Tribology: A Historical Overview of the Relation Between Theory and Application

Javier Echávarri, Eduardo de la Guerra and Enrique Chacón

Abstract Tribology is the science and engineering of rubbing surfaces. This article presents a historical overview of tribology evolution from prehistory to the highly advanced stage reached nowadays. Phenomenological analyses based on observation and experimentation gave rise to a progressive understanding of the processes of friction, wear and lubrication, with application to many industrial problems. Multiple industrial reports published during the last few decades have shown the huge impact of tribology on economy and ecology, such as the classical Jost Report in the United Kingdom (1966), that has been followed up to the present by similar investigations worldwide.

Keywords Tribology · Friction · Wear · Lubrication · Bearing · Hydrodynamics

1 Introduction to Tribology

The word "tribology" was introduced in the 1960s, as the science and engineering of rubbing surfaces. It includes the study and application of the principles of friction, wear and lubrication.

Therefore, tribology is multidisciplinary in nature, and closely related to physics, chemistry and mechanics of materials among other disciplines. In recent years, research in tribology has reached a highly advanced stage from a theoretical and experimental standpoint, with application to every sector of industry, e.g., automotive industry: each automobile presents approximately 2000 tribological contacts.

Learning more about tribological phenomena has led to improvements in mechanical systems, namely reduction of wear and the likelihood of failure, increase in energy efficiency, reduction of maintenance and repair costs, savings in raw materials and the reduction of noise and vibration.

Some organizations historically produce outstanding activities in tribology, e.g. the Institution of Mechanical Engineers (IMechE, founded in London in 1847), the

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American Society of Mechanical Engineers (ASME, founded in 1880), the American Society for Testing Materials (ASTM, founded in 1898), the American Gear Manufacturers Association (AGMA, founded in 1916), the Society of Tribologists and Lubrication Engineers (STLE, founded in 1944 by ASLE, the American Society of Lubrication Engineers) and the Japanese Society of Tribologist (JAST, founded in 1956). Several of these organizations belong to the International Tribology Council.

These associations and many others promote meetings and conferences on tribology worldwide, such as the "Leeds-Lyon Symposium on Tribology", held every year since 1973, and the "World Congress on Tribology", held every 4 years since 1997. They also publish journals of tribological interest, e.g. "Journal of Engineering Tribology" (Proceedings of the IMechE), "Journal of Tribology" (Transactions of ASME), "Tribology International", "Wear" and "Tribology Letters".

2 On the Significance of Tribology

Several authors (Reti 1967; Dowson 1998) have drawn attention to a sixteenth century indication of the economical importance of tribology in archives kept in Simancas, Spain. These archives refer to a large, complex machine, constructed by Juanelo Turriano (1501–1585), for raising considerable amounts of water under atmospheric pressure by means of a set of towers. Each tower included pivoted pipes and buckets with backward and forward motion which raised the water in stages (Fig. 1). The size of its moving parts and the dynamic forces received during operation made the tribological effects of this machine very significant in relation to the continuous wear of the machine and the ensuing need for costly reparations.

This early attention to the economic significance of tribology is in line with Renaissance authors like Leonardo da Vinci (1452–1519), who recognized the interest of studying friction forces and performed experiments with remarkable conclusions.

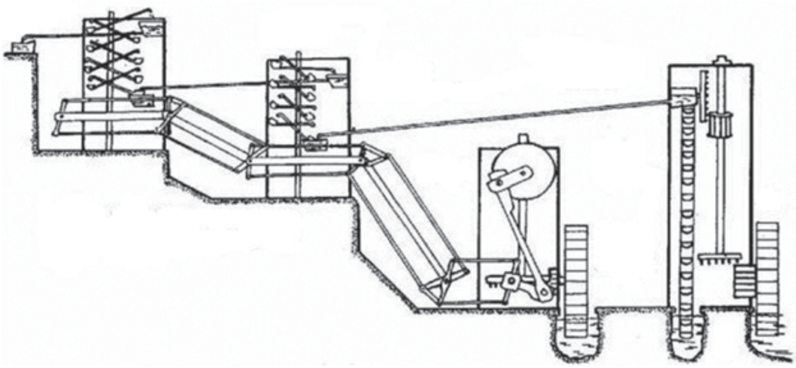

Fig. 1 Reconstruction of Juanelo's machine. (Reti 1967)

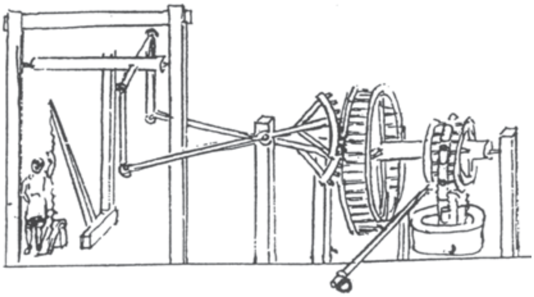

Fig. 2 Jerónimo de Ayanz's machine for raising water. (García Tapia 2001)

Furthermore, the interest in studying energy loss due to tribological phenomena was depicted by Jerónimo de Ayanz (1553–1613). Figure 2 shows a lever with a counterweight in a machine for raising water (García Tapia 1990, 2001). Thus, a comparative measurement of the efficiency of the different machines may be possible by the position of a weight on a rocker arm.

Later on, influenced by Leonardo da Vinci's work, Guillaume Amontons (1663–1705) wrote in 1699 "…among all those who have written on the subject of moving forces, probably not a single one has given sufficient attention to the effect of friction in machines…".

Despite the evolution in tribology during the Renaissance and even more so during the Industrial Revolution, it was not until the last few decades that several published reports clearly quantified the massive impact of tribology on economy and ecology. Peter Jost's classical Report for the Department of Education and Science of the United Kingdom (1966) first used the term "tribology", defined as "the science and technology of interacting surfaces in relative motion and related subjects practices". This report quantified possible savings by means of improved tribological practices and gave an idea about the tribological needs of industry. Figure 3 presents the distribution of potential savings according to Jost's findings.

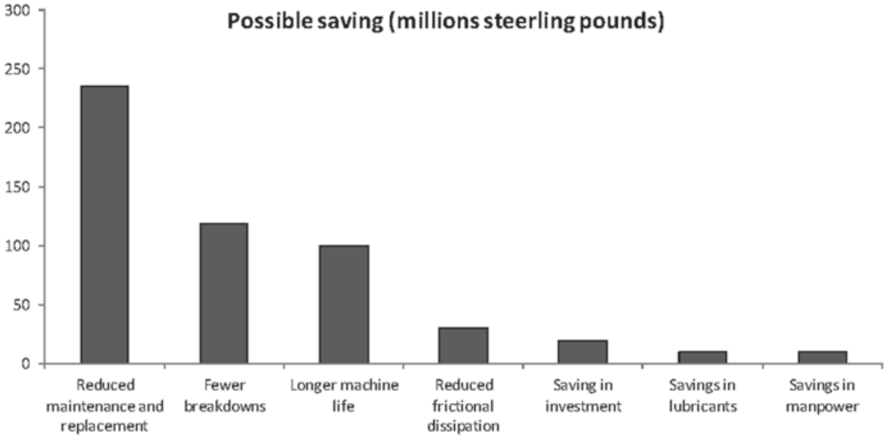

Fig. 3 Savings indicated by the Jost report in the United Kingdom—1966 levels. (Based on Jost 1966)

This report was followed by similar investigations worldwide (Pinkus and Wilcock 1977; Jost 2001). Each one established that the application of tribology could save between 1 and 2 % of an industrial country's gross national product (GNP). In other words, up to 30 % of consumed energy was exhausted in trying to overcome friction.

3 Tribology in the Past

By looking at anthropological remains used to generate fire by friction in primitive cultures, it may be assumed that the history of tribology covers developments from prehistory. In fact, the use of flintstones or dry wood for making fire suggests that early human beings had some knowledge about temperature and frictional heating.

Figure 4 represents different fire-generating techniques used during prehistoric times (Mauss 1967). Some of them involve certain complexity, e.g. the bow-based device requires converting linear into rotary motion, generating initial tension in a rope-pulley system, multiplying the speed, using primitive bone or stone bearings, etc.

As early human's basic life needs of food and heat were secured, he was able to devote more time to crafts and construction. This led to the development of devices which frequently required the use of plain bearings. Figure 5a shows an evolution of the bow system designed to generate fire, used in the Stone Age for drilling (Strandh 1979). Further evidence of the use of plain bearings are door-sockets, which could have been made with these sorts of drilling machines. Figure 5b shows a stone door-socket that includes an inscription, found in Mesopotamia and dated 2500 BC (Singer 1954).

The discontinuous motion of these previous devices gave rise to the first evidence of continuous rotary motion in the potter's wheel. Later on, we can find other examples in wheeled vehicles used in early civilizations, e.g. the south-pointing chariot built in China between 2600 and 1100 BC. It was used for pointing the way home by using a figure moved by an early differential gear. Figure 6 shows two drawings of the south-pointing chariot with its bearings.

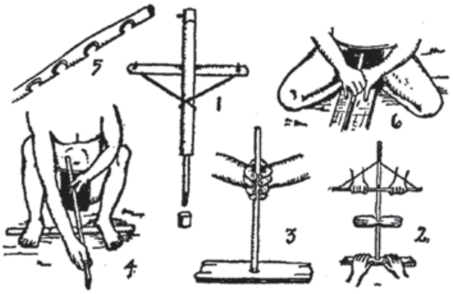

Fig. 4 Fire-making techniques: *1* Yukaghir bow drill, *2* pump movement drill, *3* hand drill, *4* saw for making fire, *5* instrument from Queensland, *6* Melanesian fire plow method. (Mauss 1967)

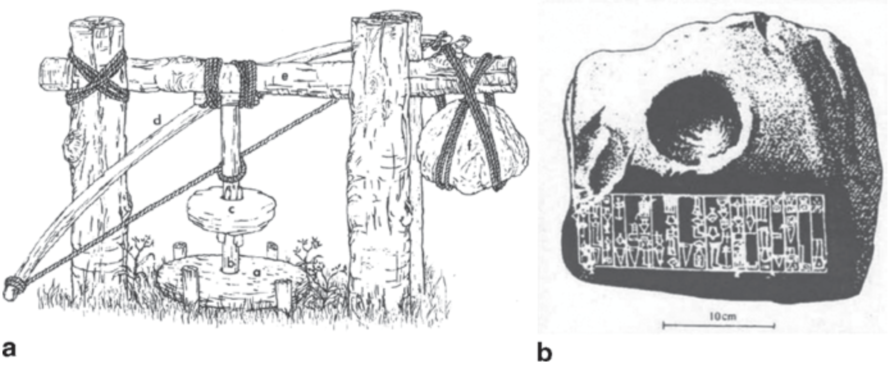

Fig. 5 **a** Bow drilling machine (Strandh 1979); **b** stone door-socket, Mesopotamia. (Singer 1954)

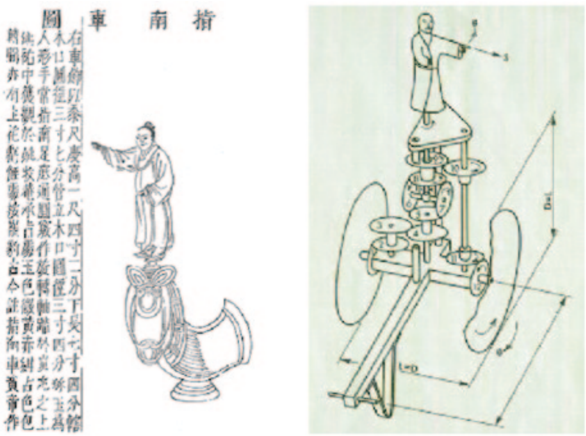

Fig. 6 Drawings of the south-pointing chariot. (Needham 1975)

Other remarkable examples are Greek tethrippons and Roman quadrigas, together with Dejbjerg celtic carts dated first century BC. It seems reasonable to think about the possibility of the existence of lubrication for the contacts in carts and chariots, taking into account the previous evidence of the use of lubricants for moving heavy statues and building blocks. By way of example, Fig. 7 shows how a statue was transported during the 12th dynasty of ancient Egypt. Just in front of the statue, there was a slave pouring lubricant on the ground in order to reduce friction, wear and heating (Dowson 1998).

Very significant technological achievements in tribology were made during the Greek and Roman periods, including lathes, wheeled transport, pulleys, gears, cranes, mills and other mechanical systems that utilized rotary motion.

We can find a remarkable example in Hero of Alexandria's system for opening doors automatically, a forerunner of the steam engine (Fig. 8). In his design, described in his work "Pneumatics" (written in the first century, translated by

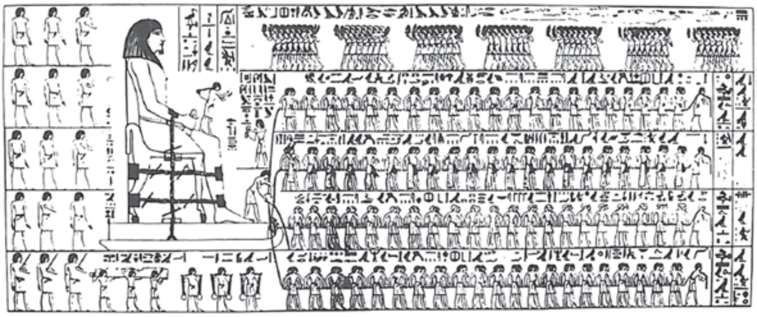

Fig. 7 Moving an ancient Egyptian statue. (Bautista et al. 2010)

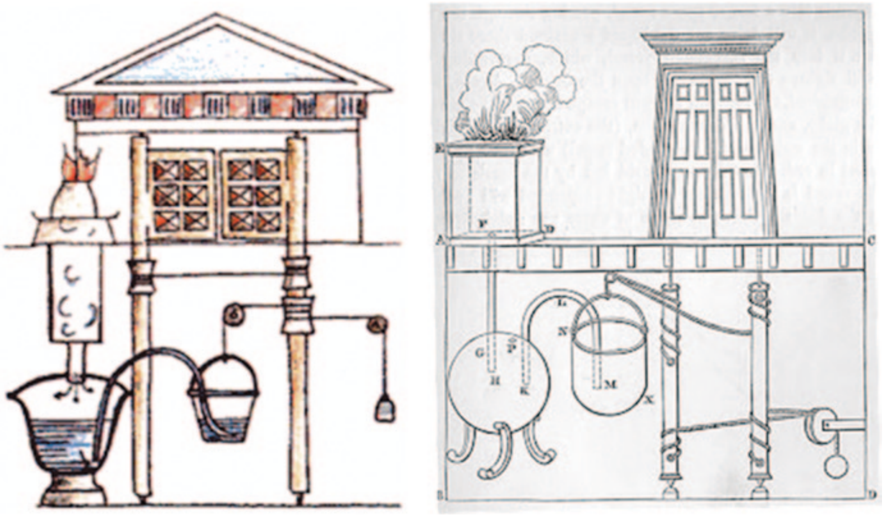

Fig. 8 Reconstruction of automatically opening doors. (Woodcroft 1851)

Woodcroft 1851), we can find pivot bearings for the door spindles. He wrote, "Let the hinges of the doors be extended downwards and turn freely on pivots in the base".

Marcus Vitruvius provided further information on the state of tribology in Greek-Roman times in his books "De Architectura" (ca. 15 BC, reedited in 1511). He digressed to explain the ingenious contrivance of Chersiphron used during the construction of the great Artemision of Ephesus for moving the columns. "When he removed from the quarry the shafts of the columns, … not thinking it prudent to trust them on carriages, lest their weight should sink the wheels in the soft roads over which they would have to pass, he devised the following scheme. He made a frame of four pieces of timber, two of which were equal in length to the shafts of the columns, and were held together by the two transverse. In each end of the shaft he inserted iron pivots, whose ends were dovetailed thereinto, and run with lead. The pivots worked in gudgeons fastened to the timber frame, whereto were attached oaken shafts.

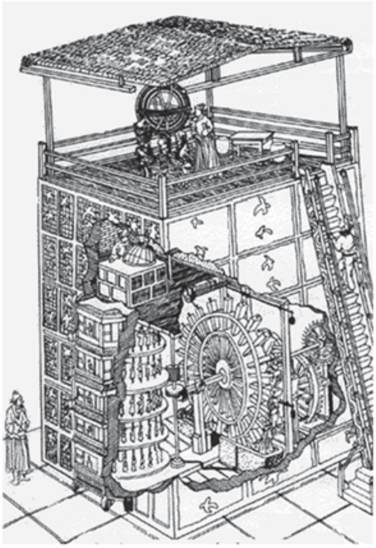

Fig. 9 Astronomical clock tower. (Lu 2000)

The pivots having a free revolution in the gudgeons, when the oxen were attached and drew the frame, the shafts rolled round, and might have been conveyed to any distance".

Tribological progress led to the development of early forms of cylindrical, taper roller and ball bearings (Williams 1994). Evidence of this was found, namely rolling elements which were trunnion mounted, in the remains of two large ships in Lake Nemi, near Rome and dating from about 50 AD.

In the Middle Ages the evolution of general machinery was modest and therefore there was no need for major evolution of existing materials, lubricants and bearings. However, the use of wooden and stone bearings gave rise to the use of metal bearings, like those of iron-on-iron included in Fig. 9, which represents an astronomical clock tower (Su Song 1089).

Indeed, main Medieval developments in tribology were found in mechanical clocks, transportation such as harvest carts and wheelbarrows, mechanical power generation such as water and wind driven machines, and in the use of hard stone inserts to protect the mouldboards of ploughs and the axles of carts. In addition, there was a steady rate of development in the use of lubricants, namely vegetable oils and animal fats. In most cases, there was a lack of theoretical knowledge and therefore the progress was related to phenomenological analyses. Thus, most advances were gained through observation and experimentation but without sufficient understanding of processes involved.

Unlike what happened in Medieval times, during the Renaissance there was a period of recovery and revitalisation in Western Europe, where classical Greek and Roman works were re-examined, improved and illustrated. Moreover, the use of the printing press disseminated the existing knowledge on a large scale. Therefore, two separate activities may be recognised at that time: professional practice of a traditional experimental nature and new theoretical studies of a scientific nature.

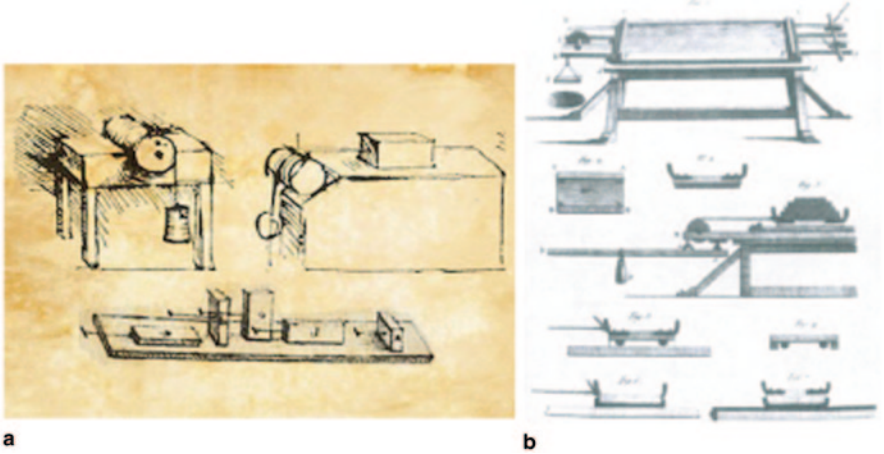

Fig. 10 **a** Sketches from Leonardo da Vinci notebooks. (Da Vinci 15th century); **b** devices used by Coulomb (Coulomb 1785)

Both lines reached important progress and gradually converged until they came together in the seventeenth century.

During the Renaissance we can find first indications of in-depth studies on the force of friction, which had been recognized by Aristotle approximately twenty centuries earlier. Leonardo da Vinci (ca. 1480) presented the first quantitative studies on friction by measuring the force of friction between objects on both horizontal and inclined surfaces. Figure 10a shows the use of cords attached to the objects to be moved, which passed over fixed rollers to weights, giving a measure of the friction force. In the same way, he measured the torque on a roller placed in a semicircular section. He observed that without lubrication "every frictional body has a resistance of friction equal to one-quarter of its weight", this observation is incorrect but quite realistic for the materials commonly used in bearings at that time (Szeri 2005).

In 1495, Leonardo da Vinci formulated the first two basic laws of sliding friction: "Friction is independent of contact area, and friction is proportional to load". These laws were rediscovered by Amontons in 1699, who used springs and was able to measure static and kinetic friction forces, and they were further developed (Fig. 10b) by Charles-Augustin de Coulomb (1736–1806).

Another law of friction is due to Isaac Newton (1642–1727): "Moving friction is not dependent on speed or velocity". These observations were physically supported by the work of Frank Philip Bowden and David Tabor (Bowden and Tabor 1950 and 1964), when they analyzed micro-scale friction taking into account the interaction between surface asperities of the contacting bodies.

Figure 11 includes Leonardo da Vinci's analysis on the difference between rolling and sliding friction. The potential of true rolling motion for low-friction supports was recognized by him, who also wrote in the Codex Madrid I: "…I do not see any difference between balls and rollers save the fact that balls have universal motion while rollers can move in one direction alone. But if balls or rollers touch each other in their motion, they will make the movement more difficult than if there

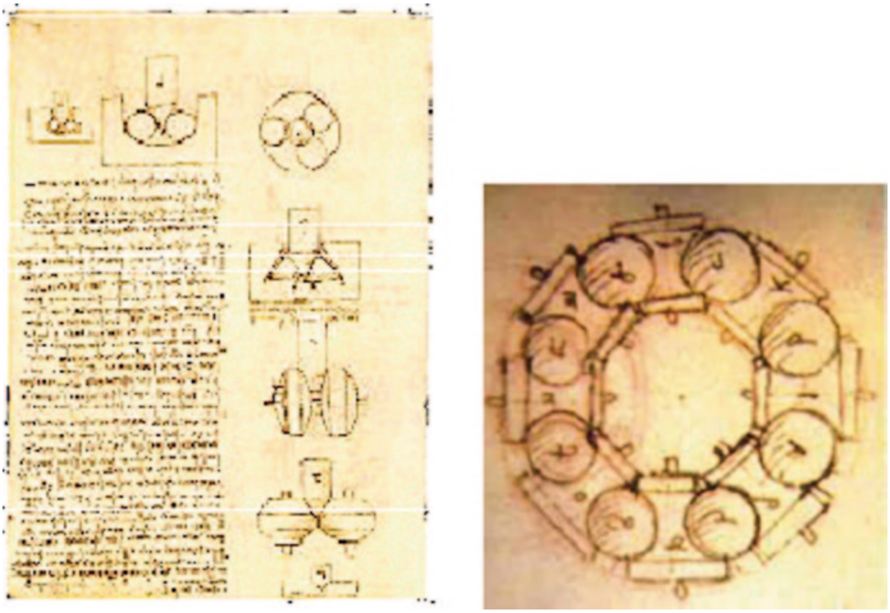

Fig. 11 Leonardo da Vinci's sketches on rolling and sliding friction. (Da Vinci 15th century)

were no contact between them, because their touching is by contrary motions and this friction causes contrariwise movements".

Subsequently, there were attempts to apply knowledge in friction to develop low-friction bearings. A first approach presented in Leonardo da Vinci's Codex Madrid I, is a bearing alloy consisting of three parts of copper and seven parts of tin melted together.

By combining their understanding of the theory and their practical genius, Renaissance engineers reached remarkable tribological developments, leading to new proposals of different types of bearings for machines. Figure 12 presents illustrations

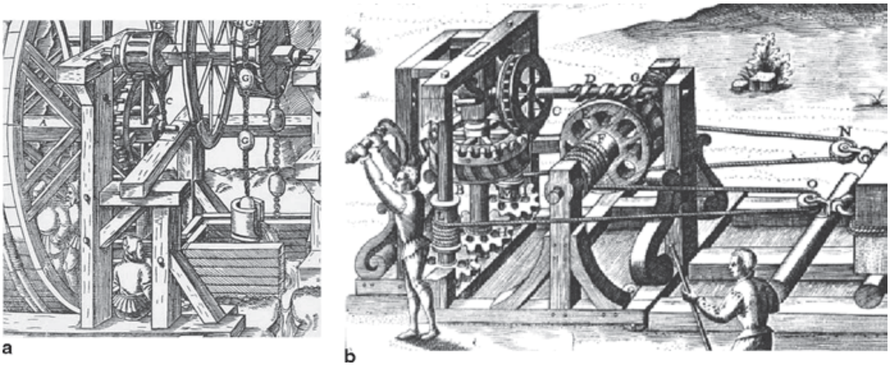

Fig. 12 **a** Details of plain bearings in a rag-and-chain pump (Agricola 1556); **b** plain bearings and rollers in a hand-operated worm gear (Ramelli 1588)

of Georgius Agricola (1556) and Agostino Ramelli (1588) which show the common use of both plain bearings and rollers in the sixteenth century. Further examples can be found in the treatises of machines by Jaques Besson (1578), Vittorio Zonca (1607) and many others.

Finally, it is worthwhile to note the experimental studies performed by Vittorio Zonca (1568–1603) concerning wear in bearings made of dissimilar materials, where steel and bronze contacts were analyzed.

4 From the Renaissance to the Industrial Revolution: The Beginnings of a New Science

During the seventeenth century there were changes in social and production structures, namely population growth, first factories (Royal Manufactures) and transport developments. These modifications were the seed for the Industrial Revolution of the second half of the eighteenth century, when all the fields of technology grew rapidly.

On the one hand, population growth involved changes in food supply, together with clothes and other services that promoted an increase of commercial activities. On the other hand, changes in production structures led to a rise in the power demand due to the change from hand-made workshops to early factories that were created to cover the increasing demand of products in the textile, metallurgy, mining and agriculture sectors.

In this context, different studies related to friction and wear were carried out in order to improve the production and performance of the machines installed in the factories. These machines were initially driven by water or animal traction, until the generalized use of the steam engine during the Industrial Revolution (Bautista et al. 2010).

4.1 Friction and Wear in Bearings

In line with the Renaissance engineers, friction and wear in bearings was identified as essential for the correct operation of machines. Therefore, the concept of Leonardo da Vinci's low-friction bearing was further developed by Hooke (1684) and Babbitt.

Robert Hooke (1635–1703) focused on friction and wear reduction in bearings of chariots by means of experimental analyses. His improvements led him to present a sailing chariot in the Royal Society in London, i.e. a chariot movable by air-power due to its low friction.

Isaac Babbitt (1799–1862) greatly improved the friction bearing design with the first friction bearing using low-friction "babbitt metal": an alloy of tin, antimony and copper. This formulation presents low shear strength and gives a reduction of 25 % in dynamic friction coefficient, if compared to previous steel-steel contacts in bearings (Hellemans and Bunch 1988).

In the same way, Leonardo da Vinci's early studies of wear in bearings finally led to Archard's wear law in 1953, based in the theory of asperity contact. It states that the volume of wear is proportional to the distance slid and to the applied load, and inversely proportional to the hardness of the softer material (Archard and Hirst 1956).

4.2 Hydrodynamic Lubrication

Despite the increasing advancement of bearings, it was not until the nineteenth century when fluid film lubrication was introduced and thus minimized friction. Fluid film lubrication, or hydrodynamic lubrication, is essential in machines that operate at high velocity, where frictional heating and wear can produce negative effects.

The mechanisms that allow the reduction of friction under fluid film lubrication were initially unknown (Hamrock 1994). The first theories of Leupold considered that the fluid film reduced the roughness or asperities of the surfaces in contact (Stachowiak et al. 2004). Then, Leslie (1804) exposed that the lubricant filled the gap between asperities diminishing the friction. Later on, Rennie (1829) proposed that the lubricant separated the surfaces in contact.

More studies on hydrodynamic lubrication were carried out by Von Pauli (1849), Barrans (1850), Hirn (1854) and Thurston (1879). Figure 13 shows a scheme of the test device used by Gustave Adolphe Hirn (1815–1890) in order to analyze the effect of diverse loads and sliding velocities.

Nikolai Pavlovich Petrov (1836–1920) and Beauchamp Tower (1845–1904) in Russia and England respectively, further developed these studies with almost simultaneous developments related to railway applications, in which the availability of mineral oils during the first half of nineteenth century played an important role. First distillation plants were installed in Prague (1810) and France (1834) and by 1850 James Young founded an oil refinery (Dowson 1998).

Mineral oils substituted previous lubricants of animal or vegetable origin (sperm whale, olive, rapeseed, etc.) because of their better behavior under severe operating conditions, typical of machines developed during the Industrial Revolution. Nowadays, mineral oils are the most widely used lubricants worldwide, though they are being substituted by synthetic oils in several specific applications, e.g. when working temperature is very high.

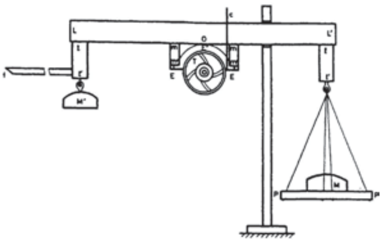

Fig. 13 Test device used by Hirn. (Hirn 1854)

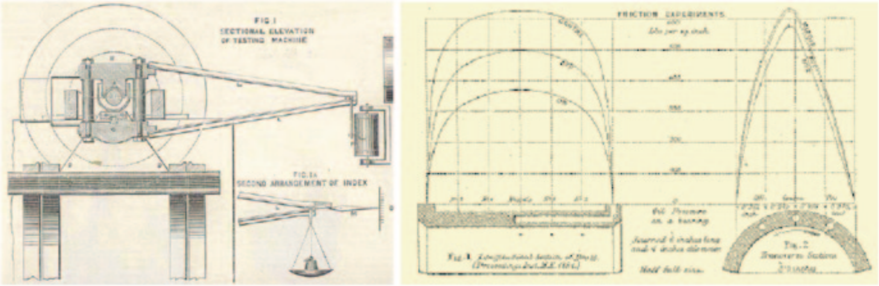

Fig. 14 Experiments performed by Tower. (Tower 1883)

Petrov (1883) analyzed the specific characteristics of Russian mineral oils, whose high viscosity caused high losses by friction in diverse applications in railway transportation. His experimentation led to a first theoretical law that gave the friction coefficient in a journal bearing as a function of the geometry, the lubricant viscosity and the operating conditions.

In 1883, Tower experimentally studied the evolution of the lubricated friction coefficient in journal bearings at high sliding velocities, under operating conditions which simulated railway axle boxes. This study was requested by the Institution of Mechanical Engineers in order to improve lubrication of journal bearings used in trains.

Tower's first tests were performed with bath lubrication and he found very low friction under high loads which suggested the existence of a fluid film. In his second series of tests, Tower made a hole in the bearing in order to analyze forced lubrication. However, he accidentally discovered that lubricant escaped through this hole at very high pressure levels, and in this way he proved the existence of a hydrodynamic wedge that carried the load. Figure 14 shows the layout of the experiment and the measurements of the pressure, obtained by placing a gauge in the hole.

Osborne Reynolds (1842–1912) derived and published (Reynolds 1886) the differential Eq. (1), which supported the results of Tower. This equation provided a physical explanation of fluid film lubrication and related the variables involved, namely pressure (p), viscosity (η), average velocity between surfaces (u), time (t) and lubricant film thickness (h).

$$\frac{d}{dx}\left[h^3\frac{dp}{dx}\right]+\frac{d}{dy}\left[h^3\frac{dp}{dy}\right]=6\eta\left[u\frac{dh}{dx}+\frac{dh}{dt}\right] \tag{1}$$

In 1904, Arnold Sommerfeld (1868–1951) solved Reynolds' equation and presented a formal theory of hydrodynamic lubrication with an analytical solution for journal bearings. The solution was based on dimensionless parameters and was highly useful for design purposes. Soon after, Michell (1905) applied the Reynolds theory to thrust plain bearings.

In this way, lubrication of bearings constitutes an example of the evolution of our understanding, beginning with observations and concluding with models of the phenomena involved.

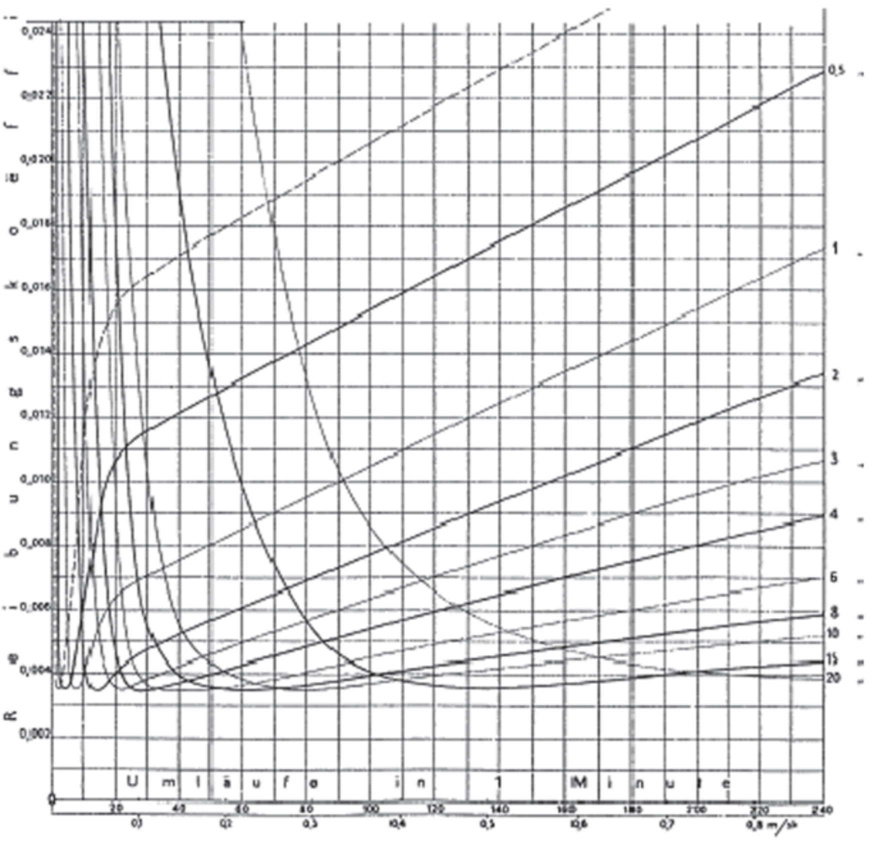

Fig. 15 Detail of Richard Stribeck's curves. (Stribeck 1902)

It is important to note the distinction between fluid film lubrication and other lubrication regimes, according to Richard Stribeck's work, published in 1902. He performed a set of systematic tests for a range of velocities (*N*) and loads, and represented the friction coefficient as a function of the Gumbel number ($\eta N/p$). Figure 15 shows a detail of Stribeck's results, where very different behaviors can be observed for the friction coefficient.

5 Tribology as a True Science

Before the twentieth century, tribology was primarily a technological endeavor, with specific matters of different sciences (Halling 1975). This consideration began to change with the development of hydrodynamic theory and its later generalization to elastohydrodynamics.

5.1 Elastohydrodynamic Lubrication

Martin (1916) applied hydrodynamic theory to two rigid discs under a high load in conditions representative of the line contact in gears. This model gave an insignificant value for the lubricant film thickness, insufficient for forming a fluid film when compared with the roughness of the contacting surfaces. Therefore, a high value was expected for the friction coefficient. In contrast, experimental results of Martin showed a low value of friction. Subsequent modification of hydrodynamic theory led to elastohydrodynamic lubrication, which took into account the elastic deformation of the contacting surfaces and the lubricant viscosity dependence on pressure.

The first remarkable approaches to the solution of the elastohydrodynamic problem were proposed in the middle of the twentieth century by Grubin (1949) and Petrusevich (1951). In 1959, Duncan Dowson and Gordon Robert Higginson (Dowson and Higginson 1959) completely developed the elastohydrodynamic theory predicting the existence of a pressure peak and a reduction of the film thickness at the outlet of the contact. These characteristics of elastohydrodynamic contacts were experimentally confirmed by Crook (1961) using an oscilloscope to measure the electrical resistance between two lubricated bodies in contact, as shown in Fig. 16.

Solving this complex problem required the development of specific models and techniques, together with advanced computing facilities. The initial solutions were improved by Bernard J. Hamrock and Duncan (1976, 1977), among others. These results considered Newtonian behavior of the lubricant and approximate isothermal work regime, where the thermal effects due to sliding contacts were neglected. However, these hypotheses were only valid under particular operating conditions.

In fact, under the severe operating conditions inherent to elastohydrodynamics, frequently common lubricants cease to behave as Newtonian fluids and exhibit pseudoplastic behavior (Bair 2007). These fluids present a rapid rise in shear stress with the shear rate, but the increase gradually drops as the shear rate rises. Various models have been developed to explain the rheological behaviour of lubricants (Jacobson 1991; Höglund 1999), such as Carreau's equation (Carreau 1972).

In general, heat generated by friction can cause a very considerable local increase in temperature and the corresponding reduction of viscosity (Gohar 1988).

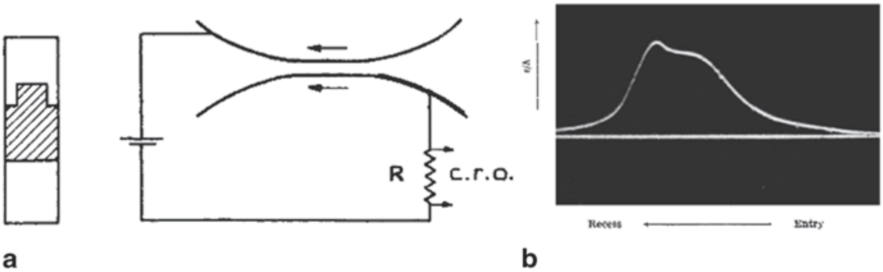

Fig. 16 Crook's experiments. **a** Layout; **b** pressure results. (Crook 1961)

This requires a thermal elastohydrodynamic study to examine how the viscosity characteristics of the lubricant change with temperature, and the subsequent effects on its behavior (Stachowiak et al. 2004). Further research (Olver and Spikes 1998) opened up the way to the so-called thermal-elastohydrodynamic lubrication, which presents multiple applications in mechanical systems that work under very high pressure, such as gears, rolling bearings and cams (Habchi et al. 2008).

5.2 Non-Fluid Lubrication

Despite the wide application field of fluid film theories, conventional liquid lubricants are not suitable for machinery working under particularly severe operating conditions, e.g., extreme temperature, very high pressure, vacuum conditions or ambient dust concentrations.

By the way of example, Kingsbury developed air-lubricated bearings (Kingsbury 1897). They presented a very low friction coefficient and worked within high temperatures but their application was limited by their low load capacity.

In other cases, solid lubricants or self-lubricating materials are used that exhibit lubricity by themselves and can be applied as coatings (Carnes 2005). They are also used as additives dispersed in liquid and grease media. The introduction of graphite as a self-lubricating material for applications such as air compressors or open gears dates back to 1906, whereas the molybdenum disulfide (patent issued in 1939) was used in oxidizing media with extreme temperatures and guaranteed a high stability with vacuum in space vehicles. In 1938 teflon was discovered, one of the most famous self-lubricating polymer materials. It is very slippery and relatively inert and can be used for biotribology applications (Harris 1991), e.g. in medical prostheses. Recently, it has also been extended the use of ceramic materials (Ziebig and Luber 1983), which are used in high-speed ball bearings and femoral heads and are very hard, inert and produce low wear rate (Fig. 17).

Fig. 17 Ceramic hip prosthesis. (Levitin 1997; Pinchuk et al. 2006)

5.3 Testing in Tribology

The difficulty of predicting the in-service behavior of the lubricant in new machinery increased due to the large number of parameters with influence: operating parameters (load, sliding velocity, temperature…), parameters of the material (hardness, elasticity, thermal properties…), surface geometry, roughness and lubricant parameters (viscosity, density, thermal properties…). We must bear in mind that there are a wide variety of mineral and synthetic lubricant bases (Spikes 1994). Moreover, its behavior is highly influenced by additives added to improve lubricant performance. This is one of the reasons why theoretical predictions frequently need to be complemented or verified through experimentation.

Testing in tribology became widespread since 1927, with the Pin and Vee Block tester shown in Fig. 18, a first commercial tester from Falex. It was designed to quantify the anti-wear and extreme pressure properties of fluid and solid lubricants measuring the wear with a ratchet wheel. Load was applied to the vee-blocks against a rotating device.

This tribometer was followed by other classical equipment (Pin-on-Disc apparatus, Four-ball tester, Timken apparatus, etc.) designed by different companies, such as Falex, Cameron-Plint and PCS-Instruments. Some of this equipment, shown in Fig. 19, constitutes a bridge between theory and industrial applications, as they are designed to determine the influence of each parameter of interest in the phenomena analyzed, providing fast and reliable results under controlled conditions.

The generalized use of certain test machines led to the development of standard tests performed in them, as the case of the back-to-back FZG gear test rig (Fig. 20). The test gears are connected to slave gears by two shafts and a static torque can be applied to the system by means of a torsion bar and a clutch. In addition, there are other complementary testers used in tribology, e.g., equipment for the characterization of properties of lubricants or test benches used for studying mechanical failures. All this testing equipment supports the theoretical progress of tribology.

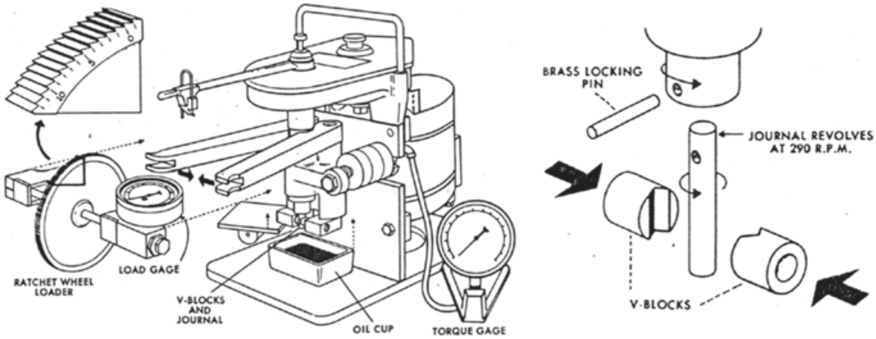

Fig. 18 Pin and vee block tester. (Falex catalog, http://www.falex.com)

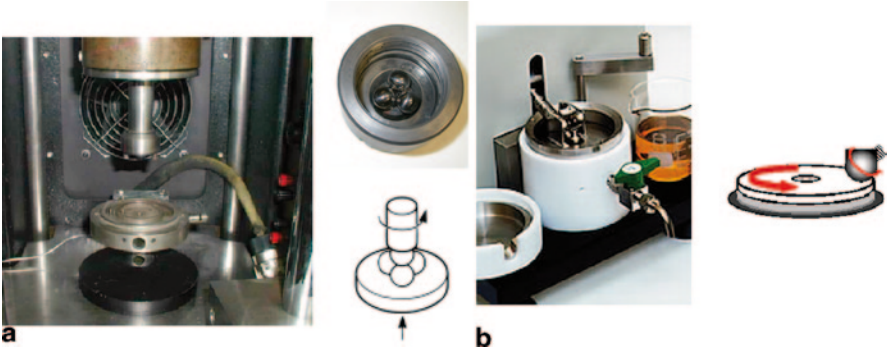

Fig. 19 **a** Four ball tester; **b** mini traction machine, with details of the contacts. (Courtesy of the company Repsol)

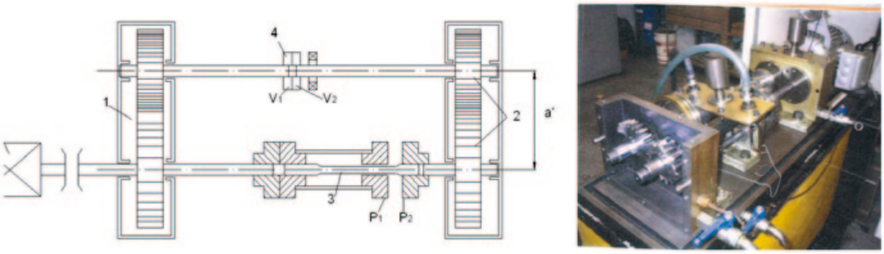

Fig. 20 FZG gear test rig: *1* Slave gear, *2* Test gear, *3* Torsion bar, *4* Clutch. (Lafont et al. 2009, and courtesy of Repsol)

5.4 Present and Future of Tribology

Tribology has become deeply embedded in science, engineering, design, manufacture and life cycle management across a huge range of application areas. As such we can now regard tribology as a mature scientific and engineering discipline.

Nowadays, the design of machines (and mechanical systems in general) can take advantage of extensive existing knowledge about tribology in order to optimize their operation and life. In fact, understanding the complex interrelationship between materials, lubricants and the working conditions and environments of machines constitutes the key to reduce friction and avoid failures caused by tribological phenomena. Even small benefits of one machine element can produce huge global savings due to the size of the marketplace.

Friction phenomenon has also been studied at the nanometer scale (nanotribology), where the atomic forces affect the behavior of the system (Harrison et al. 1998). Other challenges in tribology are the development of new generation lubricants and additives, the improvement of contacting surfaces (microgeometry, coatings, etc.), further development of tribometry and biotribology applications for tissue growth and prostheses (Spikes 2001; Carnes 2005).

6 Conclusion

A historical overview of the significance of tribology during its long history has been presented, with focus on the theoretical developments and their application to technical problems. As demonstrated, tribology is related to the performance of every mechanical device because wear, friction and lubrication present a key influence on critical aspects such as efficiency, in-service life, breakdowns and need for maintenance and repair.

References

Agricola G (1556) De Re Metallica. Reprinted in 1950 by Dover publishing
Amontons G (1699) De la Résistance causée dans les Machines. Mémoires de l'Académie Royale A, pp 257–282, 1699
Archard JF (1953) Contact and rubbing of flat surface. Journal of Applied Physics 24(8):981–988
Archard JF, Hirst W (1956) The wear of materials under unlubricated conditions. Proceedings of the Royal Society of London A-236:397–410
Bair S (2007) High pressure rheology for quantitative elastohydrodynamics. Tribology and interface engineering series, No. 54. Elsevier, Amsterdam
Barrans J (1850) On an improved axle box for railway engines and carriages. Proceedings of the Institution of Mechanical Engineers 2, pp. 3–8
Bautista E, Ceccarelli M, Echávarri J, Muñoz JL (2010) A brief illustrated history of machines and mechanisms. Springer, Berlin
Besson J (1578) Theatrum Instrumentum et Machinarum, Lugduni Vincent
Bowden FP, Tabor D (1950 and 1964) The friction and lubrication of solids. Oxford University Press, Part I (1950); Part II (1964)
Carnes K (2005) The ten greatest events in tribology history: as chosen by the readers of TLT magazine. Tribology & Lubrication Technology 61(6):38–47
Carreau PJ (1972) Rheological equations from molecular network theories. Transactions of The Society of Rheology 16(1):99–127
Coulomb CA (1785) Theories des machines simples, en ayant égard au frottement de leurs parties, et a la roider des cordages. Mém Math Phys X:161–332
Crook AW (1961) Elastohydrodynamic lubrication of rollers. Nature 190(4782):1182–1183
Da Vinci L (15th century) Codex Madrid I and II, Codex Atlanticus and Codex Arundel
Dowson D (1998) History of tribology, 2nd edn. Longman, London
Dowson D, Higginson GR (1959) A numerical solution to the elastohydrodynamic problem. The Journal of Mechanical Engineering Science 1(1):6–15
García Tapia N (1990) Patentes de Invención Españolas en el Siglo de Oro. Industrial Property Register, D.L
García Tapia N (2001) Un Inventor Navarro. Jerónimo de Ayanz y Beaumont. Pamplona Department of Education and Culture
Gohar R (1988) Elastohydrodynamics. Ellys Horwood Ltd., London
Grubin AN (1949) Fundamentals of the hydrodynamic theory of lubrication of heavily loaded cylindrical surfaces. In: Ketova KF (ed) Proceedings of symposium on investigation of the contact of machine components, Book No. 30, pp. 115–166. Moscow, Russia
Habchi W, Eyheramendy D, Bair S, Vergne P, Morales-Espejel G (2008) Thermal elastohydrodynamic lubrication of point contacts using a Newtonian/generalized Newtonian lubricant. Tribology Letters 30:41–52
Halling J (1975) Principles of tribology. Edition, illustrated. MacMillan Press, London

Hamrock BJ (1994) Fundamentals of fluid film lubrication. McGraw-Hill, New York

Hamrock BJ, Dowson D (1976) Isothermal elastohydrodynamic lubrication of point contacts, Part I-theoretical formulation. ASME Journal of Lubrication Technology 98:223–229

Hamrock BJ, Dowson D (1977) Isothermal elastohydrodynamic lubrication of point contacts, Part III-fully flooded results. ASME Journal of Lubrication Technology 99:264–275

Harris TA (1991) Rolling bearings analysis, 3rd edn. Wiley, New York

Harrison JA, Stuart SJ, Brenner DW (1998) Atomic-scale simulation of tribological and related phenomena. In: Bhushan B (ed) Handbook of micro/nanotribology. CRC, New York, pp 525–594

Hellemans A, Bunch B (1988) The timetables of science. Simon & Schuster, New York

Hirn GA (1854) Etudes sur les principaux phénomènes que présentent les frottements médiats et sur les diverses manières de déterminer la valeur mécanique des matières employées au graissage des machines. Bulletin de la Société Industrielle de Mulhouse, 26, No. 129, pp 188–277

Höglund E (1999) Influence of lubricant properties on elastohydrodynamic lubrication. Wear 232:176–184

Hooke R (1684) The posthumous works of Robert Hooke. Waller and Seer, London

Jacobson BO (1991) Rheology and elastohydrodynamic lubrication. Tribology series, vol 19. Elsevier, Amsterdam, pp 1–381

Jost P (1966) Lubrication (tribology), education and research. A Report on the present position and industry's needs, published as an English government report on 9 March 1966

Jost P (2001) The tasks of tribology societies on a changing world. Opening address, Second World Tribology Congress

Kingsbury A (1897) Experiments with an air lubricated bearing. Journal of the American Society for Naval Engineers 9, pp 267–292

Lafont P, Díaz A, Echávarri J (2009) Diseño y Cálculo de Transmisiones por Engranajes. Publicaciones de la ETS de Ingenieros Industriales, Madrid

Leslie J (1804) An experimental inquiry into the nature and propogation of heat. T. Gillet Printer, Salisbury Square

Levitin M (1997) Friction reduction in hip implants treated with regular microrelief. Regmi-Tech, Haifa, p 12

Lu Z (2000) The development of water-powered machines in China in 10–14th Century. In: Proceedings of HMM 2000. Kluwer Academic Publishers, Dordrecht

Martin HM (1916) Lubrication of gear teeth. Engineering, vol 102. London, pp 199–221

Mauss M (1967) Manuel D'Ethnographie. Payot, Rivages (eds), Paris, France

Michell AGM (1905) The lubrication of plane surfaces. Zeitschrift für Mathematik und physik 52(Pt. 2):123–137

Needham J (1975) Science and civilisation in China. Cambridge University Press, Cambridge

Olver AV, Spikes HA (1998) Prediction of traction in elastohydrodynamic lubrication. Proceedings of the Institution of Mechanical Engineers Part J-Journal of Engineering Tribology 212:321–332

Petrov NP (1883) Friction in machines and the effect of the lubricant. Inzh Zh St-Peterb 1:71–140; (2:227–279; 3:377–436; 4:435–464)

Petrusevich AI (1951) Fundamental conclusions from the contact-hydrodynamic theory of lubrication. Izvestiya Akademii Nauk SSSR SSSR (OTN) 2:209–223

Pinchuk LS, Nikolaev VI, Tsvetkova EA, Goldade VA (2006) Tribology and biophysics of artificial joints. Elsevier, Amsterdam

Pinkus O, Wilcock DF (1977) Strategy for energy conservation through tribology. Tribology in energy technology workshop, Washington: Tribology in Energy Technology Workshop 1977, ASME

Ramelli A (1588) Le Diverse et Artificiose Macchine del Capitano Agostino Ramelli dal Ponte della Tresia, Paris, France

Rennie (1829) Experiments on the friction and abrasion of the surfaces of solids. Philosophical Transactions of the Royal Society of London 119:143–170

Reti L (1967) El artificio de Juanelo en Toledo. Magazine of Toledo provincial council, No. 60, 1967, pp. 3–46

Reynolds O (1886) On the theory of lubrication and its application to Mr. Beauchamp Tower's experiments, including an experimental determination of the viscosity of olive oil. Philosophical Transactions of the Royal Society of London 177:157–234

Singer C (1954) A history on technology. Clarendon Press, Oxford

Sommerfeld A (1904) Zur hydrodynamischen theorie der Schmiermittelreibung. Zeitschrift für angewandte Mathematik und Physik 50:97–155

Spikes HA (1994) The behaviour of lubricants in contacts; current understanding and future possibilities. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology 208(1): 3–15

Spikes HA (2001) Tribology research in the twenty-first century. Tribology International 34:789–799

Stachowiak GW, Batchelor AW, Stachowiak GB (2004) Experimental methods in tribology. Tribology series, 44. Elsevier, Amsterdam

Strandh S (1979) Machines. An illustrated history. Littlehampton Book Services, Worthing

Stribeck R (1902) Die Wesentlichen Eigenshaften der Gleit und Rollen lager. Z Ver dt Ing 46(38): 1341–1348

Su Song (1089) Xin Yi Xiang Fa Yao. (Horological treatise)

Szeri AZ (2005) Fluid film lubrication. Theory and design. Cambridge University Press, Cambridge

Thurston RH (1879) Determination of the laws and coefficients of friction by new methods and with new apparatus. The Railroad Gazette, New York

Tower B (1883) First report on friction experiments (friction of lubricated bearings). Proceedings of the Institution of Mechanical Engineers Nov., pp 632–659

Vitruvius M (1511) De Architectura. Edited by Fra Giocondo, Verona, (reprinted in 1513, 1522 and 1523).

Von Pauli FA (1849) Uberden Widerstand der zapfenreibung. Kunst and Gewerbeblatt des polytechnischen Verein des Konigreich Bayern, vol 8/9, pp 452–469

Williams JA (1994) Engineering tribology. Oxford University Press, Oxford

Woodcroft B (1851) The Pneumatics of Hero von Alexandria. Walton & Maberly, London

Ziebig A, Luber H (1983) Bioceramic hip joint components-industrial production and testing procedures to ensure high functional reliability. In: Vincenzini P (ed) Ceramics in surgery. Elsevier, New York

Zonca V (1607) Novo Teatro Di MACHINE ET EDIFICII Per uarie et Sicure operationi Co[n] le loro figure tagliate in Rame é la dichiaratione, e dimostratione di ciascuna. Opera necesaria ad Architetti, e a quelli, ch[i] di tale studio si dilettano. Di VITTORIO ZONCA. Architetto della Magnifica Communita di Padoua. In Padoua Appresto Pietro Bertelli.