1. Introduction.

In this chapter, the tribology and wear damage due to galling is discussed. The role of coating in preventing wear and providing low friction is also discussed. The chapter provides a brief overview of various type of deposition processes and the different types of conventional coatings available in the market.

1.1. Tribology.

For our society to be viable in the long run, energy is a crucial resource. In the transportation, industrial, and power generation sectors, friction uses up a lot of energy and is expensive to repair or replace. Wear, lubrication, and friction all affect how effectively and long-lastingly industrial machinery operates. During a conference in Cardiff in 1964, engineers from around the UK voiced concerns about lubrication, friction, and wear. Professor H. Peter Jost coined the term "tribology" in 1966; it is derived from the Greek words "tribos," which means "rubbing," and "logos," which denotes science. The study of friction, wear, and lubrication is referred to as tribology, which is the science of rubbing [1]. It deals with friction, wear, and lubrication and is the science and technology of interacting surfaces in relative motion. Engineering bodies' moving surfaces undergo friction, which results in a steady loss of material. The interactions between rubbing surfaces during tribology are quite complicated. To gain insight into the tribological processes, it takes knowledge from many different fields of science and engineering is required, including solid mechanics, heat transfer, thermodynamics, fluid mechanics, lubrication, rheology, material science, chemistry, physics, applied mathematics, machine design, performance, and reliability.

Friction is the key to the functionality of numerous systems in tribological interactions. Low friction is preferred in ball bearings, gears, hip joints, door hinges, etc. High friction is desired to transfer torque and release kinetic energy in many applications, like clutches and brakes. While walking and operating a vehicle, high friction also plays a significant role (interaction between tyre and road) [2].

When two or more surfaces are in relative motion and come into direct contact with one another, a typical phenomenon known as progressive material loss occurs. Wear frequently has a negative impact on the machinery's performance and service life. Any engineering disasters may have a fundamental cause, the gradual loss of material, resulting in failure or unintended breakdown. High wear rates are desired in some tribological processes like polishing, grinding, machining, etc.,. Similarly, a rapid wear rate and low friction between the pencil and paper are advantageous for writing [2].

The tribological applications determine whether minimum or maximum friction and wear are required. When tribopairs interact under an unlubricated situation, they have high sliding friction. As a result, considerable amounts of energy are needed to overcome the frictional losses, which results in high frictional heat generation, which frequently causes an increase in wear rate. Surface engineering tools like coating can indefinitely enhance a surface's tribological properties. For the tribological situations, the coating selection is based on the type of wear damage to control. The type of wear damage occurring in tribosystems depends on several factors, such as working temperature, sliding speed, the applied load, hardness, and elasticity of the material. The wear damages can be adhesive, abrasive, corrosive, fatigue, and erosive in nature. Different types of loading, contact, and environmental situations lead to different types of wear mechanisms. Hence, it becomes difficult to correlate or compare wear damages across various tribosystems. The wear damages focused in the present study are due to the wear occurring in reciprocating sliding situations (mostly comprising fatigue and abrasive wear modes) and wear occurring due to galling (predominant with adhesive wear mode). The wear damages due to reciprocating sliding situations had been studied widely, but the wear damage due to galling wear needs attention.

1.2. Galling.

Wear damage occurring in a reciprocating or rotary kind of sliding situation is well known and studied in detail by many researchers [3–5]. Galling is a type of wear that impairs the quality and performance of surfaces. It appears as excrescences or "bumps" brought on by plastic deformation. In contrast to progressive kinds of surface degradation like abrasive and adhesive wear, galling can happen after only a brief period of contact or sliding distance. It frequently occurs locally rather than uniformly across the nominal area of contact. Quantitative measurement of galling is difficult since the material can be moved but not lost. The American Society for Testing and Materials has established several industry-standard galling test procedures [6,7]. These common tests are intended to be utilized in a room-temperature environment. However, some temperature-sensitive applications, such as turbocharger parts and aerospace bearing components, run at high temperatures and necessitate elevated-temperature testing techniques. However, the mechanized test rig designed by Harsha et al. [8] used in the present study can conduct galling tests up to 300 ˚C as per ASTM G196 [7]. Galling is mechanically linked to severe plastic deformation by shear. Therefore, it would be expected that material attributes like yield strength and hardness would correlate with galling resistance. There are still other things to contemplate about, for instance, some materials have a tendency to work-harden more than others, increasing their resistance to further deformation as they are gradually bent. Ives et al. [9] conducted a review of a variety of variables influencing galling resistance. These included sliding of self-mated versus dissimilar couplings as well as crystal structure, stacking fault energy, applied stress, surface finish, and heat treatment. They discovered that body-centered materials do not have the same galling resistance as hexagonal metals (like Co and Mg). Therefore, coating the substrate with materials having good galling resistance can enhance the galling properties of the substrate. However, very little literature exist that explores the galling tendency of coatings [10–12], and none are based on new ASTM standards.

1.3. Coatings.

Mechanical components and structures are designed for specific purposes. These components must be fabricated while adhering to stringent material selection requirements. These limitations include the mechanical characteristics (such as compression, tension, torsion, yield, fatigue, creep, and bending), the desired functionality (such as hydrophobicity, wear resistance, and friction properties), the thermal characteristics (such as thermal expansion and conductivity to transfer heat flux), the electrical conductivity, the dynamic load bearing (such as vibrations and high-speed rotation), and the corrosion resistance. In addition, additional factors including material availability, cost, safety, and toxicity must be taken into account. The latter group is crucial in completing the material selection procedures before producing mechanical components and structures. For instance, silver is well known to have high electrical conductivity values, yet it is prohibitively expensive to fabricate a large quantity of silver for electrical conductivity applications [10]. The shape memory effect (SME) and superelasticity (SE), which are helpful in building new actuators, are well-known properties of NiTi alloys. These alloys also offer exceptional biocompatibility as bone implants that can be paired with SME, SE, or both to create innovative biomedical devices for microsurgeries inside the human body. However, Ni ions are poisonous or belong to a damaging class of elements for living organs. They are released as a consequence of the corrosion process of NiTi in physiological conditions [11]. The high thermal and electrical conductivity of copper makes it useful for brazing materials, but it also has low stiffness and wear resistance. Due to the increased susceptibility of copper to wear mechanisms, in the case of copper rotary cooling fins, the durability of the mechanical parts reduces dramatically [12]. Different techniques, including heat treatment, alloying procedures, and coatings, have been proposed to address these problems and to improve the material properties for certain purposes. Coating layers can cut costs and ignore material scarcity because their thickness rarely exceeds a few micrometers, coating techniques have the largest percentage of material improvement among these methods. As a result, fewer ingredients are required to build coating layers on many substrate materials. Coatings can provide a variety of qualities, including improved surface hardness, thermal and electrical insulation, hydrophobicity, improved wettability, altered surface roughness, and more.

Due to the diversity of applications and needs in various industries, different coating technologies are available. These procedures involve a wide range of online and offline parameters and result in many material's microstructure, efficacy, appropriateness, and durability. However, coating techniques are effective in particular applications depending on the desired functionality, with corrosion and wear protection being the most crucial [13]. Investigating the various deposition techniques used by coating materials will reveal their benefits and drawbacks for the intended application. Physical vapour deposition (PVD), chemical vapour deposition (CVD), sol-gel, thermal spray, and polymer coatings are only a few readily available technologies. Still, they are also among the most efficient and useful. Each of these techniques offers a variety of deposition techniques, materials, second phases, thicknesses, and densities, making them appropriate for various applications. For a particular type of coating, consideration must be given to mechanical stability, corrosion characteristics, biocompatibility (for biomedical applications), and enhancement of material behaviour [14]. Although coating methods offer the aforementioned advantages, they have drawbacks that reduce their dependability. The most important ones to take into account are the damaging effects of loose atmospheric protection (such as the penetration of inclusions and contaminants into the substrate), negative thermal effects (such as distortion, crack, delamination, etc.), and the properties of coating materials (such as melting point, availability in various forms of foils, powders, and rods, biocompatibility, etc.).

The choice of materials is critical in creating a successful coating because they serve all protective functions. In order to create a protective layer, various substances, such as metals, ceramics, and polymers, can be employed [15]. However, finding the ideal composition for the deposited layer may be challenging due to the diversity of coating techniques and material qualities. To solve this problem, it is necessary to take into account the most well-liked options, such as Al, Ti, Zr, Ni, Pt, Co, Hf, Al_2O_3, MgO, ZrO_2, Y_2O_3, PEEK, and PTFE, while also keeping an eye out for any possible new choices. While all feedstock materials have some degree of corrosion or wear resistance, their melting points, mechanical characteristics, and chemical compositions differ in addition to being offered in various powder, rod, and plate forms.

1.4. Coating methods.

In various industries, from the aerospace and automotive sectors to tiny biomedical devices and implants used in the human body, coating procedures protect a specific component or area of a structure exposed to severe and corrosive environments. Some of the widely used coating methods are:

1.4.1. Electroplating.

A substrate is immersed in a chemical bath during the electroplating process, which frequently consists of water mixed with metal salts intended for deposition. As the substrate is submerged for a longer time, a thicker film is formed by the metal salts adhering to it in a consistent pattern. Electroplating is a more specialized type of plating that uses electricity. The anode, which is powered by an external battery or rectifier, is connected to the substrate. The oxidation of the metal particles in the liquid causes them to attach to the substrate surface when the electricity is turned on. The fundamental rule for Electroplating is that it is directly proportional to the amount of charge and the duration of current, the higher charge results in the thicker deposition layer, even if different metals attach at varying speeds and thicknesses.

1.4.2. Chemical solution deposition (CSD).

In contrast to Electroplating, CSD uses organometallic powders and an organic solvent. Although its outcomes are equivalent to plating procedures, CSD is less complicated and more affordable.

1.4.3. Sol-gel.

One of the most effective coating techniques for biomedical equipment is sol-gel coating. The variety of studies on this technique and its applications might make it easier to set up and conduct experiments while maintaining the validity of the results [16]. Conversely, Sol-gel can improve pre-existing coating layers in terms of corrosion and ion release. Sol-gel can easily seal pores in coating structures or damaged layers because of its liquid-permeating nature. The "Sol" solution is created by dissolving calcium phosphorous precursors in ethanol or distilled water. The resulting mixture is heated at various temperatures to enable the aqueous component of the solution and raise the viscosity to the required level to create a “gel” phase out of the solution.

1.4.4. Dip coating.

The dip-coating process creates almost exclusively transparent oxide layers with excellent surface quality and planarity on transparent substrates. The usage of additional substrates is also an option. Up to 1 µm of precisely determined film thickness can be deposited. It is possible to combine several additive layers. There are five steps in the dip-coating procedure:

- Immersion: The substrate is dipped into the coating material's solution at a steady rate.

- Start-up: The substrate is beginning to be hauled up after some time submerged in the solution.
- Deposition: As the thin layer is dragged up, it deposits itself on the substrate. To prevent aberrations on the surface, the withdrawal is made at a consistent speed. The speed controls the coating's thickness
- Drainage: Any extra liquid will flow off the surface.
- Evaporation: The solvent leaves the liquid and leaves behind the thin layer. Evaporation for volatile solvents, like alcohols, begins during the deposition and drainage processes.

1.4.5. Spray coating.

Spray coaters are tools that apply coatings using atomization. These devices spray the target with a misted coating fluid that has been transformed into a mist. Spray coaters have been utilized for various applications due to their sophisticated and varied design, including thin film coating of flat sheets such as transparent conductive films for touch screens, solar cell components, and semiconductor photoresists. Generally, two types of spray coatings are used:

1.4.5.1. Air spray coating.

In air spray systems, the coating fluid is transformed into a fine mist and sprayed onto the target using compressed air. An air spray pistol is a typical device that employs a similar process. The coating fluid is ejected from the nozzle at high pressure from compressed air, and the fluid then collides quickly with the residual air. The air resistance at that point causes the coating fluid to break apart and slow down, and before it reaches the target, it transforms into a mist. According to widespread consensus, air spray systems spread excessive coating fluid, leading to a disproportionately high material loss. However, the apparatus has been created in a clever and varied manner. For instance, some systems use a nozzle that can transform the coating fluid into a fine mist that permits stable coating over uneven surfaces, while others can sustain high-speed spraying. Other systems can automate the stage and nozzle and control advanced movement. According to the target area, necessary efficiency, and coating purpose, various products are offered. The polymer composite coating in this study was prepared using air spray.

1.4.5.2. Ultrasonic spray coating.

There is a chip at the nozzle tip of ultrasonic spray systems (atomization surface). The coating fluid spreads throughout the chip due to ultrasonic waves' vibration, and the surface becomes ruffled. The fluid falls to the surface as a thin mist when the ultrasonic output surpasses the surface tension. These devices are helpful for uniformly coating a small area since they can produce fine and homogeneous drops. Another benefit is that little material is lost due to the system's little splashing and unneeded dispersion of the coating fluid. The nozzle can be chosen from various lengths, sizes, and shapes depending on the architecture of the coating needed. Setting the appropriate flow and vibration frequency to achieve a uniform coating fluid spray will allow you to regulate the coating film's thickness and quality. These technologies are used for conductive and insulating films on electronic components, semiconductor photoresists, hard coating, anti-glare coating, hydrophobic coating, and oleophobic coating, among other things.

1.4.6. Physical vapour deposition (PVD).

With applications ranging from aesthetic items to industrial equipment, the PVD technique is renowned for providing corrosion and wear resistance as well as thin protective layers on the surface of materials exposed to corrosive media [17]. The benefit of this approach is that the coating layers' mechanical, corrosion, and cosmetic qualities could be changed as needed. PVD is a process that occurs in a high vacuum and involves the transfer of solid/liquid materials to a vapor phase, followed by a metal vapour condensation that results in the formation of a stable and dense film. A detailed discussion of the PVD technique and its improvement over time will be done in the subsequent chapters.

1.4.7. Chemical vapour deposition (CVD).

CVD is a different classification of vapour deposition. A solid, high-quality, and high-resistance coating layer is produced on any substrate using this procedure, which is frequently utilized in the semiconductor sector [18–21]. Mechanical parts that are in constant contact and require protection from corrosion and wear can employ CVD. In this procedure, a wafer-shaped substrate is exposed to a mixture of volatile material precursors, where a chemical reaction results in the deposition of a layer on the material's surface. However, some of the byproducts of these chemical processes, which are eliminated by the vacuum pump's continuous inflow, may still be present in the chamber. Among the coating processes discussed, the CVD technique is the costliest.

1.5. Coating types.

Based on the coating architecture, the following types of coatings are available:

1.5.1. Monolithic Coatings.

TiN, CrN, and ZrN were the single metal nitrides that made up the first generation of hard PVD coatings. Since the middle of the 1980s, they have been used commercially for both aesthetic purposes and cutting applications due to their appealing look and better hardness when compared to high-speed steel and cemented carbide: ZrN has a white gold hue, Ti has a characteristic yellow gold hue, and Cr appears like silver. By incorporating additional elements such as C, Al, and Cr into the TiN lattice, alloyed coatings increase hardness, wear resistance, toughness, and oxidation resistance. The most popular monolithic coatings and their characteristics and uses, are displayed in **Table 1**.

1.5.2. Multilayer coatings.

The deposition of multilayer structures further enhanced the hard PVD coatings' characteristics. It is possible to increase the multilayer structure's resistance to wear, corrosion, and oxidation by choosing an appropriate combination of components. Similar to monolithic coatings, multilayer structures have stronger toughness and lower hardness. A multilayer coating is typically preferable for large dynamical loads, such as roughing, since the "sandwich" structure absorbs the crack by sublayers.

1.5.3. Structurally or compositionally graded coatings.

Structurally or compositionally graded coatings work better because the coating structure and material characteristics are adjusted as the coating thickness increases. The creation of compositionally graded wear-resistant coatings can be accomplished in a variety of ways. The most popular techniques involve changing the precursor materials or adjusting the reactive gases [22]. They also help in reducing residual stresses.

1.5.4. Nanocomposite coating.

In recent years, many important industries, including the automobile, aerospace, petroleum, and electronics, have demonstrated growing interest in nanocomposite coatings. Nanocomposite coatings are designed to offer useful surface coatings that are aesthetically pleasing, reasonably priced, and have exceptional qualities for anticorrosion, antibacterial, antifogging, and adhesive applications. Nanocomposite coatings' distinctive features include improved barrier properties, weight reduction, greater mechanical strength, and increased heat, wear, and scratch resistance for long-lasting performance. These coatings exhibit exceptional hardness and excellent crack growth/propagation resistance. The limitation of grain expansion can result in a fine-grain structure and a strong covering by segregating the second phase at grain borders. The highest hardness of 30 GPa to over 60 GPa was observed for most of nanocomposite coatings. The domain size of the crystalline phase in nanocomposite coatings should be less than 10 nm, and the layer thickness (amorphous) between nanocrystals needs to be a few atomic bond lengths. The lack of dislocations in the nanocrystalline phase is the primary cause of the enhanced hardness values in nanocomposite coatings.

Table 1.1. Properties of various coatings.

Coating	**Colour**	**Hardness (GPa)**	**CoF**	**Maximum usage Temperature (˚C)**	**Application**	**Reference**
CrN	silver	18-22	0.4-0.5	700	Use for non cutting applications: extrusion, deep drawing, metal die casting, machining copper,etc.	[23]
TiN	gold	24-30	0.3-0.4	600	Coating for cutting, forming, decoration, tribological purposes, etc.	[24]
ZrN	white-gold	18-20	0.4-0.6	500	Machining of titanium and aluminum alloys	[25]
TiAlN	violet-black	28-40	0.3-0.6	800	High performance coating for cutting (drilling, milling, reaming, turning); suitable for dry machining; also for moulds and dies.	[26]
TiCrN	dark grey	21-25	0.4-0.6	700	Sheet forming, corrosion inhibition, etc.	[26]
AlCrN	blue-grey	30-35	0.3-0.6	1100	Gear cutting tools, aluminium die casting, forging, punching, etc.	[27]

1.6. Summary.

The chapter presents an overview of tribology and conventional coatings. The limited use of lubricants during the harsh tribological contact conditions have led to development of various coatings. These coatings are a combination of multiple hard and soft materials, and can be tailored to achieve the desirable properties of our requirement. Several deposition techniques are also available, producing desired characteristics of coating. Coatings can be a suitable substitute for the conventional lubricants, as they can achieve equal or better lubrication and antiwear properties and are eco-friendly. The chapter also gives a brief idea about wear damage due to galling, and the limited work done in preventing galling through coatings.