Introduction to Tribology

The science of *Tribology* (Greek *tribos*: *rubbing*) concentrates on ***contact mechanics of moving interfaces*** that generally involve energy dissipation. It encompasses the science fields of ***Adhesion, Friction, Lubrication*** and ***Wear***.

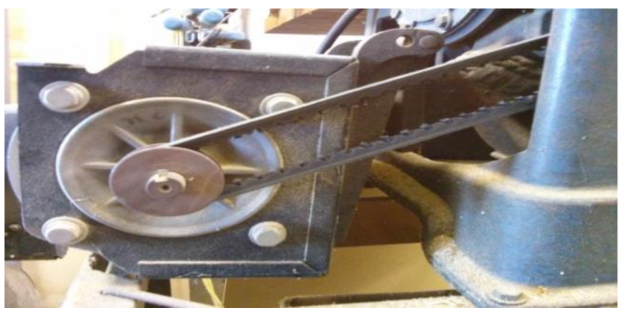
Why is Tribology Important?

Traditional Applications

Tribology is the study of surfaces moving relative to one another, a phenomenon that affects our lives in a multitude of ways every day. The term tribology is based on the Greek word for rubbing and, although the term itself was not coined until 1964, there are images of tribology in action from as long ago as ancient Egypt, when early tribologists used oil to help facilitate sliding of large statues. Generally, tribology includes three key topics: friction, wear and lubrication. Friction is the resistance to relative motion, wear is the loss of material due to that motion, and lubrication is the use of a fluid (or in some cases a solid) to minimize friction and wear. The field is necessarily interdisciplinary and utilizes skills from mechanical engineering, materials science and engineering, chemistry and chemical engineering and more. Tribology is both technologically-relevant and scientifically-fascinating, and it's definitely an exciting time to be a tribologist!

Most mechanical components have one or more moving parts. This means that something is moving relative to something else, so there is tribology happening. In some components, such as bearings and gears, the goal is to minimize the resistance to sliding or rolling so that as little energy as possible is lost to friction. In other components, such as brakes and clutches, we want maximum sliding resistance in order to limit the relative motions.

There are also many manufacturing processes that rely on tribology, such as rolling, turning, stamping, grinding and polishing. Further, most transportation methods depend on tribology, not only within the mechanical components that drive them, but also at the contact between the wheels and the surfaces on which they slide or roll. There are also examples of tribology in construction and exploration equipment such as excavators, oil rigs, mine slurry pumps and tunnel digging drills. The processes of friction and wear, and the use of lubricants to control friction and wear are ubiquitous in a variety of industries.



Everyday Examples of Tribology

In addition to the more traditional applications of tribology, there are many more devices and other products that we use regularly whose functions rely on tribology. They include products and processes that arise in healthcare, sports, nature and more. In some cases we want to maximum the friction (such as on the soles of our shoes) and in others we want to minimize friction (such as on the bottom of a bobsled).

There are many examples of tribology and tribology-enabled function in the world of sports. For example, the bottoms of athletic shoes are fine-tuned to provide just the right amount of resistance to sliding for a given sport. Also, footballs and balls for other sports have to be designed to be grip-able, but not too sticky. There are many examples in sports equipment where tribology can be the difference between winning or not. Common examples in winter sports include snow skis, bobsleds and curling stones.

There are also many natural processes where tribology is relevant. Some of these processes occur on very large length scales. For example, earthquakes occur when friction builds up over time until the earth cannot withstand the force and there is a shift, and erosion due to water or wind is the process of the earth wearing away over time. Other tribological phenomena occur on much smaller scales. For example, the feet of geckos have evolved to enable them to preferentially stick to surfaces (or not) so that they can effectively walk on walls. Also, scales on snakes provide the specialized contact with the ground that they need to move along both quickly and quietly. Nature has found many innovative solutions to tribological challenges.

Lastly, there are many other examples of tribology in fields as varied as music - for example drawing a bow across violin strings to play notes - and cosmetics - where significant resources are invested to make skin or hair products that have the right feel. Pretty much everywhere we turn there is another example of tribology!

Role of Tribology in Energy Efficiency

Tribology is particularly important in today's world because so much energy is lost to friction in mechanical components. To use less energy, we need to minimize the amount that is wasted. Significant energy is lost due to friction in sliding interfaces. Therefore, finding ways to minimize friction and wear through new technologies in tribology is critical to a greener and more sustainable world.

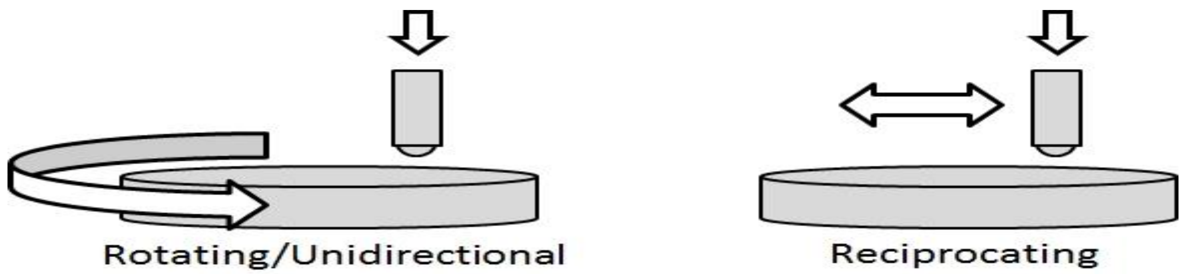
Global energy consumption is expected to grow in upcoming years, straining both resources and the environment. At the same time, a huge amount of energy is lost to friction: for example, seven quads of energy are wasted annually due to friction in passenger cars globally. Further waste occurs due to wear of contacting materials, as the energy required to replace parts is substantial, and the economic, environmental, and safety costs of wear-induced failures can be extensive. Moreover, many of the challenges facing new energy-efficient technologies - such as wind turbines - are tribological in nature. Therefore, tribology is critically important to addressing some of the world's key issues related to energy efficiency and the economic and societal implications of energy usage.

Friction

Friction is, by definition, the resistance to motion. The magnitude of this resistance is a function of the materials, geometries and surface features of the bodies in contact, as well as the operating conditions and environment. It is often desirable to minimize friction to order to maximize the efficiency of a component or process. Generally speaking, friction increases with load and surface roughness and can be decreased by the use of a lubricant.

Friction is the tangential resistance to motion between two contacting solid bodies. In 1699, Amontons proposed two "laws" of friction: (1) friction force is independent of nominal (or apparent) contact area between the two bodies, and (2) friction force is directly proportional to the surface-normal component of load. The second of these two laws gives us the equation $F = \mu W$, where F is the friction force, W is the load and μ is the friction coefficient. To understand this relationship, consider the inclined plane experiment shown in the figure on the left below. As the plane is gradually tilted up and the incline angle Θ is increased, the component of the force due to the weight of the block in the direction of sliding increases. The friction coefficient, which is the ratio of the friction force F to the normal force W, is simply equal to tan ϴ. Also, the magnitude of the friction before sliding begins is always greater than that during sliding. This difference is illustrated in the figure on the right below, where the pre-sliding friction is called the static friction and the friction after sliding begins is called the kinetic friction.

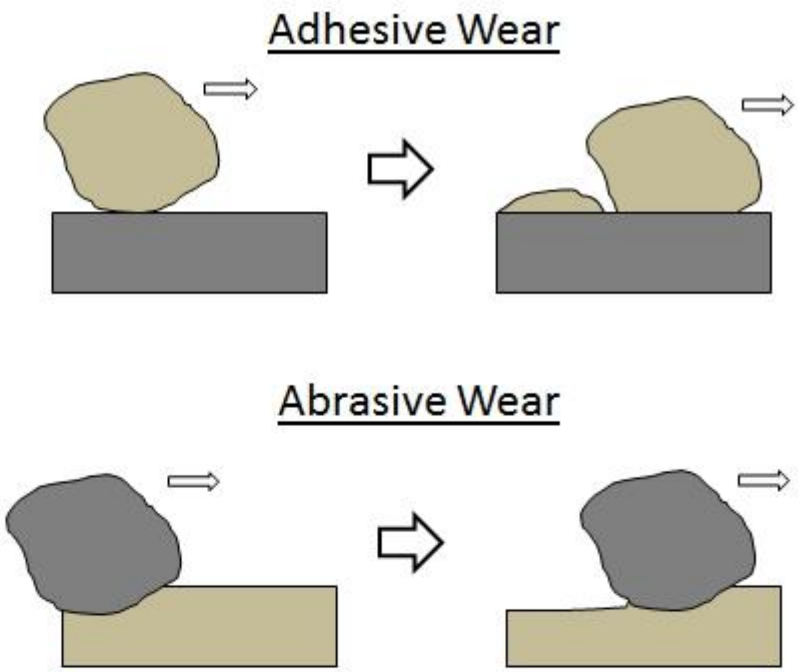
In reality, friction is not just a function of load and angle, but is also a complex function of the material and surface properties of the two contacting bodies. Friction is measured using an instrument called a tribometer, where the lateral force (friction) and normal force (load) are measured while one body moves relative to another. Most tribometers measure friction either during reciprocating or unidirectional motion. As illustrated in the figure below, reciprocating motion occurs when one body is slide back and forth over another and unidirectional motion occurs when one body travels through a circular path on the other.



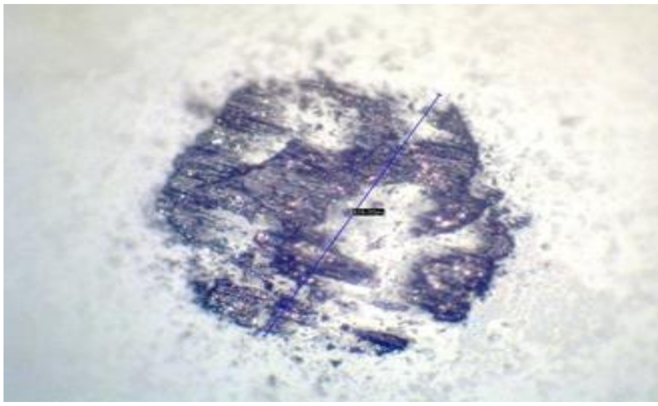
Wear

Wear is the loss of materials, usually due to sliding. Typically wear is undesirable as it can lead to increased friction and ultimately to component failure. Like friction, wear is typically minimized by using a lubricant to separate the two bodies so that they do not directly touch one another.

The two most common types of wear are abrasive, in which a harder material removes material from a softer one, and adhesive, in which two bodies adhere to one another locally, so that material is transferred from one to the other. These two wear modes are illustrated below. In adhesive wear, the two sliding surfaces, or features on those surfaces, called asperties, temporarily form junctions between the two materials. Then, as sliding continues, those junctions have to be broken. If a junction is weak enough, shear will occur at the original interface between the two bodies and there will be negligible wear. However, if a junction is stronger than one of the two materials, then shear may occur within the material, resulting in adhesive wear. Abrasive wear occurs when a harder material ploughs into a softer surface, removing material from it. This mode of wear tends to be more severe than adhesive wear in most cases. In abrasive wear, if ploughing is done by an asperity on the harder material, the process is called two-body wear; if ploughing occurs through contact with a wear particle or debris, then the process is called three-body wear.



The amount of wear can be measured in several different ways, most of which involve measurement of either mass change or the size of a worn region. The latter is more common since it can be applied for any case where there is a worn region (wear scar) that is large enough to measure. Wear scar size can be measured using an optical image, such as that shown below, or using profilometry. In the case of an optical image, parameters such as the wear depth or wear volume must be calculated using a measured wear scar dimension and the known geometry of the contacting body. A profilometer can give a direct measurement of both the in-plane dimensions and depth of the wear scar. Wear can be reported simply as a volume or as one of the in-plane dimensions of the wear scar, such as the wear depth shown in the example below. In this example, the wear increases with number of cycles, as expected, and one of the samples exhibits more wear resistance than the other.

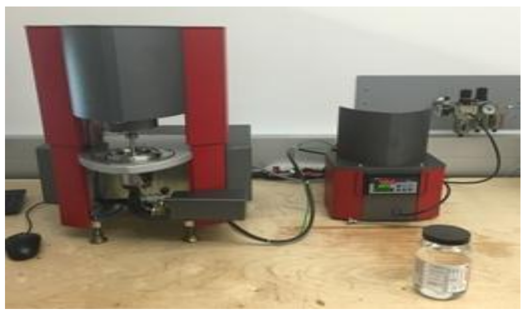


Wear is typically quantified using what is called a wear rate, which is how fast material is removed from the surface. Although several different units for wear rate are acceptable, a common unit is volume, V, per distance, d. In this form, the wear rate (V/d) can be described by Archard's wear law: V/d = K W / H, where W is the load, H is material hardness and K is a material-specific wear coefficient. This expression states that, as expected, there will be more wear at higher loads and on softer materials. To facilitate comparison between tests performed at different loads, the wear rate is often normalized by the load such that wear is reported in units of volume per distance per load. The other term in Archard's wear law is the wear coefficient. There is much discussion about this coefficient since its value varies by orders of magnitude and is highly dependent on materials, surface features as well as operating and environment conditions. However, generally speaking, the trends predicted by the simple Archard wear equation have been found to describe experimental observations well in many cases.

In addition to adhesion and abrasion, another common wear mode in mechanical components is surface fatigue. Fatigue is, as the name implies, a process that occurs after many sliding cycles. It is common in components that have rolling elements where subsurface stresses lead to cracks within the material. These cracks grow towards the surface over time, eventually resulting in worn material, a process known as pitting. Other modes of wear that can occur in some components and under some conditions are impact by erosion or percussion, chemical wear (such as corrosion), and electrical-arc-induced wear.

Lubricants and Lubrication

Lubricants are primarily used to separate two sliding surfaces to minimize friction and wear. They also perform other functions, such as carrying heat and contaminants away from the interface. Lubricants are often liquids, typically consisting of oil and added chemicals, called additives, which help the oils better perform specific functions. However, there are some applications where lubricants can be gases or even solids. The basic premise of liquid lubrication is that, although there is resistance to shear within the fluid due to its viscosity, that viscous resistance is much smaller than the frictional resistance during dry sliding. The performance of a lubricated contact is therefore largely determined by viscosity. Viscosity is a fluid's resistance to flow and is the ratio of shear stress to shear strain rate. A fluid in which viscosity is a constant, i.e. there is a linear relationship between stress and strain rate, is called Newtonian. However, in reality, many lubricants experience changes in viscosity due to temperature, pressure and shear rate during operating, and so behave as non-Newtonian fluids under some conditions. Controlling these variations is important because viscosity plays a key role in determining lubricant film thickness. A very small viscosity will result in a film that is too thin to prevent surface asperities from coming into contact, while a very large viscosity will result in sufficient surface separation, but may also lead to unacceptably high viscous friction. In general, we want to use the least viscous fluid that results in complete surface separation. Viscosity is measured using an instrument called a rheometer as shown below.



Although the friction in lubricated interfaces is typically less than that without a lubricant, there is still friction, and the magnitude of that friction depends on the fluid viscosity and operating conditions. The effects of relative speed, load and viscosity on friction are described by the Stribeck curve. This curve identifies three key lubrication regimes: boundary, mixed and full film. At low speed, low viscosity, or high load, the fluid cannot support the load and there is direct surface-surface contact. This is called boundary lubrication, where only lubricant molecules adsorbed on the surface provide any friction reduction, and the friction is relatively high under any conditions. At high speed, high viscosity, or low load, the fluid completely separates the two surfaces. This is called the full film or hydrodynamic lubrication regime. In this regime, friction increases with speed, viscosity and the inverse of load because those conditions result in more viscous resistance to shear. Between boundary and full film lubrication, there is a regime called mixed lubrication where some parts of the interface are separated by fluid and others are not. Various components operate in one or more of the lubrication regimes during operation.

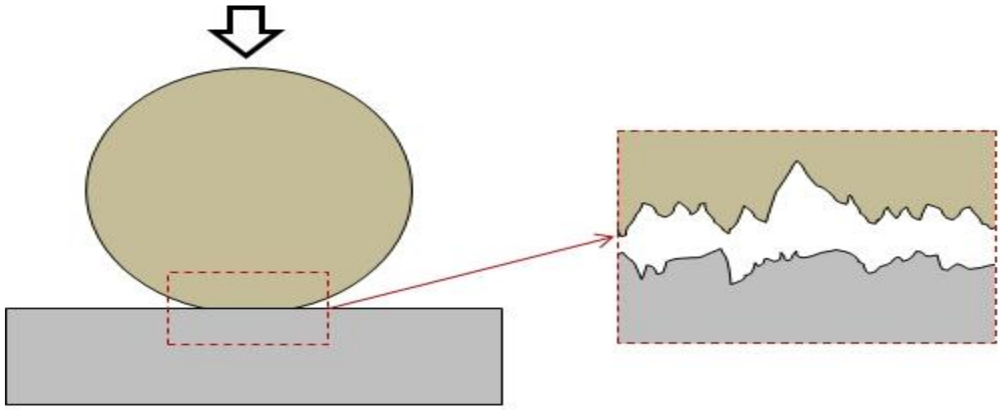
Lubricants are formulated to meet the demands of a wide variety of applications. Formulations begin with one or more mineral or synthetic base oils. Base oils can be derived from several sources, including crude oil, natural gas, and plants or animals, where the source of the base oil will determine many of the formulated fluid's final properties. Most base oils are fortified with chemical additives to enable optimum performance. Additives may be dissolved or suspended in the fluid and typically comprise between 0.1 and 30 percent of the total oil volume. There are additives to perform a variety of functions, including minimizing the variation of viscosity with operating conditions, minimizing boundary friction, increasing chemical stability, and controlling contamination.

Liquid lubricants are extremely effective and are certainly the most widely used types of lubrication. However, there are some conditions or components where liquids are not an option. In some cases, particularly those where light weight is important and the loads are low, an interface can be lubricated by a gas. For example, in air bearings, a thin film of pressurized air can provide a low-friction, load-bearing interface. Another alternative is using solids as a lubricant. Solid lubricants are typically materials that provide low friction because there is little resistance to shear within the materials themselves. For example, materials such as graphite or molybdenum disulfide are layered and so can accommodate shear between their atomic layers. Other solid lubricants are based on soft materials, such as noble metals, whose inherent resistance to shear stress is low. Although solid lubricants are not viable in some cases, the number and variety of applications that might use them, either instead of or in addition to a liquid, is growing rapidly due to recent advancements in materials tribology.

Other Topics in Tribology

There are several topics that are integrally related to the core areas of friction, wear and lubrication, but that deserve their own description. These are surface roughness, contact mechanics and nanotribology. Each topic will be briefly introduced here.

The behavior of sliding interfaces can be significantly affected by the roughness of the surfaces of the two bodies. Surface roughness is typically measured using profilometry and is often reported as the root-mean-square value of the height of the surface features, or asperities. Other parameters that describe surface roughness are the average of the surface heights and the skewness and kurtosis of the distribution of surface heights. The effect of roughness on friction and wear is dependent on the type of sliding. For example, larger roughness will increase friction and wear in an interface that is dominated by abrasion while it may decrease friction and wear in an adhesive interface. Regardless, roughness is a key property of any sliding interface.



Another property of contacting bodies that can affect sliding is elastic deformation. Many tribological interfaces are subject to very high loads and, more importantly, high pressures. In these cases, the bodies themselves deform elastically, which can facilitate sliding in a lubricated interface. This situation is called elasto-hydrodynamic lubrication, since the film thickness is due to both the elastic deformation of the bodies and the hydrodynamic flow of the fluid. Elastic deformation is described by classical contact mechanics, typically Hertz contact theory, which enables us to predict the amount of deformation for a given geometry, elasticity and load.

An emerging field within tribology is friction, wear and lubrication at the nanoscale, called nanotribology. Nanotribology is relevant to a variety of novel small-scale devices as well as characterization tools, all of which rely on the nanoscale contact between two materials to function. Nanotribology is also scientifically fascinating because some of the "laws" that we use to describe larger-scale tribological phenomena no longer apply at the nanoscale. A significant amount of research in this area is performed using an atomic force microscope, where an extremely sharp probe interacts with a surface. The contact between the probe and surface is only nanometers in size. Such contacts have been found to exhibit unique and sometimes counter-intuitive behavior, and understanding that behavior is the focus of many exciting research projects currently underway.

REVIEW QUESTIONS

1. Define Tribology
2. Why is tribology important?
3. Briefly explain the following terms: (i) Friction (ii) Wear (iii) Lubrication (iv) Lubricant
4. State the functions of the following: (i) Tribometer (ii) Profilometry (iii) Rheometer
5. Differentiate between adhesive wear and abrasive wear.
6. What is nanotribology?