ernst Meyer

Elements of Friction Theory and Nanotribology

Enrico Gnecco and Ernst Meyer



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

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

© Cambridge University Press 2015

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2015

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

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

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.

ENRICO GNECCO is a Senior Scientist at IMDEA Nanoscience, Madrid, where his research focuses on friction phenomena on the atomic scale, controlled manipulation of nanoparticles and theoretical bases of nanotribology.

ERNST MEYER is Professor of Experimental Physics at the University of Basel and module coordinator in the NCCR for Nanoscale Science. He is a former Chairman of the European Science Foundation collaborative network 'Nanotribo'.

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 Amon-ton’s 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 Mougín, 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 Szożkiewicz, Pasqualantonio Pingue, Ruben Perez, Juanjo Mazo, Renato Buzio, Ugo Vibusa and Stefano Brizzolari. We also thank Karyn Bailey, Emily Trebilcock, Roisin Munnely, 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.

Contents

<i>Preface</i>	<i>page xi</i>
1 Introduction	1
1.1 Historical notes	1
2 Dry friction and damped oscillators	5
2.1 Amontons' law	5
2.2 Applications to representative mechanical systems	7
2.3 Viscous friction	12
Part I Elastic Contacts	17
3 Elements of the theory of elasticity	19
3.1 Strain	19
3.2 Stress	20
3.3 Isotropic elastic materials	21
3.4 Equilibrium of elastic bodies	24
3.5 Elastic waves	25
4 Normal contacts	27
4.1 Pressure on an elastic half-space	27
4.2 Indentation of an elastic half-space	31
4.3 The Hertz theory	33
4.4 Beyond the Hertz theory	39
4.5 Influence of friction on normal contact	41
5 Tangential contacts	44
5.1 Traction on an elastic half-space	44
5.2 Partial slip	46
5.3 Sliding of elastic objects	50
5.4 Influence of oscillating forces	52

6	Elastic rolling	54
6.1	Steady elastic rolling	54
6.2	Three-dimensional rolling	57
6.3	Sphere in a groove	59
6.4	Tire mechanics	60
7	Beams, plates and layered materials	62
7.1	Elastic deformation of beams	62
7.2	Plate theory	66
7.3	Elastic instabilities	68
7.4	Shells	69
7.5	Indentation of elastic plates	70
7.6	Indentation of thin elastic layers	71
	Part II Advanced Contact Mechanics	73
8	Rough contacts	75
8.1	Surface roughness	75
8.2	Early models of rough contacts	78
8.3	The Persson theory	81
8.4	Advanced concepts in the Persson theory	85
8.5	Contact of wavy surfaces	88
9	Viscoelastic contacts	90
9.1	Stress–strain relation	90
9.2	Constitutive models	92
9.3	Viscoelastic indentation	95
9.4	Rubber friction	97
9.5	Rolling on viscoelastic bodies	99
10	Adhesive contacts	101
10.1	The Johnson–Kendall–Roberts model	101
10.2	The Derjaguin–Muller–Toporov model	102
10.3	The Maugis–Dugdale model	103
10.4	The Persson theory with adhesion	105
10.5	Adhesion in biological systems	108
11	Thermal and electric effects	109
11.1	Thermal effects in polymers	109
11.2	Flash temperature	110
11.3	Heat transfer between rough surfaces	112
11.4	Electric contact resistance	113

12	Plastic contacts	115
12.1	Plasticity	115
12.2	Criteria of yielding	118
12.3	Plastic flow	120
12.4	Plastic indentation	120
12.5	Compression and traction of a plastic wedge	122
12.6	Hardness	124
12.7	Plowing	125
12.8	Elastic–plastic indentation	126
12.9	Rolling on plastically deformed bodies	129
12.10	Rough plastic contacts	130
12.11	Plasticity of geomaterials	131
13	Fracture	133
13.1	Fracture modes	133
13.2	The Griffith criterion	135
13.3	Dynamic fracture	136
13.4	Fracture in rubber-like materials	138
14	Stick–slip	140
14.1	Stick–slip	140
14.2	Contact ageing	141
14.3	Lubricated friction	142
14.4	The Burridge–Knopoff model	146
14.5	Plastic flow	148
14.6	Earthquakes	151
Part III	Nanotribology	153
15	Atomic-scale stick–slip	155
15.1	The Prandtl–Tomlinson model	155
15.2	Energy barrier	159
15.3	Thermal effects	161
15.4	Long jumps	163
15.5	Dynamic superlubricity	165
15.6	Constant driving force	165
15.7	The Frenkel–Kontorova model	168
15.8	Electronic and phononic friction	170
16	Atomic-scale stick–slip in two dimensions	174
16.1	The Prandtl–Tomlinson model in two dimensions	174
16.2	Structural lubricity	178
16.3	Sliding of adsorbate layers	180

17	Instrumental and computational methods in nanotribology	183
17.1	Atomic force microscopy	183
17.2	Other scanning probe modes	186
17.3	Other experimental techniques in nanotribology	188
17.4	Molecular dynamics and nanotribology: methods	190
17.5	Molecular dynamics and nanotribology: results	191
18	Experimental results in nanotribology	196
18.1	Friction measurements on the atomic scale	196
18.2	Lateral and normal stiffness	199
18.3	Load dependence of nanoscale friction	200
18.4	Velocity dependence of nanoscale friction	201
18.5	Temperature dependence of nanoscale friction	202
18.6	Effect of contact vibrations	203
18.7	Friction anisotropy	204
19	Nanomanipulation	207
19.1	Contact mode manipulation	207
19.2	Dynamic mode manipulation	208
19.3	Nanoparticle trajectories during AFM manipulation	209
19.4	Lifting up molecular chains	214
20	Wear on the nanoscale	216
20.1	Wear on the nanoscale	216
20.2	Surface rippling	220
21	Non-contact friction	224
21.1	Experimental methods to measure non-contact friction	226
21.2	Internal friction of cantilevers	228
21.3	Origins of non-contact friction	231
21.4	Giant non-contact friction	237
21.5	Near-contact friction	237
Part IV	Lubrication	241
22	Drag in a viscous fluid	243
22.1	The Navier–Stokes equation	243
22.2	Flow of a viscous fluid	245
22.3	Motion in a viscous fluid	247
22.4	Boundary layers and skin friction	250
22.5	Drag crisis	253
22.6	Streamlined bodies	253

23	Lubrication	256
23.1	Hydrodynamic lubrication	256
23.2	Elastohydrodynamic lubrication	262
23.3	Hydrostatic lubrication	262
23.4	Solid lubrication	263
24	Viscous phenomena in confined or spreading liquids	265
24.1	The Eyring model	265
24.2	Capillary bridges	267
24.3	Fluid flow between rough surfaces	270
24.4	Squeezed films	272
24.5	Spreading of liquids	275
Appendix A	Friction force microscopy	278
Appendix B	Viscosity of gases	282
Appendix C	Slip conditions	284
	<i>References</i>	285
	<i>Index</i>	301

1

Introduction

The study of friction, wear and lubrication between two surfaces in relative motion is called *tribology*. This term is derived from the Greek verb ‘tribos’, which means ‘to rub’. On one hand tribology aims at a scientific foundation of these phenomena. On the other hand it aims at a better design, manufacture and maintenance of devices which are affected by these ‘annoyances’. Tribology has a very important economical outcome. According to one of the first reports on this issue, tribological problems accounted for 6% of the Gross Domestic Product in industrialized countries in the 1960s [160]. This percentage may have increased by now. Tribological problems are found in pinions, pulleys, rollers and continuous tracks, in pin joints and electric connectors, and may cause more failure than fracture, fatigue and plastic deformation. On the other hand, friction is highly desirable, or even essential, in power transmission systems like belt drives, automobile brakes and clutches. Friction can also reduce road slipperiness and increase rail adhesion. Before starting our rather theoretical description of tribology, it is important to recall the milestones that have marked the progress in this subject from the dawn of civilization.

1.1 Historical notes

More than 40 000 years ago a complex process such as the generation of frictional heat from the lighting of fire was already well known. Nowadays the same process is studied by a branch of tribology, which is known as ‘tribochemistry’ and is focusing, more generally, on friction-induced chemical reactions. The early use of surface lubricants to reduce friction is unambiguously proven by a famous painting from ancient Egypt, in which a ‘prototribologist’ supports the work of a few dozen slaves by pouring oil in front of the heavy sled that they are pulling (Fig. 1.1). More than four thousand years later Leonardo da Vinci (1452–1519) started a systematic investigation of tribology, as documented by his drawings (Fig. 1.2). Leonardo’s

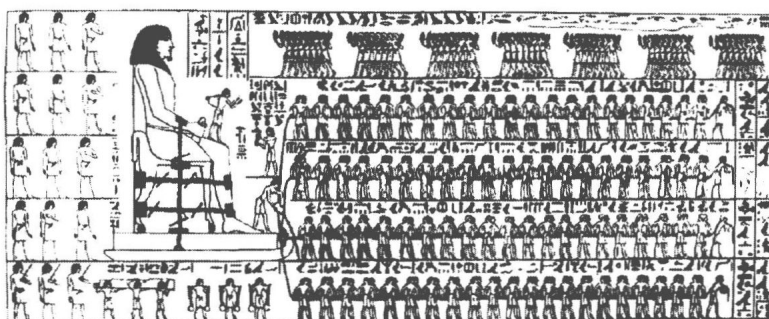


Figure 1.1 Transportation of an Egyptian colossus from the gravestone of Tehuti-Hetep (ca. 1880 B.C.). Note the officer at the feet of the statue lubricating the ground in front of the sled.

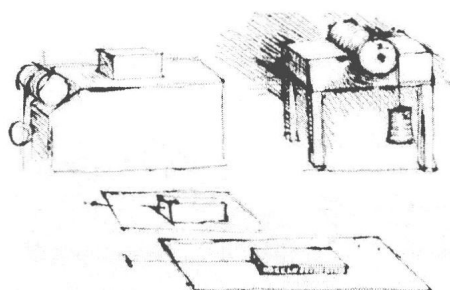


Figure 1.2 Original sketches of the friction experiments performed by Leonardo.

intuition and perseverance resulted in the formulation of the first friction law, which states the proportionality between friction and normal force. Nevertheless, this key observation quickly sank into oblivion until the French physicist Guillaume Amon-ton rediscovered it in 1699. The Swiss Leonhard Euler, possibly the greatest mathematician of the eighteenth century, was the first person who clearly distinguished between static and kinetic friction. Euler also made an attempt to relate friction to microscopic processes by speculating that friction is ultimately caused by the interlocking of rigid irregularities. A few years later, Charles de Coulomb, best known for his work on electricity and magnetism, observed that the kinetic friction is almost independent of the sliding velocity, whereas the static friction may vary depending on the time of stationary contact of the surfaces.

A turning point in the history of tribology was the theory of frictionless contact of non-conformal elastic solids. This theory was developed by the German physicist Heinrich Hertz in 1882 when he was only 23 years old, and forms the basis of modern contact mechanics. The Hertz theory was extended to include the contribution of adhesive forces by Kenneth Johnson and coworkers almost 90 years later. The difference between apparent and real contact areas was pointed out only