Elements of Friction Theory and Nanotribology

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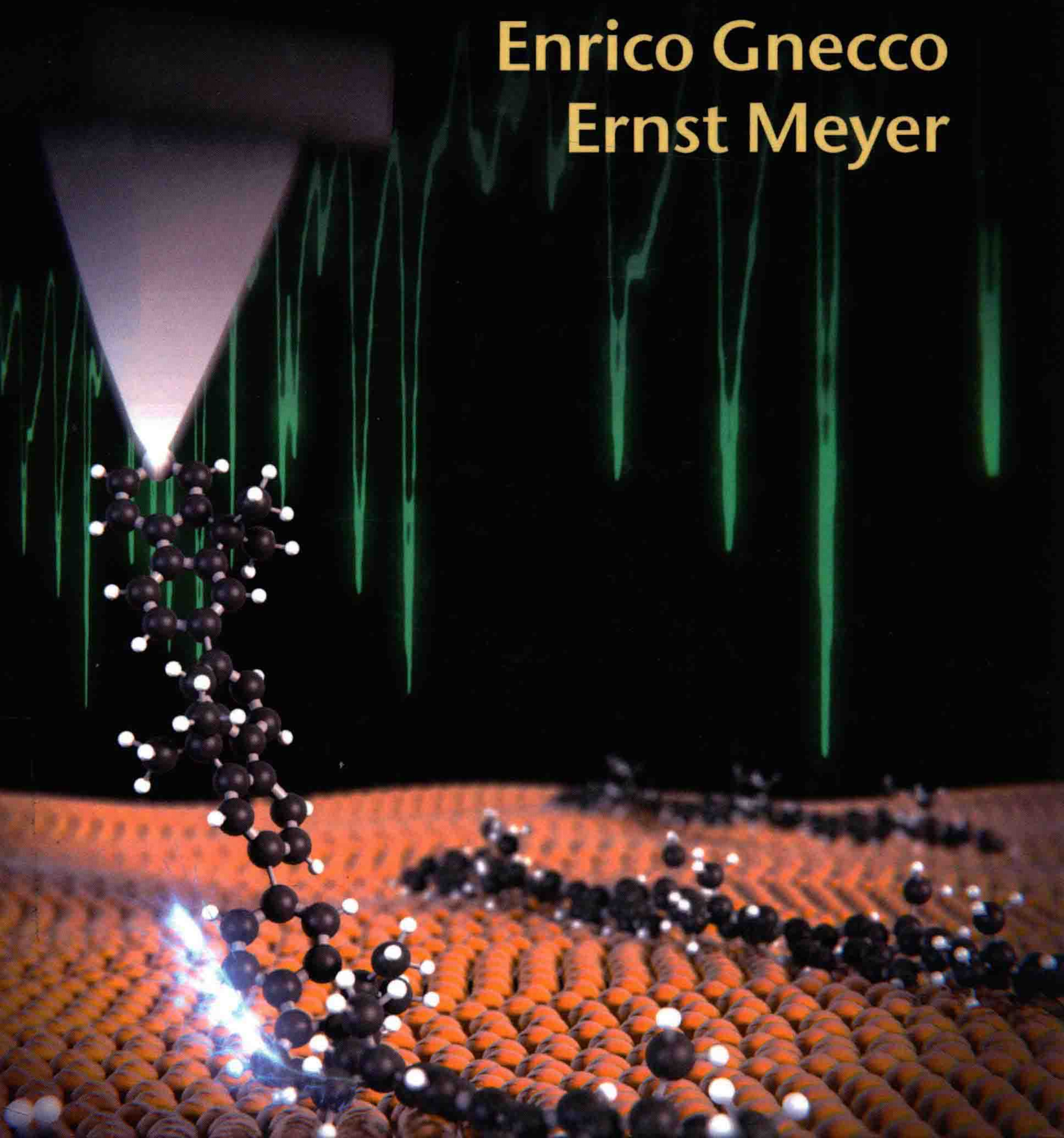

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Preface

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

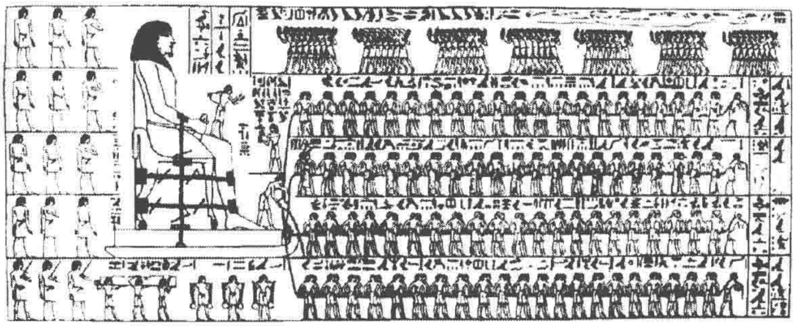

Figure 1.1 Transportation of an Egyptian colossus from the gravestone of Tehuti-Hetep (ca. 1880 B.C.). Note the officer at the feet of the statue lubricating the ground in front of the sled.

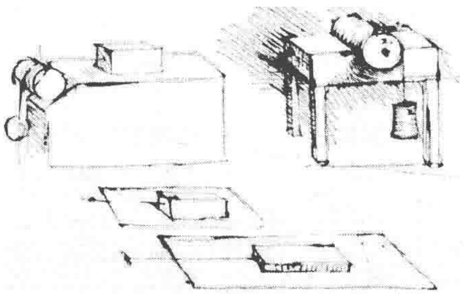

Figure 1.2 Original sketches of the friction experiments performed by Leonardo.

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 in 1942 by Frank Bowden and David Tabor. They also proposed that the friction between two clean metal surfaces originates from the formation and rupture of cold weld junctions and concluded that, if the deformation of the junctions were entirely plastic, the coefficient of friction should be around 0.33, as indeed is measured in many metal pairings. The relation between friction and roughness was further investigated, among others, by John Archard (1957), Greenwood and Williamson (1966) and Bo Persson (2002), who proved, under more and more realistic conditions, that the real contact area is approximately proportional to the normal force.

A key process, when two surfaces slide past each other, is the so-called stick–slip. Stick–slip is caused by elastic instabilities and, in the context of atomic-size contacts, it was first modeled by Ludwig Prandtl in 1928, and experimentally substantiated sixty years later by atomic force microscopy (AFM). The slip can be thermally activated, which leads to characteristic variations of friction with temperature and driving velocity. Thermal activation is also important in capillary condensation and plastic flow, and may lead to various 'ageing' effects which are the focus of numerous theoretical and experimental investigations nowadays. On geological scales, stick–slip is also a key mechanism in earthquakes, as first recognized by Brace and Byerlee in 1966.

The advent of experimental techniques allowing one to measure friction down to the nanoscale and of fast computers allowing one to simulate the atomic interactions between two sliding surfaces resulted in the rise of the so-called 'nanotribology'. While the stick–slip motion of nanometer sized asperities can be readily investigated by AFM, other techniques such as the quartz crystal microbalance and the surface force apparatus have allowed researchers to measure the friction between adsorbate films and substrates or, respectively, between two atomically flat surfaces with intercalated lubricant films. On the other hand, molecular dynamics simulations are throwing light, more and more accurately, on the atomic origins of friction.

Without lubricants, almost no machine made of metal would work, and the Industrial Revolution would not have occurred. The theory of hydrodynamic lubrication was pioneered by Euler, Bernoulli, Poiseuille, Navier and Stokes between 1730 and 1845. It was the last mentioned who discovered that the frictional drag on a spherical particle slowly moving in a fluid is proportional to the velocity of the sphere. A series of key experiments was conducted by Gustave Hirn, who observed that the friction in a bearing is proportional to the sliding velocity and to the viscosity of the lubricant oil. An interpretation of his results, based on hydrodynamic lubrication and not on the more established concept of interlocking asperities, was first given by Nikolai Petrov in 1883, whereas the theory of fluid mechanics was fully established by Osborne Reynolds. Even if the Reynolds theory is still widely used in the design of modern lubricated machinery, this theory breaks down when the separation between the two sliding surfaces becomes comparable to their roughness. Systematic investigations of this problem were performed by Richard Stribeck, who introduced a curve which still holds his name (1902). The concept of boundary lubrication was introduced in 1922 by the biologist William Hardy while studying friction on solid surfaces covered by fatty molecules with hydrocarbon chains of different lengths.

As mentioned above, plastic flow plays an important role in contact ageing. The theory of plasticity, from the Greek verb 'plassein', meaning 'to shape', is also important in determining the stability of soils. Criteria for the yielding of these materials were proposed in early works by Coulomb and the Scottish engineer William Rankine, whereas the first scientific studies of plasticity in metals started only in 1864, when the French engineer Henri Tresca (whose name is also associated with the construction of the Eiffel Tower) published his famous criterion for yielding. This criterion was improved by Richard von Mises in 1913 and fundamental investigations of plasticity flourished in Germany in the early twentieth century under the leadership of Prandtl, who introduced the concept of plastic flow. The theory of plasticity is supported nowadays by powerful computer simulations, which are essential to control technological processes such as the rolling of strips or the extrusion of rods and tubes.

Our overview would not be complete without mentioning wear processes. Wear was well known to our ancestors, who exploited it to create artistic sculptures and useful tools by rubbing dense stones against softer ones in different ways. In spite of its importance, the variety and complexity of wear phenomena make the development of general physics laws interpreting wear processes quite challenging. Related to wear (and to friction) is the study of fracture mechanics, which was initiated by the British engineer Alan Griffith during World War I. The Griffith's criterion, which is based on simple energetic considerations, can elegantly explain the failure of brittle materials. Fracture dynamics is not fully understood and is nowadays a subject of beautiful theoretical and experimental investigations.

2

Dry friction and damped oscillators

In this chapter we introduce the two categories of friction forces experienced by a rigid object sliding on a solid surface or moving in a viscous fluid. These forces have a different nature. Sliding friction increases with the normal force and is usually independent of the velocity. Viscous friction depends on the shape of the object and is proportional to the velocity, provided that this is low enough. Furthermore, while an object in a fluid can be set into motion by an arbitrarily low force, this is not the case if the same object lies on a solid surface, since a static friction force needs to be overcome in this case. Static friction allows us to join objects together using screws. It also has a key role in the propulsion and braking of vehicles and in transmission belts. Sliding (or kinetic) friction is important in pivots and collar bearings, not to mention uncountable situations in everyday life. Viscous friction can be exploited in mechanical dampers to mitigate the effects of forced oscillations. Since the theory of these oscillations is of pivotal importance in physics and engineering, it will be recalled in this chapter, whereas a detailed description of various situation involving viscous drag is provided in the last part of the book.

2.1 Amontons' law

In order to start and to keep moving a solid block on a solid surface, different *friction forces* F_{fric} have to be overcome and opposed. The *static friction* F_{s} corresponds to the minimum tangential force required to initiate sliding. The *kinetic friction* F_{k} perfectly balances the tangential force needed to maintain the sliding at a given (average) speed. These forces are intrinsically different. The static friction does not do any work, while the kinetic friction equals the dissipative work done at the interface divided by the distance covered by the block.

According to *Amontons' law* [5], the friction force is proportional to the normal force F_{N} acting on the block:

$$F_{\text{fric}} = \mu F_{\text{N}}. \tag{2.1}$$

Table 2.1 *Typical coefficients of static and kinetic friction.*

Physical situation	μ_s	μ_k
Rubber on concrete	1.0	0.8
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Glass on glass	0.94	0.4
Copper on steel	0.53	0.36
Wood on wood	0.25–0.5	0.2
Wood on wet snow	0.14	0.1
Metal on metal (lubricated)	0.15	0.06
Wood on dry snow	–	0.04
Teflon on teflon	0.04	0.04
Ice on ice	0.1	0.03
Synovial joints in humans	0.01	0.003

Furthermore, it is independent of the nominal area of contact. The ratio between F_{fric} and F_{N} is the *coefficient of friction* μ, and it is usually different for static and kinetic friction. The static friction coefficient depends on the time of stationary contact (so-called *contact history*), on the elastic and geometric properties of the contacting surfaces and on the way in which the driving forces are applied. On the other hand, the kinetic friction coefficient is much better defined once the temperature, humidity, velocity and surface properties are reproducible. The values of the friction coefficient are usually lower than one, and the static coefficient μ_s is always equal to or larger than the kinetic coefficient μ_k.

As far as we are concerned with macroscopic contacts, we will also accept the validity of *Coulomb's law* and assume that, under dry conditions, F_k is independent of the sliding velocity. This is not the case at very low or very high velocities, where thermal effects or, respectively, inertial effects become important.

A representative list of friction coefficients is given in Table 2.1. For lubricated metal surfaces typical values of μ_s are in the range of 0.1–0.3. Higher values are observed after prolonged sliding if the lubricant film is worn off. For common engineering surfaces the friction coefficient does not depend significantly on the surface roughness, unless the surfaces are extremely smooth or rough. Amontons' law is also modified in the presence of strong adhesive forces.

Suppose now that a block rests on a plane inclined by an angle α, as in Fig. 2.1. If α is slowly increased, the block will start moving when

$$\tan\alpha = \mu_s. \tag{2.2}$$

This value defines the *angle of friction* (or *angle of repose*) α_c. If $\mu_s = 0.1$ the angle of friction is about 6°. Thus, the coefficient of static friction can be simply estimated by measuring α_c.