1
Introduction

1.1
The Term Tribology

The term tribology is derived from the Greek *tribos*, which means "rubbing," and includes all of the sciences and technologies of interacting surfaces in relative motion. The main areas of research and application are friction, wear, and lubrication. The term was first used 1966 in the Jost Report, a study conducted in the United Kingdom which investigated the amount money lost annually due to friction and wear. Tribology is multidisciplinary in nature, and includes mechanical engineering (especially machine elements as journal and roller bearings and gears), materials science, with research into wear resistance, surface technology with surface topography analysis and coatings, and the chemistry of lubricants and additives. The relatively younger disciplines of tribology are: (i) bio-tribology, which includes (among other topics) wear, friction, and the lubrication of total joint replacement; and (ii) nanotribology, where friction and wear are studied on the micro- and nanoscales.

A wide variety of professional bodies or societies have been formed during the second half of the twentieth century, with many institutions of mechanical engineering having incorporated divisions of tribology. Likewise, societies of lubricating engineers or societies of tribology have organized professional meetings on an international scale. For example, in Germany there exists a tribology society – the Gesellschaft für Tribologie (GfT) – which has seven regional subcommittees, and conducts not only an annual international meetings but also numerous regional meetings with professional presentations. The international tribology meetings of the Technische Akademie Esslingen (TAE) have, for many decades, been organized in Germany by W. Bartz as another forum for tribological exchange, and are among the most heavily attended worldwide.

Industrial Tribology: Tribosystems, Friction, Wear and Surface Engineering, Lubrication
Theo Mang, Kirsten Bobzin, and Thorsten Bartels

ISBN: 978-3-527-32057-8

1.2
Importance of Tribology

Over the years, the governments of the most industrialized countries have developed extensive strategies to reduce energy waste. In 1966, the so-called Jost Report [Lubrication (Tribology) – Education and Research; published by Her Majesty's Stationery Office, London, 1966] demonstrated the enormous waste that occurred due to the misrecognition of tribology in the UK. Likewise, in 1977, an American government-financed report suggested that US$16.25 billion could be saved by the correct use of tribological knowledge. Similar studies have also been conducted in other countries; for example, W. Bartz carried out a study which related to Germany between 1979 and 1983 [1] while in 1990 P. Jost defined the potential savings as a percentage of the GDP, to determine calculated values of 1.3–1.6%. The results obtained for various countries are listed in Table 1.1, taking 1.6% as a basis for the year 2008 (a conservative estimate when taking actual energy prices into account). In this case, the GDP was based on the CIA, List of Fact Book (2008).

Notably, whilst the study of W. Bartz takes into account only lubricated contacts, it categorizes the possibilities of saving into: (i) *primary savings*, due to reductions in mechanical friction; (ii) *secondary savings*, due to a lesser exchange of machine parts owing to wear reduction; and (iii) *tertiary savings*, where a new material is used for the production of new parts, thus raising the energy content of the materials [1].

Currently, the integration of tribology represents a modern aspect in life cycle assessment, with the main targets being environmental and economic performance. In this case, the main roles of tribology are not only to reduce friction in a machine, but also to extend the machine's service life.

1.3
History of Tribology

The history of tribology is as old as the history of humankind, the main driving force being the facilitation of daily activities by reducing friction. This especially the case for weapons, tools, crafts, or construction.

Table 1.1 Potential savings (in US$ billion) by correct use of tribological knowledge (1.6% of GDP 2008).

European Union	303
United States	186
China	68
Japan	63
Germany	50
France	48
United Kingdom	36

The first man-made *bearings* to be identified date back to the middle Stone Age (Mesolithic period, 11 000–5500 years ago), with the use of stone door sockets, bearings for wheeled vehicles, and bearings for stone potter's wheels. There is also some indication that these 5000-year-old wheel bearings were lubricated with bitumen. Another early use of lubricants (most likely water) is shown in an Egyptian painting from the tomb of Tehuty-Hetep at El Bersheh (1800 BC); this shows a man pouring lubricant onto the ground in front of a sledge, on which a colossal sculpture is being transported. Although this man has often been referred to as the "first tribologist," Dowson [2] has also described an Egyptian tribologist who was 600 years older, and who had applied lubricant in similar fashion to the example of El Bersheh, in front of a sledge when transporting a heavy statue. Clearly, the transportation of heavy statues and building blocks, using wooden rollers beneath the sledges, was seen as a tribological innovation, with the application of early roller bearings being recorded during the first millennium BC [3].

One of the most important innovations from a tribological point of view has been the *wheel*, with the transition from sledges to wheeled vehicles first being seen about 3500 BC. The remains of many wheels dating back to the third millennium have been found in Europe and Asia. When recording the Greek and Roman period (900 BC to AD 400), Dowson [2] made a detailed chronology of tribology, defining political and social events and general technical developments. The description began with the production of bitumen and oils from petroleum and the use of iron bearings in olive mills (500 BC, of bronze rolling bearings in China (200 BC), and also a list of lubricants dating back to Roman times (0 BC). Later, a description was made of bronze journal bearings for wheels and axles (AD 300). Within the western hemisphere, a host of technical knowledge from the Greek and Roman period was lost during the Middle Ages. One of the most interesting examples was the change in materials, as bronze and iron bearings were gradually changed from wood and stone. Further activities in technical development were identified in the Islamic world between the ninth and twelfth centuries, with technical developments more evident in the eastern part of the Roman empire, and in the Byzantine region.

The first scientific developments of tribology began during the Renaissance (1450–1600 AD), with the most important studies of friction and wear being conducted by Leonardo da Vinci (1452–1519), the great painter architect and engineer, whose manuscripts contained over 5000 pages. The most important information regarding friction, bearing materials or roller bearings have been found in the *Codex Atlanticus* and in the Codex Madrid I and II. Some of Leonardo's studies demonstrated the forces of friction on horizontal and inclined planes, and the influence of the apparent contact area on friction. Another highlight of Leonardo's studies was a description of a low-friction bearing alloy, and of an early form of ball-bearing cage or of ball-and-roller pivot bearings. The most important mathematical result of Leonardo's studies was that the force of friction is not only directly proportional to the applied load, but also independent of the apparent area of contact.

About 50 years before Leonardo's tribological studies, the German Cardinal Nikolaus von Kues (Nikolaus Cusanus, 1401–1464) described the cycloids of gears.

An intensive description of mining technology was provided by Georg Agricola (1494–1555), and published in *De re metallica*. Agricola's tribological interests (mainly in book VI) demonstrated that there had been no development in tribological applications since the Greek and Roman eras when, typically, the bearings on wheel barrows were shown as simple circular holes in wooden side-planks.

During the seventeenth century, the increasing demand for mechanical power served as the main driving force to develop machines for the mining industry, or for windmills or water wheels, in relation to low-friction bearings. Consequently, considerable developments were achieved in the science of tribology during this century, by Hooke, Newton, and Amontons.

Robert Hooke (1635–1703) investigated the processes that occurred during rolling friction that were related, for example, to the hardness of wheels and the deformation of the surface, as well to the adhesion between wheel and ground. Consequently, Hooke presented a series of concepts on bearing design, seals, materials, and lubrication.

In December 1699, in Paris, *Guillaume Amontons* presented the details of his experimental results and interpretations relating to friction, and consequently defined the first and second laws of friction:

- First law: The force of friction is directly proportional to the applied load.
- Second law: The force of friction is independent of the apparent area contact.

But, since Leonardo da Vinci had reported essentially the same findings more than 200 years previously, it might be more honest to speak of da Vinci's laws of friction, and to mention Amontons only briefly!

During the mid-eighteenth century, in Berlin, the famous mathematician *Leonard Euler* (1707–1783) published two famous papers concerning friction. Euler defined, mathematically, the force required to move a weight up a slope of inclination to the horizontal: F (force) $>$ P (weight) tan α, and introduced μ as the coefficient of friction ($\mu = \tan \alpha$). The most important outcome of Euler's studies was his differentiation of kinetic friction from static friction. In Germany, in 1706, Leibnitz (1646–1716) was the first to distinguish between rolling and sliding friction. Another highlight of the studies of tribology during the eighteenth century, when lubrication was investigated at only a low level, was the hypothesis of Isaac Newton (1642–1727) who, in his law of viscous flow, defined the "*defectus lubricitatis*" that today is known as the internal friction of fluids, or *viscosity*.

It was almost 200 years later that the fluid film lubrication film theory was developed, by *Osborne Reynolds*.

During the first half of the eighteenth century, important progress was seen in the development not only of roller bearings, but also of gears. In this case, the use of animal and vegetable fats as lubricants had been noted for some time, and these included lard oil (in 1699; Amontons, de la Hire), tallow (in 1735), and vegetable oils (Leupold).

1.3.1 The Industrial Revolution

The period between 1750 and 1850 is generally referred to as the "Industrial Revolution," when rapid technological changes occurred alongside social and economic developments. In the textile industry, for example, the mechanization of spinning and weaving influenced the progress in tribology with regards to the use of effective bearings and lubricants. Similar advances were identified in the development of steam engines for agriculture, and also for the railways. The use of steam power or the intelligent use of machine tools led to improvements in tribological studies. Perhaps the most important investigator during this period was Charles Augustin Coulomb, who defined friction formulas based on his own impressive experiments. These included an apparatus to study rolling friction, as well as studies on inclined planes and rough surfaces, and frictional resistance on sliding. Within the field of lubrication, the basics of fluid mechanics were devised by (among others) Leonhard Euler, Daniel Bernoulli, and M. L. Poiseuille (whose name was given to the unit of dynamic viscosity, the Poise). Claude Navier, a French mathematician (1785–1836) included the viscous terms in Newton's law for flowing fluids, while the English physicist and mathematician G.G. Stokes defined the basics of viscous flow. Subsequently, the equations developed in this way became known as the Navier–Stokes equations.

Many different vegetable and animal oils were used during this period, including olive oil, rapeseed oil, palm oil, coconut oil, sperm oil, lard oil, or tallow oil. However, the first distillation of mineral oil in Prague (in 1812) led to the use of many more mineral-oil based lubricants, with the first graphite-containing lubricant being patented in the United Kingdom in 1835.

1.3.2 Between 1850 and 1945

The basic tribological studies in this period were characterized by many famous investigators, including:

- studies of rolling friction by Reynolds (in 1875);
- Heinrich Hertz's analysis of contact between elastic materials (in 1881);
- N.P. Petrov's studies on unloaded journal bearings (in 1883);
- the development of viscosimeters by Engler, Saybolt and Redwood (between 1884 and 1886);
- the hydrodynamic theory of Tower and Reynolds (1865);
- friction measurements on journal bearings by Richard Stribeck (in 1902);
- the analytical solution of Reynold's equation by Sommerfeld (in 1904);
- further investigations on Stribeck's results and defining the major source of dry friction by Ludwig Gümbel (between 1914 and 1925);
- Langmuir's studies of thin surface films (in 1917);
- continuous improvements of the journal bearing by Tower, Kingsbury, Michell, and Rayleigh (between 1915 and 1925);

- the discovery of the mechanism of polar compounds by Hardy (in 1922);
- the use of extreme pressure and antiwear additives (in 1927); and
- the use of synthetic lubricants in Germany (synthetic esters and synthetic hydrocarbons), VI improvers, antioxidants and corrosion inhibitors (during the 1930s).

Some time later, in 1945, A. Ertel developed the basic formulas for the elastic hydrodynamic lubrication (EHL) (see Chapter 3).

1.3.3
From 1950 to the Present Day

During this period, awareness grew that friction, wear and lubrication represented an important area of technical engineering, notably in relation to the efficiency of operating machines. In 1966, a committee of the Department of Education and Science, headed by Peter Jost, produced the "Jost Report" in which the term tribology was born, together with a worldwide recognition of the importance of wear, lubrication, and friction. In Germany, the energy crisis of the 1970s led to the creation of projects aimed at energy savings via tribological activities [3], while the German Ministry of Research and Technology sponsored major projects in areas of tribology. During the 1980s, a recognition of the economic importance of tribology was complemented by an ecological awareness, with the first biodegradable lubricants produced from harvestable fatty materials being developed during the early part of the decade. In 1997, the University of Aachen (RWTH) began a 12-year interdisciplinary research project for ecological tribo-systems (financed by Deutsche Forschungsgemeinschaft). Globally, this study incorporates important research projects for tribology, including areas of mechanical engineering, materials science, surface technology, ecological aspects, safety at work criteria, and the chemistry of biodegradable lubricants.

During the 1950s, 1960s and 1970s, fluid film lubrication was developed – on both theoretical and experimental bases – into the elastohydrodynamic lubrication. This approach was based on previously acquired knowledge regarding elastic distortion and viscosity pressure characteristics. In 1959, Dowson and Higginson first described a procedure that was seen as a starting point for various later solutions for different lubricated contacts. Today, elastohydrodynamic lubrication has become fully established, and is complemented by methods to characterize surface topography.

Within the twentieth and twenty-first centuries, the details of tribological knowledge relating to the base sciences, to lubricants, and to wear or machine elements, have been published in numerous reports and books, among which are included (listed in chronological order):

Engler, C. and von Höfer, H. (1916) *Das Erdöl IV. Die Prüfung und Verwendung des Erdöls und der Erdölprodukte*, Hirzel-Verlag.

Gümbel, L. and Everling, E. (1925) *Reibung und Schmierung im Maschinenbau*, Krain.

Vogelpohl, G. (1940) Die geschichtliche Entwicklung unseres Wissens über Reibung und Schmierung. *Öl und Kohle*, **36**, 89–93 and 129–134.

Motschoß, C. (1940) *Die Geschichte des Zahnrads*, VDI-Verlag, Berlin.

Hersey, M.D. and Norton, A.E. (1942) *Lubrication*, McGraw-Hill.

Palmgren, A. (1954) *Grundlagen der Wälzlagertechnik*, Francksche Verlagsbuchhandlung, Stuttgart.

Bowden F.P. and Tabor, D. (1950) *The Friction and Lubrication of Solids*, McMillan.

Kühnel, R. (1952) *Werkstoffe für Gleitlager*, Springer-Verlag.

Boner, C.J. (1954) *Manufacture and Application of Lubricating Greases*, Reinhold, New York.

Fuller, D.D. (1956) *Theory and Practice of Lubrication for Engineers*, John Wiley & Sons.

Vogelpohl, G. (1958) *Betriebssichere Gleitlager, Berechnungsverfahren für Konstruktion und Betrieb*, Springer.

Kuss, E. (1960) Über das Viskositätsdruckverhalten von Mineralölen, *Materialprüfung*, **2** (6), S189–S197.

Göttner, G.H. (1961) *Einführung in die Schmierungstechnik*, Karl-Marklein-Verlag.

Kragelski, I.V. and Vinogradova, I.A. (1962) *Coefficient of Friction*, Mashgiz.

Braithwaite, E.R. (1964) *Solid Lubricants and Surfaces*, Pergamon Press.

Cameron, A. (1966) *Principles of Lubrication*, Longman.

Dowson, D. and Higginson, G.R. (1966) *Elastohydrodynamic Lubrication – The Fundamentals of Roller and Gear Lubrication*, Pergamon Press.

Bartz, W. (1968) *Vergleichende Untersuchung des Seitenflusses von Gleitlagern bei Schmierung mit strukturviskosen und reinviskosen Stoffen*, VDI-Verlag. This was the first of various international congresses to be held over a period of four decades.

Schey, J.A. (1970) *Metal Deformation Processes – Friction and Lubrication*, Marcel Dekker.

Neale, M.J. (ed.) (1973) *Tribology Handbook*, Butterworths.

Sarkar, A.D. (1976) *Wear of Metals*, Pergamon.

Czichos, H. (1978) *Tribology – a system approach to the science and technology of friction, lubrication and wear*, Elsevier.

Mang, T. (1981) *Die Schmierung in der Metallbearbeitung*, Vogel-Verlag.

Klarmann, D. (ed.) (1982) *Schmierstoffe und verwandte Produkte*, Verlag Chemie.

Czichos, H. and Habig, K.-H. (1992) *Tribologie – Handbuch*, Vieweg-Verlag.

Mang, T. and Dresel, W. (eds) (2001, 2007), *Lubricants and Lubrication*, John Wiley & Sons.

References

1 Bartz, J.W. (1988) *Energieeinsparung Durch Tribologische Maßnahmen*, Expert Verlag, Ehringen.

2 Dowson, D. (1998) *History of Tribology*, 2nd edn, Professional Engineering Publishing Limited, London, Bury St Edmunds.

3 Bartz, J.W. (1988) *Zur Geschichte der Tribologie*, Expert Verlag, Ehringen.