Chapter 1 Introduction

This chapter furnishes a brief introduction about the tribology and related domains including friction, wear, and lubrication. Further the chapter highlights lubricant types and its classifications. The benefits of using vegetable-based lubricant are also discussed with brief introduction of lubricant additives.

1.1. Tribology

"It is the science and technology of interacting surfaces in relative motion and the associated practices." The term includes the subjects of friction, lubrication, and wear. The tribology is interdisciplinary in nature, which includes mechanics, physics, chemistry, thermodynamics, heat transfer, materials, and metallurgy of interacting surfaces. Figure 1.1 shows brief classifications of tribology.

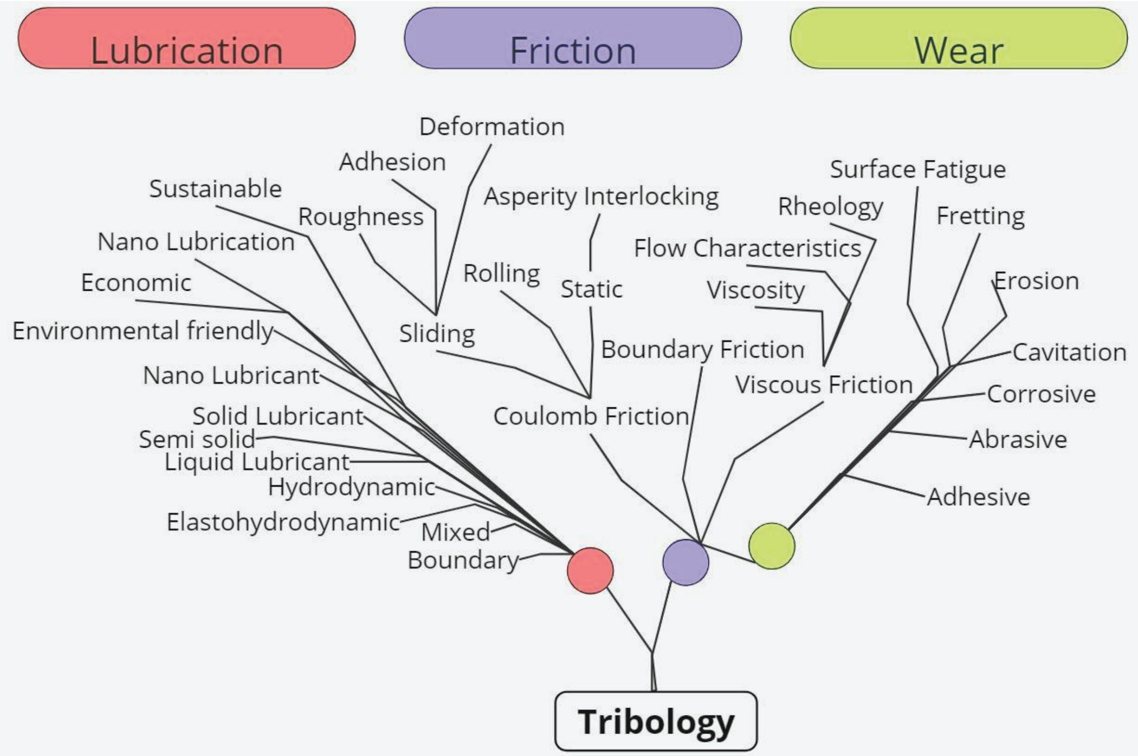


Figure 1.1 Tribology and its constituent areas

Knowledge of tribology helps to design efficient products with reliable performance, reduced friction, improved energy efficiency, and minimized wear and tear. It leads to cost savings through lower maintenance and operational efficiency, enhances safety, and fosters innovation in materials and system design for various industrial applications.

1.1.1. Friction

Friction is the force of resistance by interacting surfaces to restrict the relative motion. Friction can arise from a variety of factors, including surface deformation, adhesion, capillary forces, van der Waals forces, chemical interactions, and so on. Friction is a non-conservative force, and any energy expended to resist it, is a lost. Friction losses lower the energy efficiency of mechanical devices and machineries. According to a recent analysis on energy consumption owing to frictional losses in passenger automobiles, just 21.5% of potential fuel energy is used to propel the car, with direct frictional losses accounting for 33% (28% if breaking is removed). Within these losses, 35% is used to overcome tire-road friction, 35% to overcome engine friction, 15% for gearbox, and 15% for brake contact friction [1].

The two basic laws of friction were given by Guillaume Amontons in 1699 and further extended these laws as more studies conducted on the topic. A Swiss mathematician Leonhard Euler suggested friction arises due to interlocking of asperity and assumed triangular asperity. He first uses the ratio of tangential to normal load, which is now well known as coefficient of friction. The friction is a system property which includes interacting pairs and its surrounding environment (e.g. air, moisture, liquid oil, contaminations). It can be categorized into dry/Coulomb and fluid film friction. Boundary friction is the combination of these two frictions where the interaction between solids is prominent along with the interaction of fluid films.

1.1.2. Wear

Wear is a gradual removal or progressive damage of the surface of the interacting materials/structural bodies. The frictional resistance to the motion of interacting surface causes surface damage. The economic consequences of wear are significant across various industries due to the degradation and failure of components, necessitating frequent repairs and maintenance. Wear impacts industries in numerous ways, including operational downtime, replacement costs, reduced product quality, compromised reliability, safety issues, and decreased service life. Depending upon the nature of wear it can be classified as adhesive, abrasive, erosive, corrosive or chemical/oxidative, fatigue, fretting, and cavitation. According to the Archard wear equation the wear volume per unit sliding distance is proportional to load and inversely proportional to hardness of the material. The hardness of the softer material is considered for distinct mating pair as the softer material shows higher wear. Efforts must be made to reduce friction and wear, minimizing economic losses.

1.1.3. Lubrication

Lubrication is a thin layer of low-shear-strength material that reduces friction and wear between interacting surfaces. These layers separate the solid bodies in contact, are typically very thin, and are often hard to detect. The knowledge related to the effective film formation and preventing damage is known as lubrication. One third of the total energy is lost to overcoming friction worldwide [2–4]. A proper lubrication is required to reduce machine break-down and maintenance costs. Based on the film formation, the lubrication can be classified as follows:

Boundary Lubrication – film thickness is lowest, high friction, severe asperity interaction, and it requires the study of chemical and molecular interactions between contacting bodies.

Mixed Lubrication – film thickness more than boundary lubrication, intermittent asperity interactions.

Elastohydrodynamic Lubrication – film separates interacting bodies with asperities elastically deformed, most effective lubrication with lowest friction and minimal wear.

Hydrodynamic Lubrication – Film thickness highest, all load shared by lubricant film, completely separated bodies.

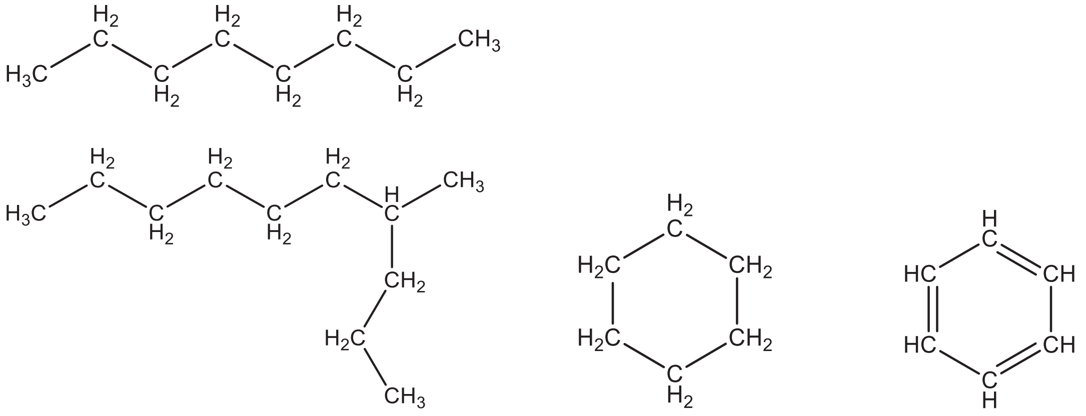
Based upon physical state the lubricants can be classified into four categories:

- Solid: Graphite, molybdenum disulphide, *h*-boron nitride, poly tetrafluoroethylene, polymers, etc.
- Semi Solid: Grease, wax, fats, etc.
- Gas: Argon, carbon dioxide, nitrogen, steam, etc.
- Liquid: Mineral oils, synthetic oils, vegetable oils, water, polymers, etc.

1.2. Classification of liquid lubricants

Liquid lubricants are applied at high speed and high load condition. This study is focussed on liquid lubricants mainly oils, which can also be classified on the basis of their origin:

- Mineral oils – based on type of carbon chain it can be paraffinic, naphthenic, and aromatic (Figure 1.2).
- Synthetic oils – Polyalphaolyfins (PAO), polyalkylene glycols (PAG), silicone, esters, etc.
- Biological oils – derived from plant or animal fats. These are found in the form of triglyceride of fatty acids (Figure 1.3).



(a) Paraffin straight and branched structure (b) Naphthenic structure. (c) Aromatic structure

Figure 2.2(a),(b) and (c) shows different hydrocarbon structure of Base Oil

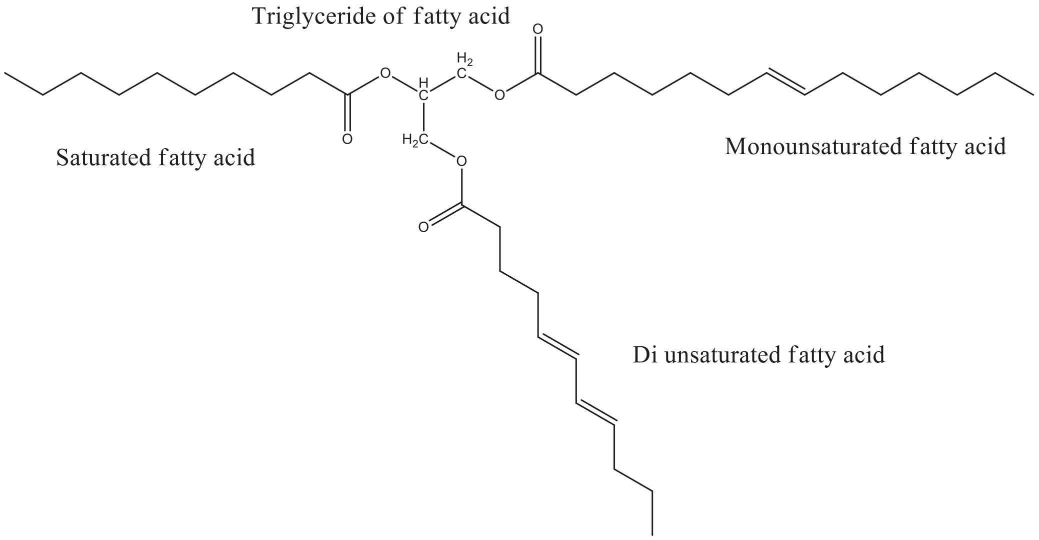


Figure 2.3 Constituent structure of vegetable oils

Mineral oil, derived from petroleum, is commonly used as a lubricant. It is valued for its stability and resistance to oxidation, making it ideal for industrial applications. Synthetic oil, on the other hand, is a chemically engineered lubricant designed for superior performance. It offers enhanced stability, reduced wear, and better performance in extreme temperatures, making it popular in automotive engines and high-performance machinery. Vegetable oil is natural oil extracted from animal fats and plants' seeds and fruits. Unlike mineral and synthetic oils, vegetable oil is biodegradable and renewable, offering a sustainable alternative. In the present thesis work, we are mainly focusing on the vegetable oil-based lubricants.

1.3. Benefits of vegetable-based lube oils

The increasing interest towards sustainability has propelled the potential use of vegetable oils as lubricants due to their environmental benefits, biodegradability, and performance characteristics. Here are the key benefits of vegetable oils-based lubricants:

- Biodegradability: Vegetable oils are highly biodegradable compared to petroleum-based oils, making them environmentally friendly. The vegetable oils are biodegradable 70 to 100% within 28 days [5]. This reduces the risk of water and soil pollution and ensures that they do not harm the environment, unlike mineral oils.
- Renewable: Vegetable oils are derived from agricultural renewable sources, these crops act as renewable resources because they can be replanted and cultivated in a continuous cycle, unlike finite fossil fuels. Additionally, their production supports agricultural industries and helps in reducing the carbon footprint, as plants absorb carbon dioxide during growth.
- Excellent Lubrication Properties: The major component of the vegetable oils is triglycerides of fatty acids. Fatty acids are known for their good boundary lubrication properties to make the lubricious thin film [6]. Due to their strong affinity towards the metal surface the film formed by such lubricants are protective and strong.

- Compatibility with additives: The vegetable oils are compatible with several polar additives to improve the lubricants properties. These compatible additives impart in improvement of oxidation stability, dispersant, extreme pressure resistance, etc.

The quality of vegetable oils varies significantly due to environmental factors, soil fertility, and weather conditions specific to different regions. To maintain homogeneity and ensure consistency, oils are often sourced from a single location. By enhancing their properties with additives, the performance of these base lubricants can be significantly improved.

1.4. Role of additives

Additives are the substances added in small portion to improve characteristics of base lubricant. One of the most promising advancements in this area is the use of nano lubricants, which are currently a focus of extensive research. These nano lubricants come in various forms, including metal, metal oxide, carbon-based, ceramic, polymeric, and composite nanoparticles, offering a wide range of options to tailor the lubricant properties for specific applications. These additives improve lubrication properties by playing roles as follows:

1. Antiwear Agents

Antiwear additives play a crucial role in forming a protective film on metal surfaces, thereby minimizing direct contact between interacting surfaces. This protective layer reduces the risk of abrasive and adhesive wear, especially in conditions involving high load and continuous motion. By maintaining the integrity of the contact surfaces, these additives extend the lifespan of machinery and components, ensuring optimal performance and durability.

2. Corrosion Inhibitors

Corrosion inhibitors protect metal surfaces from chemical degradation caused by exposure to moisture, oxygen, or other corrosive agents. These additives form a stable, nanostructured protective film over the metal surface, which acts as a barrier against environmental attacks. This not only prevents rust formation but also enhances the reliability and lifespan of the equipment by safeguarding its structural integrity.

3. Dispersants

Dispersants are essential for maintaining the cleanliness of engineering surfaces by preventing the agglomeration of solid contaminants. These additives thoroughly suspend particles such as dirt, wear debris, or sludge within the oil, ensuring they do not settle on critical components. By keeping the particles dispersed, dispersants maintain consistent lubrication properties, improve system efficiency, and reduce the risk of equipment failure.

4. Extreme Pressure (EP) Additives

Extreme pressure additives are designed to prevent metal-to-metal contact in severe conditions, including high loads, extreme pressures, or elevated temperatures. They form a sacrificial layer on the interacting surfaces, which shears off under extreme conditions to protect the underlying material. This feature is particularly useful in heavy machinery and high-stress applications, as it prevents surface damage, reduces wear, and enhances the load-carrying capacity of the lubricant.

5. Friction Modifiers

Nano lubricants are highly effective in reducing friction between sliding or rolling surfaces. Friction modifiers alter the surface properties or introduce rolling and sliding mechanisms that minimize resistance to motion. The nanoscale size of these additives ensures uniform distribution, providing smooth operation and improved energy efficiency. This property is vital for reducing power losses, enhancing fuel efficiency, and minimizing heat generation.

6. Oxidation Inhibitors

Oxidation inhibitors prevent the degradation of lubricants caused by chemical reactions with oxygen. These additives react readily with oxygen to form stable compounds, thereby delaying the oxidation process. By preventing the formation of sludge, varnish, and acidic byproducts, oxidation inhibitors improve the thermal stability and longevity of lubricants, ensuring consistent performance even under high-temperature conditions.

7. Viscosity Index Improvers

The viscosity index of a lubricant determines its ability to maintain a consistent viscosity over a wide temperature range. Various polymeric molecules are used as viscosity index improvers by minimizing the change in viscosity with temperature variations. They prevent the lubricant from becoming too thin at high temperatures or too thick at low temperatures. This stability ensures reliable lubrication, reduces mechanical wear, and enhances the efficiency of machinery in varying environmental conditions.

1.5. Nanomaterials as an additive

Nano additives can be classified based on their basic elements such as:

- Metal based
- Non-metal based
- Hybrid / composite

Metal based nano additives mainly consist of pure metal, metal oxides, nitride, sulphides, metal salts, etc. These additives show better mechanical strength, hardness, structural and thermal stability. This class of nano additive provides better antifriction performance especially under boundary conditions. The tribological effect of metal oxide nanoparticles closely depend on their particle size and geometry. Sulphides have better surface adsorption and chemical activity towards the rubbing surfaces [7]. Thus, it forms a good tribo film over the rubbing surfaces.

Non-metal based nano additives comprise all other additives whose constituting elements are apart from metals. Carbon and polymeric nanomaterials come under this section. The examples of carbon-based nano additives are nano diamond, fullerenes, carbon nano tube, graphene, etc. Polymeric materials, like polytetraflouro-ethylene (PTFE) [8], Poly (sodium 4-styrenesulphonate) [9] polyvinyl pyrrolidone [10] are used as additives in different lubricants.

Hybrid or composite nanolubricants additives are the class of materials in which two or more types of additives are mixed or combined to act simultaneously in a tribo phenomenon. Compared with metals, non-metals, and polymeric additives, the hybrid/composite additives have outstanding performance due to the synergistic effect of their constituent materials. They can be formed by combining or mixing of different metal oxide[11], oxide-sulphide, metal-metal oxide [12], carbon-based-metal oxide and sulphide [13–15] polymeric-metal carbide and carbon[16,17]. Hybrid materials offer a wide scope for research, driven by their enhanced availability and versatility resulting from the combination of various additives. By blending two or more types of nanoparticles with unique and complementary properties, these lubricants deliver outstanding benefits like reducing friction, minimizing wear, and handling high loads and temperatures more effectively. From cars and airplanes to factories and energy systems, hybrid nanolubricants are finding their place in industries where smooth performance and reliability are essential. Moreover, they can be customized to suit specific needs, making them incredibly versatile. As industries focus more on efficiency and sustainability, hybrid nanolubricants offer a promising path to create greener and advanced solutions.

The detailed studies on hybrid nano-lubricants are discussed in literature review section.