Elements of Friction Theory and Nanotribology

Enrico Gnecco
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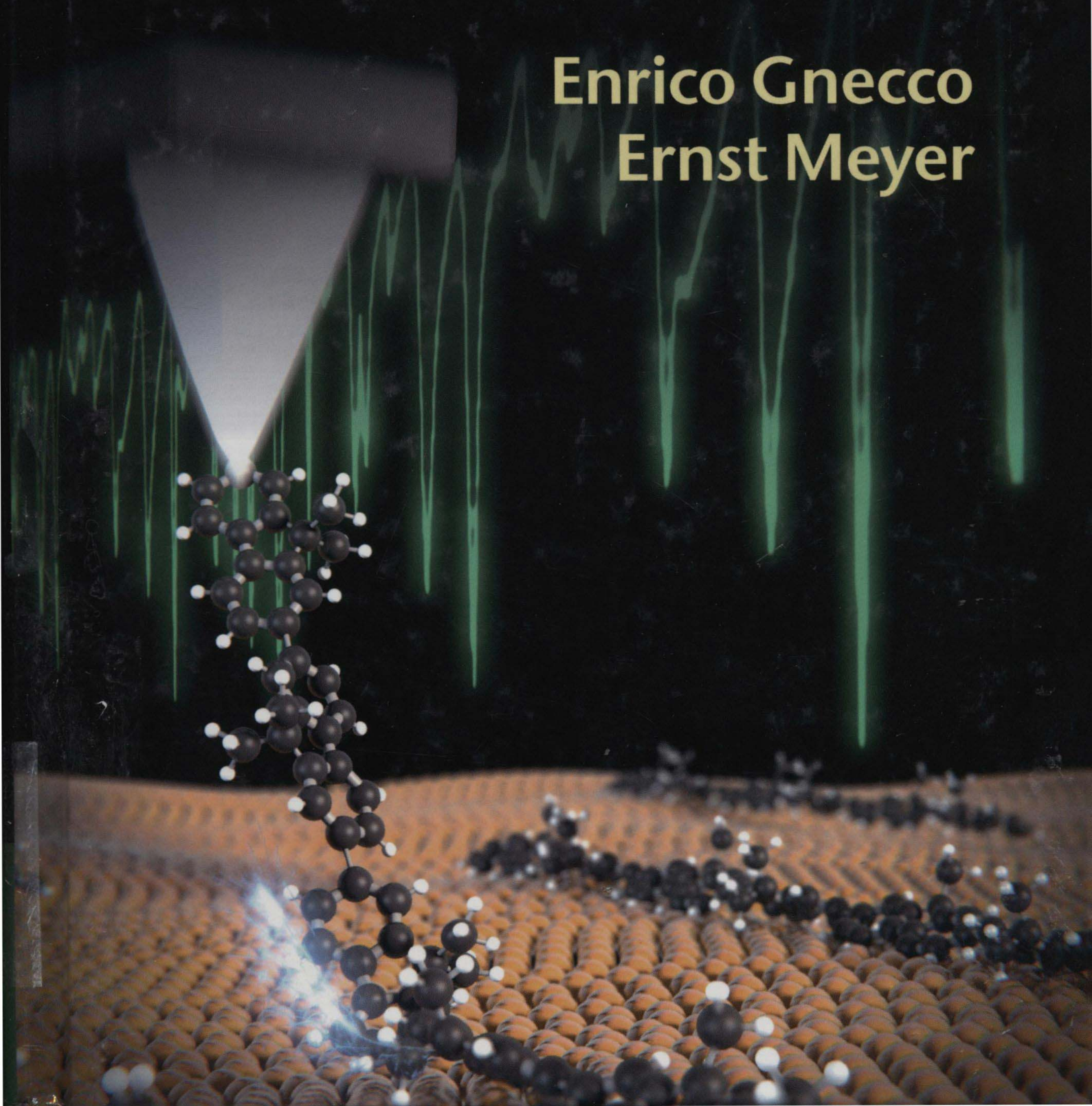

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Elements of Friction Theory and Nanotribology

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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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.

Contents

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

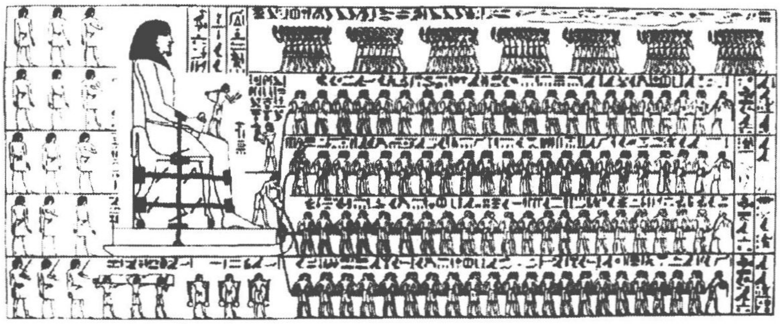

Figure 1.1 Transportation of an Egyptian colossus from the gravestone of Tehuti-Hetep (ca. 1880 B.C.). Note the officer at the feet of the statue lubricating the ground in front of the sled.

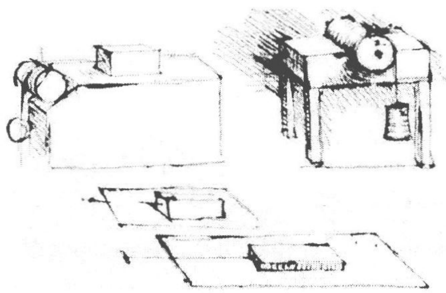

Figure 1.2 Original sketches of the friction experiments performed by Leonardo.

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 Amontons 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