FRICTION, WEAR AND LUBRICATION

MEMM 1343

BACKGROUND

Tribology in a traditional form has been in existence since the beginning of recorded history. There are many well documented examples of how early civilizations developed bearings and low friction surfaces. The scientific study of tribology also has a long history, and many of the basic laws of friction, such as the proportionality between normal force and limiting friction force, are thought to have been developed by Leonardo da Vinci in the late 15th century.

However, the understanding of friction and wear languished in the doldrums for several centuries with only fanciful concepts to explain the underlying mechanisms. For example, it was proposed by Amonton in 1699 that surfaces were covered by small spheres and that the friction coefficient was a result of the angle of contact between spheres of contacting surfaces.

Tribology is therefore a very new field of science, most of the knowledge being gained after the Second World War. In comparison many basic engineering subjects such as thermodynamics, mechanics and plasticity, are relatively old and well established.

MEANING OF TRIBOLOGY

Tribology, which focuses on friction, wear and lubrication of interacting surfaces in relative motion, is a new field of science defined in 1967 by a committee of the Organization for Economic Cooperation and Development. “Tribology” is derived from the Greek word “tribos” meaning rubbing or sliding.

Friction is a principal cause of wear and energy dissipation. Considerable savings can be made by improved friction control. It is estimated that one-third of the world's energy resources in present use is needed to overcome friction in one form or another.

Wear is the major cause of material wastage and loss of mechanical performance and any reduction in wear can result in considerable savings.

Lubrication is an effective means of reducing friction and controlling wear. Tribology is a field of science which applies an operational analysis to problems of great economic significance such as reliability, maintenance and wear of technical equipment ranging from household appliances to spacecraft.

The question is why “the interacting surfaces in relative motion” (which essentially means rolling, sliding, normal approach or separation of surfaces) are so important to our economy and why they affect our standard of living.

The answer is that surface interaction dictates or controls the functioning of practically every device developed by man. Everything that man makes wears out, almost always as a result of relative motion between surfaces. An analysis of machine break-downs shows that in the majority of cases failures and stoppages are associated with interacting moving parts such as gears, bearings, couplings, sealings, cams, clutches, etc. The majority of problems accounted for are tribological.

Our human body also contains interacting surfaces such as human joints, which are subjected to lubrication and wear.

Tribology affects our lives to a much greater degree than is commonly realized. For example, long before the deliberate control of friction and wear was first promoted, human beings and animals were instinctively modifying friction and wear as it affected their own bodies. It is common knowledge that the human skin becomes sweaty as a response to stress or fear. It has only recently been discovered that sweating on the palms of hands or soles of feet of humans and dogs, but not rabbits, has the ability to raise friction between the palms or feet and a solid surface. In other words, when an animal or human senses danger, sweating occurs to promote either rapid flight from the scene of danger, or else the ability to firmly hold a weapon or climb the nearest tree.

A general result or observation derived from innumerable experiments and theories is that tribology comprises the study of:

The characteristics of films of intervening material between contacting bodies, and

The consequences of either film failure or absence of a film which are usually manifested by severe friction and wear.

Film formation between any pair of sliding objects is a natural phenomenon which can occur without human intervention. Film formation might be the fundamental mechanism preventing the extremely high shear rates at the interface between two rigid sliding objects.

In simple terms it appears that the practical objective of tribology is to minimize the two main disadvantages of solid to solid contact: friction and wear, but this is not always the case.

In some situations, as illustrated in Figure 1, minimizing friction and maximizing wear or minimizing wear and maximizing friction or maximizing both friction and wear is desirable.

For example, reduction of wear but not friction is desirable in brakes and lubricated clutches.

Reduction of friction but not wear is desirable in pencils.

Increase in both friction and wear is desirable in erasers.

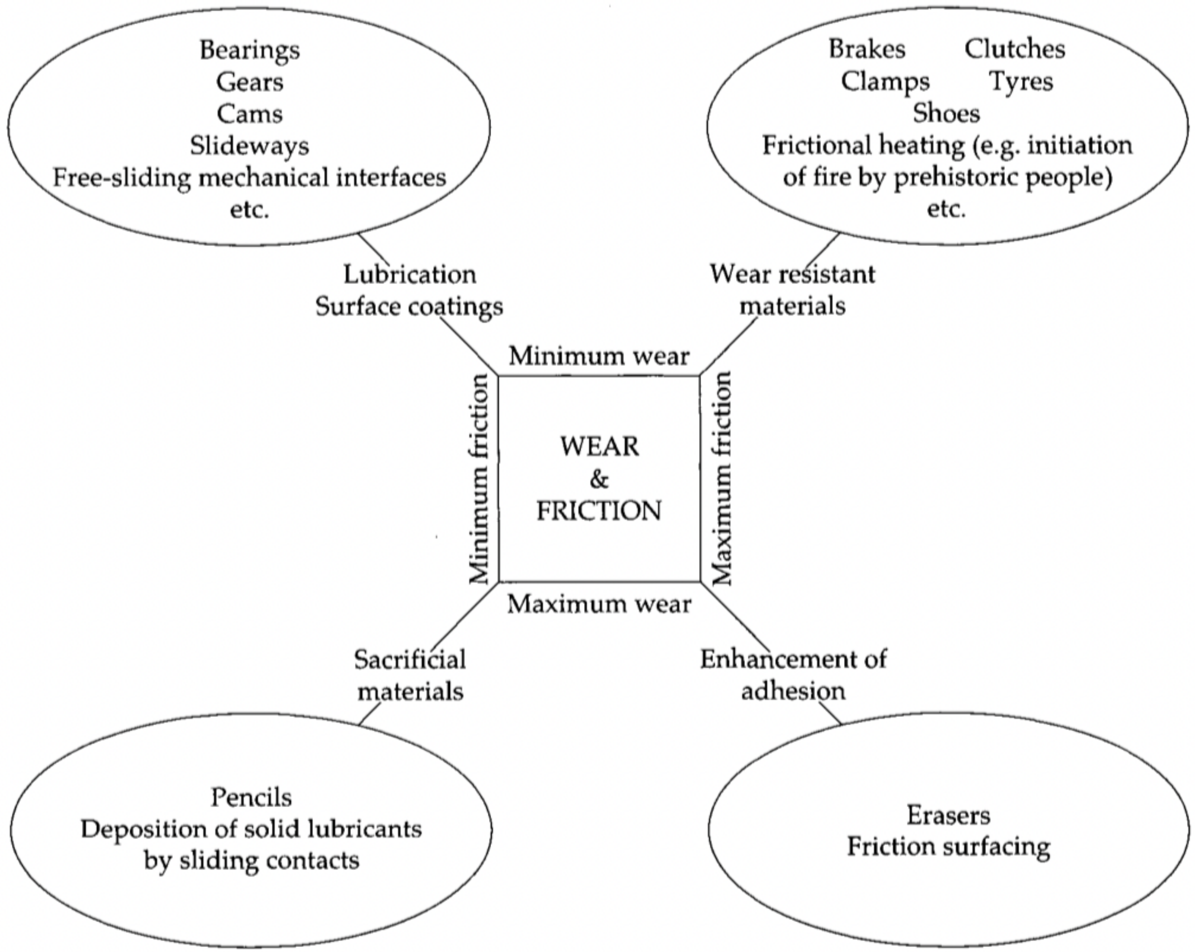


Figure 1: Practical objectives of tribology.

LUBRICATION

Thin low shear strength layers of gas, liquid and solid are interposed between two surfaces in order to improve the smoothness of movement of one surface over another and to prevent damage. These layers of material separate contacting solid bodies and are usually very thin and often difficult to observe.

In general, the thicknesses of these films range from I to 100 micron, although thinner and thicker films can also be found. Knowledge that is related to enhancing or diagnosing the effectiveness of these films in preventing damage in solid contacts is commonly known as 'lubrication'. Although there are no restrictions on the type of material required to form a lubricating film, as gas, liquid and certain solids are all effective, the material type does influence the limits of film effectiveness.

For example, a gaseous film is suitable for low contact stress while solid films are usually applied to slow sliding speed contacts. Detailed analysis of gaseous or liquid films is usually termed "hydrodynamic lubrication" while lubrication by solids is termed "solid lubrication".

A specialized form of hydrodynamic lubrication involving physical interaction between the contacting bodies and the liquid lubricant is termed "elastohydrodynamic lubrication" and is of considerable practical significance.

Another form of lubrication involves the chemical interactions between contacting bodies and the liquid lubricant and is termed "boundary and extreme pressure lubrication".

In the absence of any films, the only reliable means of ensuring relative movement is to maintain, by external force fields, a small distance of separation between the opposing surfaces. This, for example, can be achieved by the application of magnetic forces, which is the operating principle of magnetic levitation or “maglev”.

Magnetic levitation is, however, a highly specialized technology that is still at the experimental stage. A form of lubrication that operates by the same principle, such as, forcible separation of the contacting bodies involving an external energy source, is “hydrostatic lubrication” where liquid or gaseous lubricant is forced into the space between contacting bodies.

Liquid lubrication is a technological nuisance since filters, pumps and cooling systems are required to maintain the performance of the lubricant over a period of time. There are also environmental issues associated with the disposal of the used lubricants. Therefore “solid lubrication” and “surface coatings” are the subject of intense research.

The principal limitations of, in particular, liquid lubricants are the loss of load carrying capacity at high temperature and degradation in service. The performance of the lubricant depends on its composition and its physical and chemical characteristics.

From the practical engineering viewpoint, prediction of lubricating film characteristics is extremely important. Although such predictions are possible there always remains a certain degree of empiricism in the analysis of film characteristics. Prediction methods for liquid or gaseous films involve at the elementary level hydrodynamic, hydrostatic and elastohydrodynamic lubrication. For more sophisticated analyses "computational methods" must be used. There is still, however, no analytical method for determining the limits of solid films.

WEAR

Film failure impairs the relative movement between solid bodies and inevitably causes severe damage to the contacting surfaces. The consequence of film failure is severe wear. Wear in these circumstances is the result of adhesion between contacting bodies and is termed “adhesive wear”.

When the intervening films are partially effective then milder forms of wear occur and these are often initiated by fatigue processes due to repetitive stresses under either sliding or rolling. These milder forms of wear can therefore be termed “fatigue wear”.

On the other hand, if the film material consists of hard particles or merely flows against one body without providing support against another body then a form of wear, which sometimes can be very rapid, known as “abrasive wear” occurs.

Two other associated forms of wear are “erosive wear” (due to impacting particles) and “cavitation wear” which is caused by fast flowing liquids. In some practical situations the film material is formed by chemical attack of either contacting body and while this may provide some lubrication, significant wear is virtually inevitable. This form of wear is known as “corrosive wear” and when atmospheric oxygen is the corroding agent, then “oxidative wear” is said to occur.

When the amplitude of movement between contacting bodies is restricted to, for example, a few micrometres, the film material is trapped within the contact and may eventually become destructive. Under these conditions “fretting wear” may result. There are also many other forms or mechanisms of wear.

Almost any interaction between solid bodies will cause wear. Typical examples are “impact wear” caused by impact between two solids.

“Melting wear” occurring when the contact loads and speeds are sufficiently high to allow for the surface layers of the solid to melt and “diffusive wear” occurring at high interface temperatures. This dependence of wear on various operating conditions can be summarized in a flowchart shown in Figure 2.

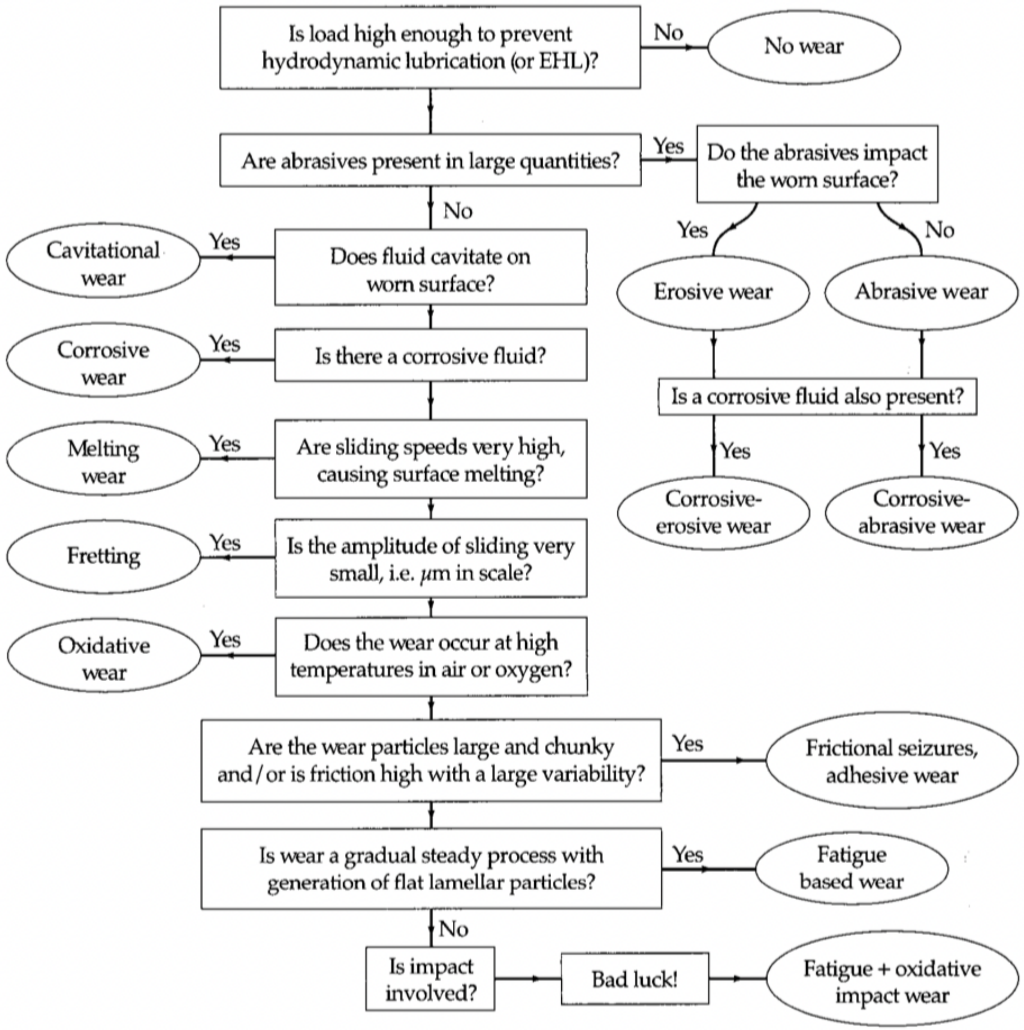


Figure 2: Flowchart illustrating the relationship between operating conditions and type of wear.

HISTORY OF TRIBOLOGY

The ancient period

The period of early civilization (post 3500 BC), saw many advances in the field of tribology including stone sockets, lubricants to reduce friction, and different surface materials to reduce wear. Possible lubricants used were water, mud, and rendered fat from sheep or cows. The picture of transportation of an Egyptian statue to the grave of Tehuti-Hetep, El-Bersheh indicates the concept of lubrication was already used by ancient Egyptians (Figure 4). The picture depicts slaves are dragging a large statue along sand or ground. One man, standing on the sledge supporting the statue, pours a liquid (oil/water) as a lubricant in order to reduce friction between sledge and ground/sand.

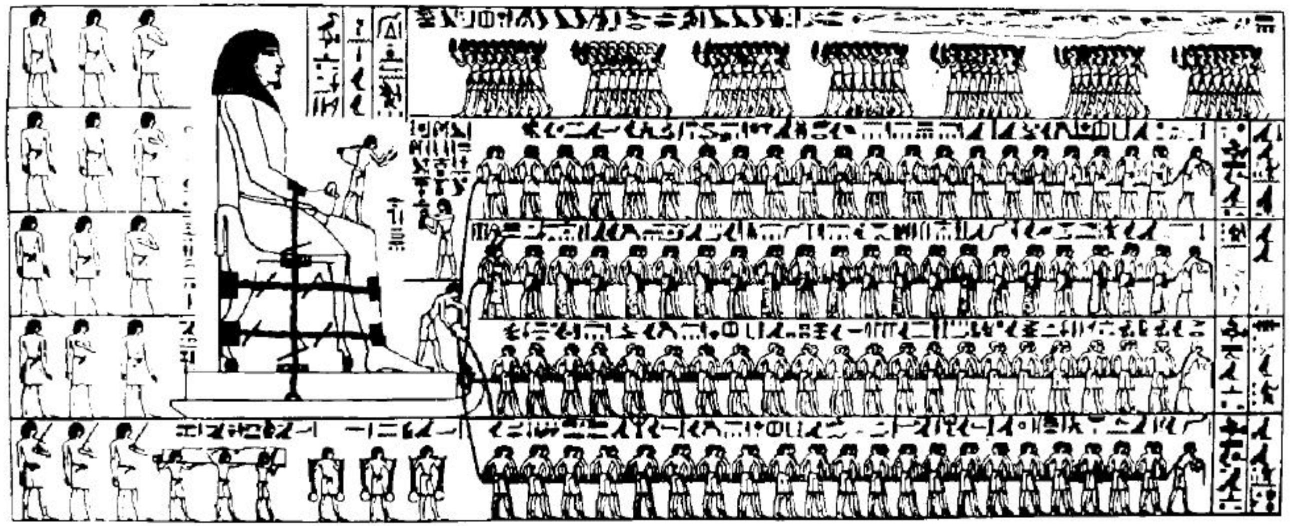


Figure 4: The picture of transportation of an Egyptian statue to the grave of Tehuti-Hetep, El-Bersheh.

The Renaissance

The Renaissance was the Age of Enlightment and saw the amazing talent of various intellectuals, artists, scientists, and writers, including Michelangelo, Raphael, Donatello, Sandro Botticelli, John Milton, and William Shakespeare. Leonardo da Vinci made invaluable contributions to today's science of tribology, although he certainly was not aware of it.

Leonardo Da Vinci was one of the first scholars to study friction systematically. His work on friction originated in studies of the rotational resistance of axles (Figure 5) and the mechanics of screw threads. He focused on all kinds of friction and drew a distinction between sliding and rolling friction.

Leonardo da Vinci understood the important role friction played in the workings of machinery and how friction limited efficiency. His ideas included the thought that friction was the result of the roughness of the material and smoother materials resulted in less friction.

Specifically, da Vinci noted that friction is not dependent of contact area, friction resistance is directly proportional to the applied load, and friction has a constant correlation.

At the end of the period (1493-1500) he was confident about the laws of friction, although the value (1/2, 1/3, ¼ and 1/8) he chose for the coefficient of friction varied considerably.

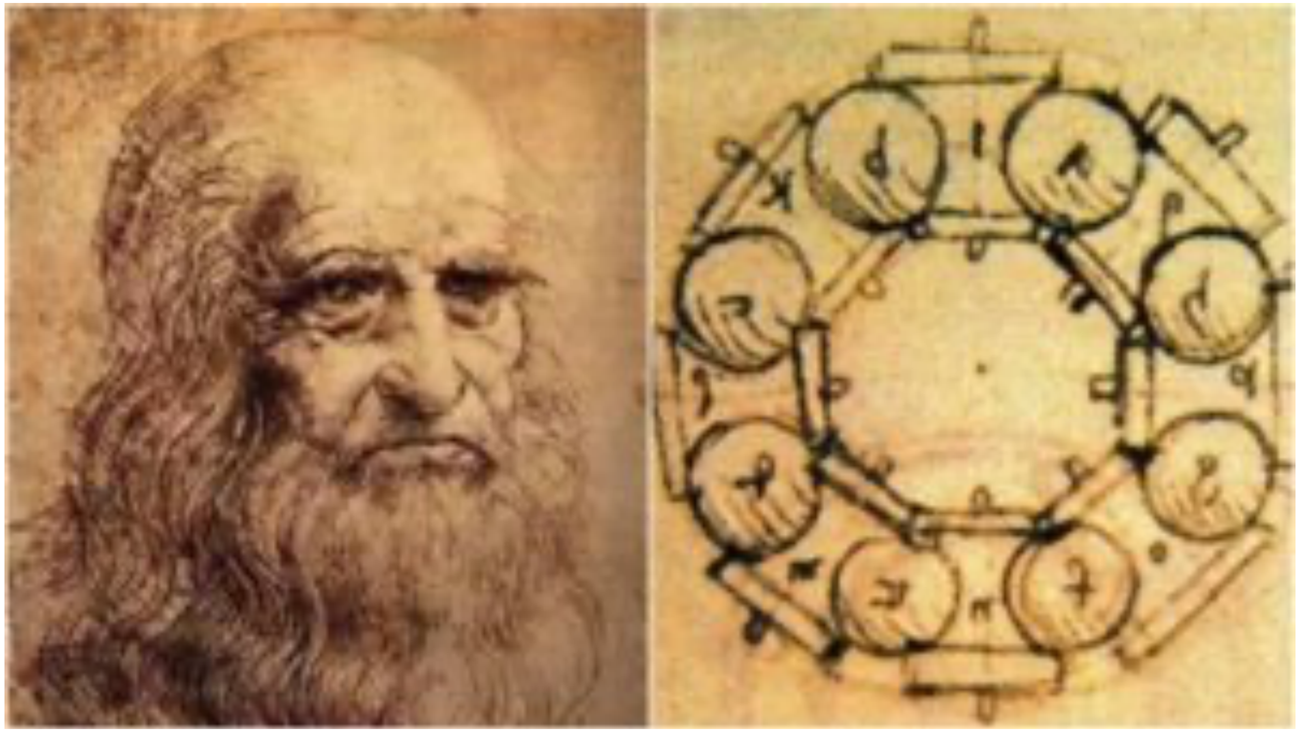


Figure 5: Image of Leonardo Da Vinci and his bearing's design.

Developments in the period prior to the First Industrial Revolution of 1600-1760 was mainly confined to Britain, as Britain did not allow the export of machinery, skilled workers, or manufacturing techniques, as they were aware of their superiority in these areas. The revolution brought about much advancement in the areas of bearings, gearings, lubricant application, and theories regarding friction and wear.

Christian Huygens invented the pendulum clock and patented the pocket watch while Robert Hooke invented the universal joint.

Scientists like Robert Hooke, Isaac Newton, and Leonard Euler advanced theories of friction and viscosity.

The monumental work done by Sir Isaac Newton in his Principia from 1687 laid down the foundations of “viscosity” and was able to bring out the concept of Newtonian and Non-Newtonian Fluids.

John Theophilus Desaguliers (1683-1744) became the first person to propose the adhesion concept of friction. He stated that friction is fundamentally caused by the force it takes to overcome adhesive forces or to breakdown adhesion.

French physicist Guillaume Amontons rediscovered the rules of friction after he studied dry sliding between two flat surfaces. He postulated three laws which is only applicable to dry friction:

1) The force of friction is directly proportional to the applied load. (Amontons' 1st Law) (Figure 6)
2) The force of friction is independent of the apparent area of contact. (Amontons' 2nd Law)
3) Kinetic friction is independent of the sliding velocity. (Coulomb's Law)

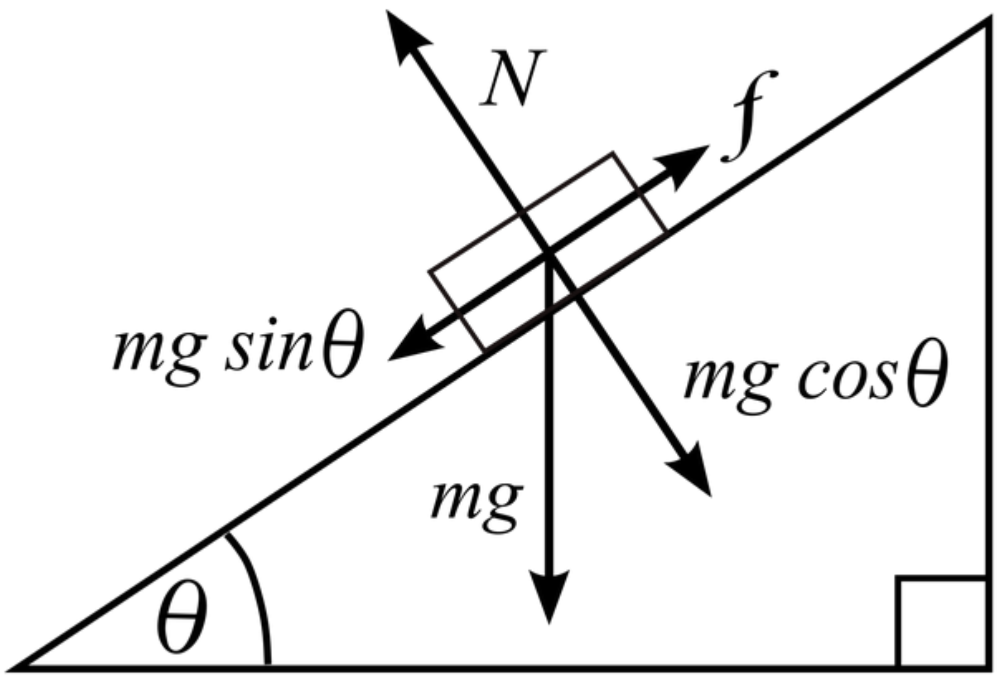


Figure 6: Correlation of friction force (f) and applied load (N).

Charles-Augustin Coulomb (1736-1806) proposed that the frictional resistance of a rolling wheel or cylinder is proportional to the load P, and inversely proportional to the radius of the wheel. Coulomb's description of rolling friction entirely neglected the material compliance.

The Industrial Revolution from 1750 to 1850 saw rural societies in Europe and the United States change into industrialized, urban societies. Goods that were formerly produced by hand were now produced in mass quantities by machines in factories. This was the era of James Watt, a Scottish inventor and mechanical engineer who created the Watt steam engine, which was fundamental to the period and the changes it brought about. John Harrison who was a self-educated English carpenter and clockmaker, invented caged roller bearing as part of his work on chronometers.

Advancements were also made in the field of gearings, journal bearings, and roller bearings. Many patents for lubricants were granted during this time. Lubricants included mixtures of graphite and pig tallow, as well as mixtures of olive oil and lime in water. George Rennie, Charles Hatchett, and George Gabriel Stokes were active scientists during this time, promoting their theories regarding friction, wear, and hydrodynamic theory.

The years of 1850 to 1925 saw amazing improvements in machine elements including the electromotor locomotive and the axle gear drive for the automobile. Vegetable and animal oil lubricants were replaced with distilled and refined lubricants such as compressor oils and refined cylinder oils. The first additives were also invented during this time period. Friction and wear theories saw great advancement by scientists such as Beauchamp Tower, Gustav Adolph Hirn, Osborne Reynolds, and Johannes Wilhelm Sommerfeld.

In 1886 Professor Osborne Reynolds published his famous work – "On the Theory of Lubrication and Its Application to Mr. Beauchamp Tower's Experiments, Including an Experimental Determination of the Viscosity of Olive Oil". In this manuscript, the famous equation of thin fluid film flow in the narrow gap between two solids was formulated. This equation is the basis of the classical lubrication theory.

In 1902 Richard Stribeck was a German scientist and engineer, living from 1861 to 1950, published the Stribeck curve, a plot that related friction with viscosity, speed and load, as shown in Figure 7.

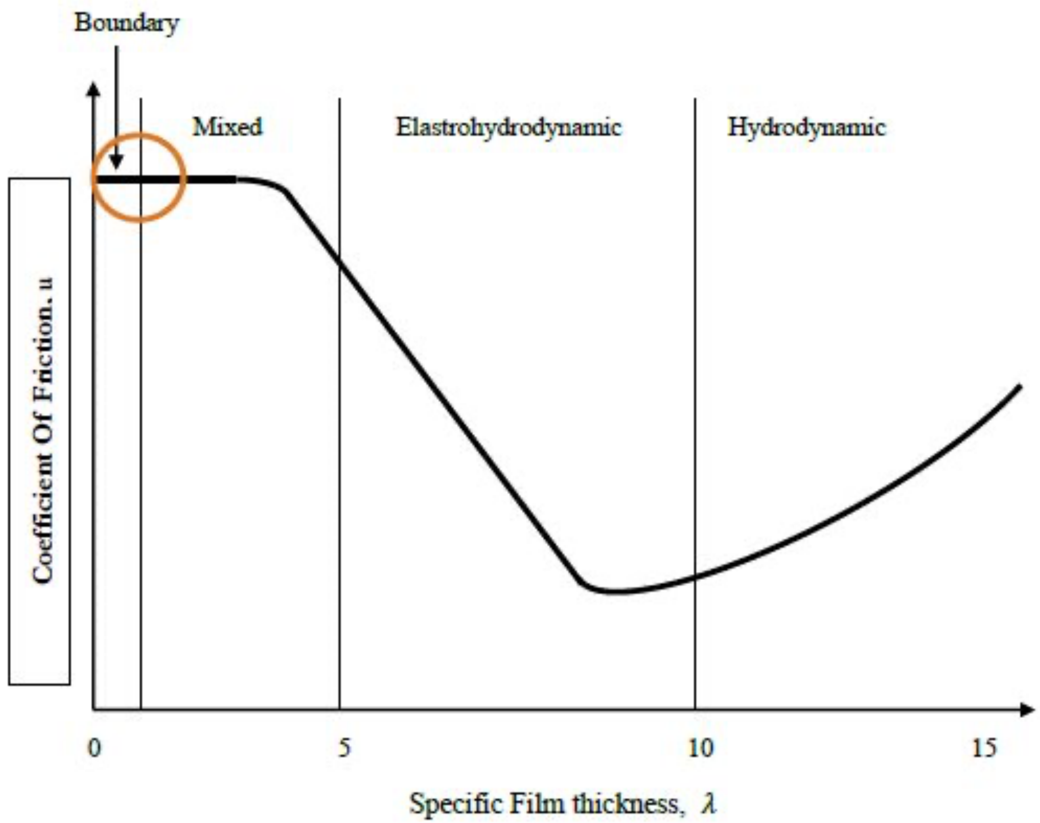


Figure 7: Stribeck curve

In the early 20th century, Philip Bowden and David Tabor gave a physical explanation for the laws of friction. They determined that the true area of contact is a very small percentage of the apparent contact area. The true contact area is formed by the asperities, as shown in Figure 8.

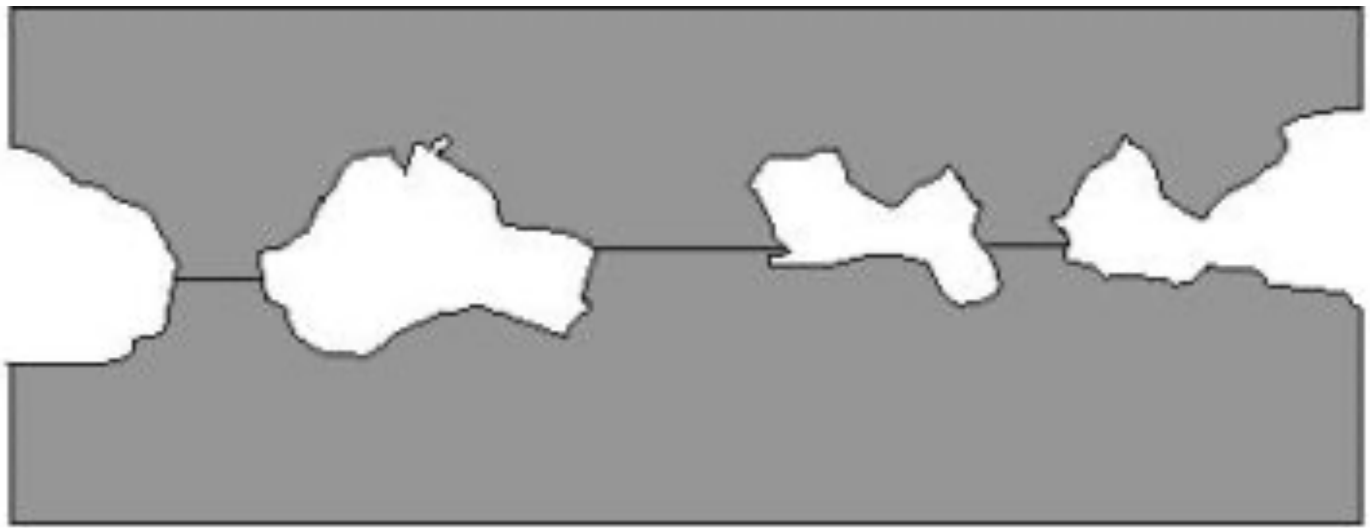


Figure 8: Asperities contacts between two surfaces.

The term tribology was mentioned for the first time in 1966 in the Jost Report, a study commissioned by the British government to investigate damage from wear. The committee headed by Peter Jost, estimated that application of basic principles of tribology could save the UK economy approx. £515 million per annum.

In 1967 a committee of Organization for Economic Co-operation and Development (OECD) formally defined “Tribology” as “the science and technology of interacting surfaces in relative motion and of related subjects and practices,” and it is an engineering field that deals with friction, wear, and lubrication.

THE IMPORTANCE OF TRIBOLOGICAL STUDY

It was estimated by Peter Jost in 1966 that by the application of the basic principles of tribology, the economy of U.K. could save approximately £515 million per annum at 1965 values.

A similar report published in West Germany in 1976 revealed that the economic losses caused by friction and wear cost about 10 billion DM per annum, at 1975 values, which is equivalent to 1% of the Gross National Product. About 50% of these losses were due to abrasive wear.

In the U.S.A., it has been estimated that about 11% of total annual energy can be saved in the four major areas of transportation, turbo machinery, power generation and industrial processes through progress in tribology. For example, tribological improvements in cars alone can save about 18.6% of total annual energy consumed by cars in the U.S.A., which is equivalent to about 14.3 billion US$ per annum.

In the U.K. the possible national energy savings achieved by the application of tribological principles and practices have been estimated to be between £468 to £700 million per annum. The economics of tribology are of such gigantic proportions that tribological programmes have been established by industry and governments in many countries throughout the world.

The problems of tribology economics are of extreme importance to an engineer. For example, in pneumatic transportation of material through pipes, the erosive wear at bends can be up to 50 times more than in straight sections. Apparently non-abrasive materials such as sugar cane and wood chips can actually cause abrasive wear.

Many tribological failures are associated with bearings. Simple bearing failures on modern generator sets in the U.S.A. cost about US$25,000 per day while to replace a £200,000 bearing in a single point mooring on a North Sea Oil Rig a contingency budget of about £1 million is necessary.

In addition there are some production losses which are very costly. The total cost of wear for a single US naval aircraft has been estimated to be US$243 per flight hour.

About 1000 megatonnes of material is excavated in Australia. Much of this is material waste which must be handled in order to retrieve metalliferous ores or coal. The cost of wear is around 2% of the saleable product. The annual production by a large iron ore mining company might be as high as 40 megatonnes involving a direct cost through the replacement of wearing parts of A$6 million per annum at 1977 values.

The analysis of the causes of friction and wear can have direct commercial implications, even in terms of who bears the cost of excessive wear or friction. For example, in one instance of a gas turbine that suffered excessive damage to its first-stage blades, detailed analysis of the cause of wear helped determine whether the owner or the insurance company would pay for the damage.

As soon as the extent of economic losses due to friction and wear became clear, researchers and engineers rejected many of the traditional limitations to mechanical performance and have found or, are looking for new materials and lubricants to overcome these limits.

Some of these improvements are so radical that the whole technology and economics of the product may change. A classic example is the adiabatic engine. The principle behind this development is to remove the oil and the lubricating system and use a dry, high temperature self-lubricating material. If the engine can operate adiabatically at high temperatures, heat previously removed by the now obsolete radiator can be turned to mechanical work. As a result, a fuel efficient, light weight engine might be built which will lead to considerable savings in fuels, oils and vehicle production costs. A fuel efficient engine is vital in reducing transportation and agricultural costs and therefore is a very important research and development task.

New ventures, even if they involve mostly conventional technologies, such as mining and processing of oil sands, can impose arduous conditions on equipment and necessitate new wear-resistant materials. Oil sands slurries are capable of wearing out a high chromium white cast iron pump impeller after only 3 months of service. It is thus necessary to find new, hard yet tough, materials for better wear resistance and extended service life for the equipment.

Other examples of such innovations include surface treated cutters for sheep shearing, surface hardened soil engaging tools, polyethylene pipes for coal slurries and ion implanted titanium alloys for orthopaedic endoprostheses. Whenever wear and friction limit the function or durability of a device or appliance, there is a scope for tribology to offer some improvement.

In general terms, wear can effectively be controlled by selecting materials with a specific properties as illustrated in Table 1.

Table 1: General materials selection guide for wear control.

Critical materials property	Wear mechanism							
	Abrasive	Erosive	Cavitation	Corrosive	Fretting	Adhesive	Melting	Fatigue
Hardness	✓	✓	❍	❍	❍	✓	❍	❍
Toughness	❍	✓	✓	❍	❍	❍	❍	✓
Fatigue resistance	✓	✓	✓	❍	✓	❍	❍	✓
Inertness	❍	❍	❍	✓	✓①	❍	❍	❍
High melting point	❍	❍	❍	❍	❍	✓	✓	❍
Heterogeneous microstructure	✓	❍	❍	✖②	❍	✓	❍	❍
Non-metallic character	❍	❍	❍	✓	❍	✓	❍	❍

✓ Important
❍ Marginal
✖ Unfavourable

① Fretting in air for metals
② Homogeneous microstructure inhibits electrochemical corrosion and, with it, most forms of corrosive wear

The bewildering range of experimental data and theories compiled so far has helped to create an impression that tribology, although undoubtedly important, is somehow mysterious and not readily applicable to engineering problems.

Tribology cannot, however, be ignored as many governments and private studies have consistently concluded that the cost of friction and wear imposes a severe burden on industrialized countries. Part of the difficulty in controlling friction and wear is that the total cost in terms of energy and material wastage is spread over every type of industry.

Although to the average engineer the cost of friction and wear may appear small, when the same costs are totalled for an entire country a very large loss of resources becomes apparent. The widely distributed incidence of tribological problems means that tribology cannot be applied solely by specialists but instead many engineers or technologists should have working knowledge of this subject.

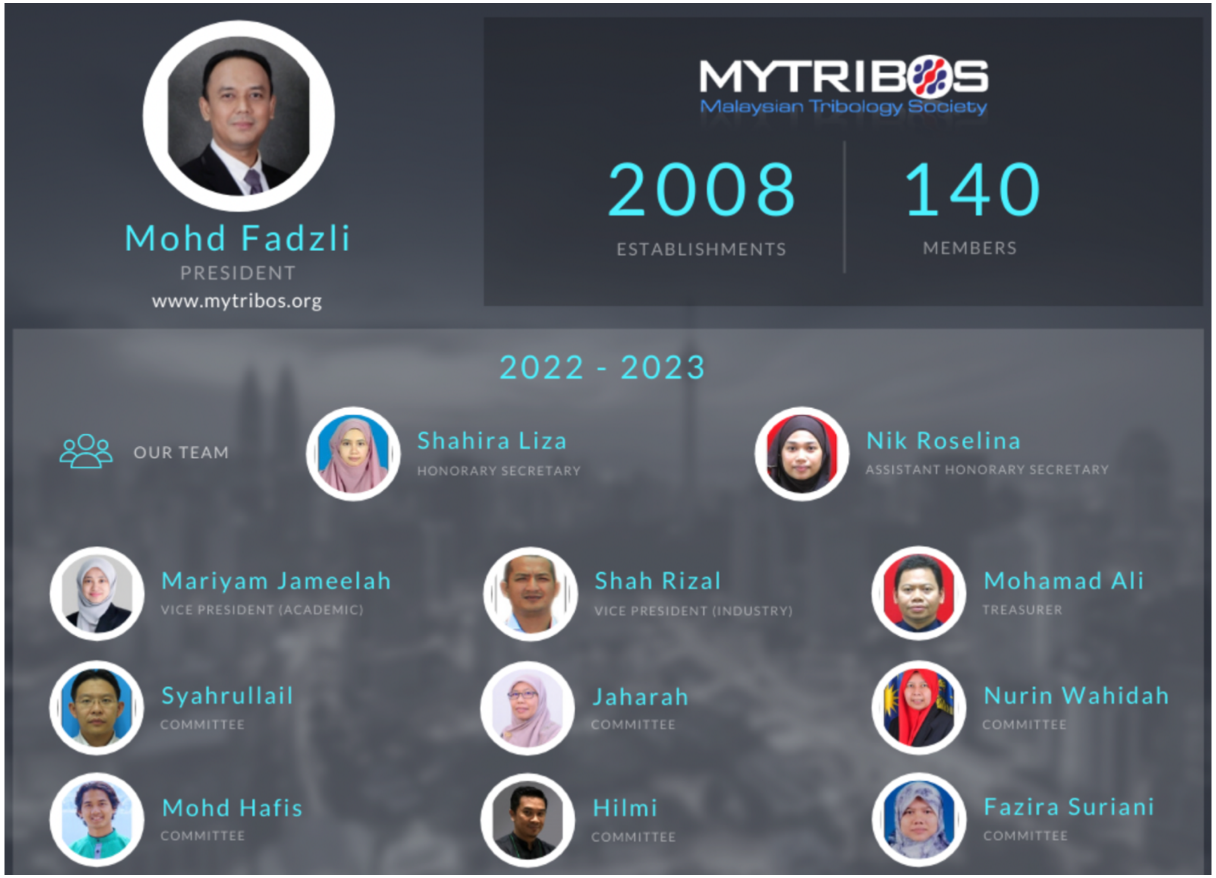
The basic concept of tribology is that friction and wear are best controlled with a thin layer or intervening film of material separating sliding, rolling and impacting bodies. There is almost no restriction on the type of material that can form such a film and some solids, liquids and gases are equally effective.

If no film material is supplied then the process of wear itself may generate a substitute film. The aim of tribology is either to find the optimum film material for a given application or to predict the sequence of events when a sliding/rolling/impacting contact is left to generate its own intervening film.

TRIBOLOGY ACTIVITY IN MALAYSIA

MALAYSIAN TRIBOLOGY SOCIETY (MYTRIBOS)

https://www.mytribos.org/



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DATE	CONFERENCE/SYMPOSIUM/SEMINAR/WORKSHOP	VENUE
September 2024	The 4th Malaysian International Tribology Conference (MITC2024)	Putrajaya
24 August 2023	5th MYTRIBOS International Symposium	Universiti Putra Malaysia
16 August 2022	4th MYTRIBOS International Symposium	Universiti Teknologi MARA, Penang
20 June 2022	3 Minutes Tribo-Talk Talent ($3MT^3$)	Online
05 - 06 July 2021	The 3rd Malaysian International Tribology Conference (MITC202ONE)	Langkawi @ Virtual Platform, Malaysia
05 November 2019	Malaysia-Singapore Research Symposium 2019	National University of Singapore
29 April 2019	3rd MYTRIBOS Symposium	Universiti Malaysia Perlis
17 - 20 September 2018	The 6th Asia International Conference on Tribology (ASIATRIB2018)	Sarawak, Malaysia
16 -19 October 2017	MYTRIBOS Special International Symposium on Energy Aspects of Tribology for Sustainable Development	Melaka, Malaysia
04 October 2017	2nd MYTRIBOS Symposium	Universiti Teknologi Malaysia
28 August 2017	2nd Tribology Poster Competition	Malaysia-Japan International Istitute of Technology
28 - 30 August 2016	APSIM2016: Special Session on the 50th Anniversary of Tribology - Sustainable Manufacturing	Kuala Lumpur, Malaysia
01 June 2016	Tribology Poster Competition	Universiti Malaya
04 February 2016	Malaysia-Japan International Symposium on Tribology Technology 2016 - Part II	Melaka, Malaysia
02 February 2016	Malaysia-Japan International Symposium on Tribology Technology 2016 - Part I	Kuala Lumpur, Malaysia
26 January 2016	1st MYTRIBOS Colloquium for Postgraduates (MTCPG2016)	Universiti Sains Malaysia
16 - 17 November 2015	Malaysian International Tribology Conference 2015 (MITC2015)	Penang, Malaysia
18 - 20 November 2013	Malaysian International Tribology Conference 2013 (MITC2013)	Sabah, Malaysia
22 - 24 November 2011	Regional Tribology Conference 2011 (RTC2011)	Langkawi, Malaysia
04 - 05 May 2009	National Tribology Conference 2009 (NTC2009)	Kuala Lumpur, Malaysia