The Development of Tribology in Lubrication Systems of Industrial Applications: now and future impact

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Abstract. Over the past 25 years, natural resources have been used up quickly, causing significant damage and contamination to the planet which is earth. Tribology, a new technology for keeping power and parts running, supported extremely fast and efficient coal and oil-powered machinery throughout history. Many different kinds of resource reserves, like those for power and parts, will be gone in a century. Revolutionary zero-emission and durability technologies are in high demand all over the world in order to create new, truly healthy and long-lasting lifestyles for humans and other living things in a symbiotic way. Tribology is expected to expand its technological innovation in order to support a new industrial trend and meet the requirements of the sector. At the moment, the primary factors influencing engine development are cost, performance, governmental requirements, and consumer requirements. In a few instances, the requirements are linked to tribology. For engines to last longer and be more reliable, tribology advancements that reduce friction and increase wear resistance will be crucial. The components under scrutiny are a part of the heavy-duty diesel engines' valvetrain mechanism. The fuel injector places a lot of strain on the injection cam, making it one of the camshaft's most problematic components. Lubrication plays a crucial role in avoiding cam failure caused by wear. The cam and roller contact, in any case, has shown to be one of the most provoking tribological plan challenges to handle. For lubricated contacts, the type and amount of wear are significantly influenced by the degree of separation between the surfaces. The term "specific film thickness" refers to this degree of separation and measures the degree to which asperities interact with one another in the lubricated contact. In order to predict lubrication regimes and, consequently, identify the injection cam's likely wear zones, this paper focuses on measuring the oil film thickness in the cam-roller contact and other machine parts that follows. The results of the experiment (the observation of worn cam surfaces) are then confronted. In the near future, a multivariate analysis will be used to ascertain how the various parameters affect oil film thickness. The following stage will

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primarily focus on modeling injection cam wear, which will also include quantifying relationships between wear and a specific film thickness.

1 Introduction

For quite a while, there has been interest in the tribological examination of different parts utilized in modern applications. Tribology is the investigation of wear, grease, and rubbing between surfaces that are moving according to each other. The investigation of a surface's tribological qualities when it isn't moving comparative with one more surface isn't viewed as tribology. Contact is available while the cooperating surfaces are moving comparative with each other. Assets are lost because of the scattering of energy brought about by grinding between surfaces. Grip and twisting are the essential drivers of grinding. The atomic restricting power holds the communicating surfaces together in cement erosion. At the point when a harder surface crushes between the severities of a milder surface and distorts it, erosion because of twisting outcomes. Wear is the chief impact of erosion. Wear makes a material's exhibition decline, and it likewise causes material waste. The materials in the end debase because of unnecessary wear [1].

Rough wear, tacky wear, destructive wear, erosive wear, and exhaustion wear are a couple of instances of a few wear instruments. At the point when pollutants, like hard particles, dust, sand, and so forth, are available between the collaborating surfaces, rough wear is delivered. This makes the material on the gentler surfaces be taken out when the bodies move in view of these hard particles. The connection of surfaces with each other causes cement wear. The surfaces moving are attracted to each other by the sub-atomic power of fascination, which makes them grip together. Metals experience a great deal of this sort of wear. While a consuming medium responds synthetically with a material, it causes consumption, which is an immediate consequence of the workplace. Like cement wear, erosive wear includes hard particles eliminating materials from gentler ones. The differentiation is that a liquid is available in the space between the surfaces. At the point when there is cyclic stacking, weakness wear occurs. Since there are such countless inversions, the cyclic stacking makes the imperfections increment. We can moderate energy and assets by concentrating on grinding and wear [1].

Cutting apparatuses, orientation, cams, and cog wheels are instances of normal modern tribological parts. Heading are utilized in mechanical frameworks to help the various turning parts, like shafts, and so on. The tube shaped turning shafts are upheld by diary heading. Diary orientation have the special property of just connecting under two conditions: first, toward the start and second, toward the finish of revolution. Just under these two conditions could diary heading at any point start to break down. At any remaining times, a compressed liquid that we gave remotely makes a hydrostatic lift between the shaft and bearing.

Gears are used in a wide assortment of utilizations and are vital for moving power starting with one shaft then onto the next. Hence, it is important to investigate different tribological parts of stuff, like reasons for disappointment and alleviation procedures. Since the teeth of the pinion wheels send power, we know that maximal stuff disintegration happens there. In this way, to some degree forestall gear disappointment, we should make specific surface changes.

Cam and Supporter is a critical part in gas powered motors. As they keep in touch with each other, they complete the ideal undertakings. Thusly, there is a high probability of surface wear because of this steady contact, which makes cams and devotees flop sooner than anticipated. We want to look at the various main drivers and contributing factors for these sorts of disappointment.

The motor is the most critical tribological part in vehicles. This is on the grounds that the motor loses the best amount of fuel energy. Erosion makes the fuel energy be lost to some extent. Mechanical misfortunes represent more than 15% of the fuel energy lost. The fuel utilization of vehicles has been seen to diminish by 1.5% when mechanical misfortunes are diminished by 10%. The tribological investigation of the materials utilized and the utilization of viable oil can both increment mechanical productivity [1].
A great procedure to save energy is to concentrate on tribology. Our assets are altogether rationed by bringing down the coefficient of grinding and wear rate. The improvement of biodegradable greases and harmless to the ecosystem materials can likewise add to supportability. This offers a wellspring of environmentally friendly power and fundamentally brings down discharges. For biodegradable greases to be broadly utilized, more examination is being finished on the production of novel materials and settling the issues with them.

2 Literature Review

2.1 Tribology

Tribology, which studies and applies friction, wear, lubrication, and associated design factors, is the science and technology of interacting surfaces in relative motion. The definitions of the terms friction, wear, and lubrication are crucial for understanding tribology.

2.1.1 Green Tribology

Green tribology is a subfield of tribology that focuses on preserving an ecological equilibrium for any potential biological and environmental effects of materials' interactions with various surfaces. The goal of green tribology is to make sure that any wear and friction between materials happens in a way that is good for the environment. Solar panels, tidal turbines, and wind turbines are also being studied by researchers in the field of green tribology. In the future, they are concentrating on being more sustainable and friendly to the environment.
The development of tribological technologies has seen new heights. New materials, oils, and plans for decreasing wear because of erosion and grinding are made consistently. In an effort to cut down on wear and tear, cut costs, and ultimately increase profits, this knowledge has been widely accepted across industries. The need for energy increases with the world's population. The use of fossil fuels has been on the rise in the past and are still widely used, increasing the daily amount of greenhouse gases that are released into the environment, which is devastating. In the fight to reduce emissions of greenhouse gases, tribology is able to provide a great deal of useful assistance.[2]
A wide range of lubricants have been use in the past, the first of which was animal fat, to reduce wear and friction. Scientists have become much more innovative over the centuries, resulting in a vast array of lubrication formulations and application strategies. New researches have been launched to find new methods of producing highly efficient lubricants and lubricating methods which are friendly to the environment. This has bred the term "**green tribology**".
Green tribology is hugely concerned with balance of ecological factors. Therefore mitigating the adverse effect of tribology on the environment including the biological impacts.[3].
This has achived by the use of various methods such as; The use of bio-lubricants which are easily biodegradable, Regulating the properties of the surface, surface texturing is being applied. The random roughness of conventionally engineered surfaces makes it difficult to control friction and wear, Considering the impact that coatings have on the environment, monitoring in real time, hazardous substances when they are being utilized, Employing sustainable energy practices at all times.

2.1.2 TRIBOLOGY AND ENERGY SAVING

The effect of wear and friction on power loss from an economical and emissions standpoint is discussed in [4]. The significance of tribology for energy savings is amply demonstrated. The paper demonstrates that roughly 23% of the energy used by humans for their activities—mostly those associated with transportation, industry, power generation, and residential—comes via tribological encounters. Both during the design phase of industrial components or systems and when they are in use (monitoring, remedial actions based on friction-wear-lubrication concerns), tribology plays a critical role.

A proper tribological design can significantly boost performance, efficiency, durability and maintainability of machine components including bearing, gears and seals. Nowadays, there is a significant industrial demand for machines with larger power densities and greater efficiency [4]. As a result, smaller dimensions are required for lighter machine components. More speeds are required, which are typically associated with hotter working conditions, in terms of achieving the very same level of power as the earlier machines, if not higher. When considering environmental factors and expenses, which are also related to greater temperatures, it results in the use of small amounts of lubricant. In this manner, the lubricated contacts are subjected to increasingly demanding conditions, necessitating a very complicated design and tests on actual machine parts [5].

Due to the vast number of transportation modes in use worldwide, tribological research pertaining to transportation (cars, planes, helicopters, and trains) can have a significant negative impact on the environment [4]. Perhaps one of the most obvious instances of how tribology can have a substantial impact on alternative energy sources is applicability of tribological discoveries to the vehicle sector. Automotive tribology is still a controversial topic [6].

Examples of studies on engines can be found in Rajasthan & Rajasthan, (2016). Another serious issue with autos is particle pollution. Tire wear is a significant source of environmental emissions of tiny polymer particles [8]. based on Siniawski, (2005), the pollution caused by tire wear and tear is just as significant as that caused by plastic bottles and bags, and it may consequently have an impact on human health.

According to research, tribological investigations can be highly helpful for reducing particle emissions from brakes and tires. Undoubtedly, among the components that have received the greatest research are bearings and gears, particularly for automotive and aerospace applications. The LEAP (Leading Edge Aviation Propulsion), a brand-new aeronautical engine that represents one of the most significant recent scientific advancements, is now being developed using new bearings and gears [7]. One of the most well-known examples of components whose size has decreased through time is the rolling bearing.

Through design advancements, bearings have evolved over the past 100 years to have lower size and friction, larger carrying capacities, faster speeds, and longer lives [7]. The hybrid bearings, which have silicon nitride rolling elements and steel rings, function well under challenging circumstances including inadequate lubrication and contaminated environments [8]. Studies on gears are carried out to achieve low-loss gears by reducing the amount of lubricant required, to achieve noise and vibration elimination (or at least reduction), to boost power density (by using smaller and lighter gearboxes than before). For example, gears were tested with lower oil levels. The goal could be to develop oil-free engines and powertrains as a last step. The integrity and stability of the ecosystem as well as current human requirements are both met by all of these tribological research, which is crucial for sustainable development. More broadly, tribology can affect a number of the 17 Sustainable Development Goals of the United Nations (United Nations, 2015), notably Goal 3, Good Health and Well-Being for People (related with biotribology), Goal 7, Affordable and Clean Energy (Increasing Energy Savings by Friction Factor), Goal 12, Responsible Consumption and Production (Reducing Waste Production by Reducing Wear), and Goal 13, Climate Action (Reducing CO2 Emissions).[4].

New environmentally friendly lubricants and the sustainability of tribology have received a lot of attention. Reports on the significance of enhancing environmental compatibility while reducing health and water concerns. New lubricating additives that are also environmentally beneficial are now being developed. Universitas & Minh, (2020) discuss many facets of green tribology.

Alternative energy sources might create new tribological issues. The maintenance issues with wind turbines serve as an important illustration. For wind turbines, new bearings, lubrication systems, and surface treatments like black oxidation are being developed [8]. Monitoring the condition of wind turbines aids in reducing operating and maintenance expenses.

2.2 Climate Change

The idea of tribology has existed since people first started making machinery. The study of interacting surfaces in relative motion is taken into account in this field. The disciplines of tribology include the research on wear, lubrication, and friction.
It includes contributions from a variety of disciplines, including computer science, chemical engineering, chemistry, mechanics, physics, and more. The multidisciplinary discipline attracts scientists and researchers with a variety of educational backgrounds and experiences, which is advancing the area to address fresh, pertinent issues [9].
Importantly, tribology is being used to reduce the amount of wasteful energy used by mechanisms, which helps to solve the issue of CO2 emissions. Tribology can be used to calculate how friction and wear affect energy use and economics.
As a result, industries like residential, manufacturing, transportation, and energy are able to reduce their overall energy use and emissions.
Our knowledge of the growing negative effects that human activity is having on the environment has grown in recent years. Scientists are becoming more concerned and making more forecasts about the effects of increased greenhouse gas emissions as the data has accumulated. The future of the earth as a whole is in danger due to increasing sea levels, changing climate patterns, an increase in extreme weather events, threats to food security, threatened biodiversity, and other factors [9].
It is believed that the most urgent problem now affecting humanity is climate change. The decision made today will significantly influence the course of humanity. By minimizing energy waste and improving the mechanism's energy efficiency, tribology scientists have been working for decades to help decrease the amount of emissions linked with a variety of sectors [9].

2.3 Energy Waste Reduction

Scientists were already working hard to address the problem of energy waste in order to produce financial savings before climate change became such a hot topic. They concentrated on addressing wear and wear-related issues with various machinery types. As a result, tribology-related technologies were able to cut operating costs by almost 95%.

According to current estimates, tribology solutions help save money by the same amount, with ways for reducing friction accounting for 74% of the savings and solutions for what protection accounting for the remaining 26% [9]
The role of tribology in the effort to reduce emissions has been underlined by recent study. Data indicates that tribological contacts are responsible for 23% of the world's total energy consumption. Additionally, of that 23%, energy consumed to overcome friction accounts for one-fifth of it.
The friction and wear that come with operating machines, vehicles, and other equipment can be significantly reduced by utilizing new tribology technologies, such as those that have created improved surfaces, materials, and lubrication, which will reduce the energy consumption of these machines and their carbon footprint [9].
According to scientific estimates, energy lost to friction and wear might be decreased by 40% overall over the next 15 years and by 18% in the immediate future (eight years). Long-term savings from this would total 8.7% of the world's total energy use.
The transportation sector would be the one to gain the most in the short term from such savings, as it could potentially cut the amount of energy used by 25%. In terms of long-term savings, transportation would again reap the most benefits (55% savings), followed by electricity generation (40% savings), manufacturing (25% savings), and residential (20%) [9].
These numbers show how effective tribology is at lowering global CO2 emissions, both immediately and, more crucially, over the long term. Although one of several tactics that must be used in concert to provide the world the best opportunity of protecting its future, the application of energy-saving tribology solutions is crucial to combating climate change [9].

2.4 Advancement in Industrial Tribology

The technological advancements associated with the industrial revolutions were undoubtedly impacted by tribological breakthroughs. On the other hand, new tribological issues arising from the industrial revolutions need to be resolved. Today, the four industrial revolutions are frequently addressed. To be consistent with the notion of industry 4.0, this essentially developed after it. As of today, some group of persons name the 3 previous industrializations as old (industry 1.0, industry 2.0, industry 3.0) [5]

2.4.1 The industrial revolutions

The usage of the steam engine distinguished the first industrialization, often known as the "age of steam" or the "industrial revolution." It has to do with mechanization and the change from an agricultural to a industrial civilization. Around the turn of the seventeenth century, it started. Industrial machinery that was powered by water and steam mostly consisted of the steam power, the textile manufacturing, and mechanical engineering. [5].
The "electrical age" refers to the second industrial revolution. Between the close of the nineteenth and the beginning of the early twentieth century [1840- 1900], there was a considerable rise in mass production that had been linked to the excessive use of electrical energy. It was marked by the widespread use of electricity and petroleum, the intense separation of labor, the growth of the rail industry, and the expansion of the steel production [5].

The "information era," or 3rd industrial revolution, is marked by significant digitalization (computerization). Information and communications technology (ICT) from the first generation is now being used in industry. In the middle of the twentieth century, the 1960s saw the start of Industry 3.0. Some academics contend that it ended in the 1990s or around the year 2000, whilst others assert that it is still in full swing today and has been seamlessly incorporated into the fourth technological revolution, the next industrial age. The employment of electronics and information technology (digital revolution) in industry is what distinguishes it. In 1969, the first PLC, MODICON 084, the programmable logic controller, entered commercial production. This day is occasionally referred to as the important date [5].

2.4.2 Tribology industrial 4th revolution

The network-based connection of actual physical objects and people with virtual ones characterizes the industry 4.0, sometimes referred to as the "period of cyber physical systems" or possibly the digital revolution. The interconnection of production systems has been significantly impacted by the ict integration, the Internet of Everything (IOT), and machines into so-called "cyber-physical systems" (CPS). Its beginning is frequently seen as the start of the twenty-first century. A significant year is 2011, when the phrase "industry 4.0" first debuted at the industrial trade show Hannover Messe as a high-tech strategy of the German industry [5]. The German industry 4.0 working group was subsequently established, and its final report described the industry 4.0 environment. Following that, its 2015 World Economic Annual Conference publicly accepted industry 4.0 themes. The third industrial revolution is being seamlessly replaced by the fourth. Some philosophers think that the term "evolution" is far more appropriate than "revolution" to express the changes because the key elements already exist and only a few additional developments take occur. Digitization is the main alteration in any instance. [5].

2.5 Impact of Tribology on the Industry

2.5.1 Tribology of polymers

The study of polymer materials' abrasion, adhesion, and fatigue in a frictional environment is the foundation of polymer tribology. Basic polymers can be used in a variety of tribological ways, most commonly as matrices and fillers in composite materials, thanks to their structural properties. Polymer nanocomposites have recently been used to create various tribology system components. These are based on the main findings from studies on polymer friction and wear, taking into account the effects of temperature and load on the contact, as well as the viscoelasticity of the polymer, including the evaluation of the actual area of contact [11](Myshkin et al., 2015)(Myshkin et al., 2015)(Myshkin et al., 2015)(Myshkin et al., 2015). We already know that ceramics cannot be used to reduce wear in the same way that metals can, like by using external lubricants.

Polymers cannot be used to translate our knowledge of tribological phenomenon mechanisms. Entanglements of polymer chains have a direct impact on the mechanical properties of polymers. Consequently, it is anticipated that particular chemical structures influence polymer based material's tribological properties [12].

Polymer tribology takes into account the regularities of friction and wear in polymers and polymer-based composites. Despite the complexity of their interrelationships, the fundamentals of polymer tribology postulates that adhesion and deformation are the two components of friction. Surface forces are responsible for the adhesion component, which is attributed to the formation of interfacial bonds at the contact points. The deformation component is caused by the polymer's resistance to deformation, which is highly influenced by the material's properties. Polymer wear is strongly influenced by a combination of erosion boundaries, mechanical properties, and polymer change under these conditions. Due to the polymer's adaptability to blending and combining with a variety of fillers, tribological applications abound. Polymer-based nanocomposites hold promise for a wider range of applications [11].

Adhesion and deformation are crucial in the investigation of friction. This method is applicable to all materials, including polymers. The creation and breaking of bonds between the actual points of contact on the surfaces controls the adhesion component of friction. Most polymers typically contain hydrogen bonds and van der Waals dispersive interactions. Interfacial bonds are broken when partner surfaces are moved and asperities are sheared away. Consider as a source of perspective a completely planar surface without ill tempers. Asperities or "bumps" will form on a surface with any roughness. First and foremost, bumps indicate that the nominal area of fully planar surfaces exceeds the effective contact area of the two interacting surfaces. The friction decreases dramatically as a result. The bump model has been used to describe the previous explanation for this phenomenon [12].

2.5.2 Tribology in hot metal forming

Hot rolling, hot forging, and hot extrusion are examples of hot forming processes that use heat to shape metal under pressure. The process of reducing the size of a bar or slab by passing heated slabs of metal through rollers is known as "hot rolling". Using this method, a short, bulky product is rolled into a longer, thinner one. This process is only used for products that typically do not necessitate precise tolerances, which is carried out at a hot rolling mill. The process of deforming metal with any press or hammer at high temperatures is known as "hot forging," or simply "forging". Hot forging can be used to make a wide range of long product shapes as well as small, precise parts. The process of pushing a hot steel blank or workpiece through a die with the desired cross-section for hot extrusion reduces the extruded piece's cross-section. The cross-section or shape of the extruded piece will be the same throughout and will have an elongated grain structure [13].

There are many machines, parts and cycles that work at high temperatures. Components used in the aerospace, power generation, and metal forming industries are examples. Metal forming has been around for centuries, but there are many different metal forming processes and a lot of unknown phenomena, especially regarding the tribology of the various processes. The majority of hot metal forming processes favor friction. It prevents metal from leaking between tool dies in open-die forging and instantly delivers back pressure in closed-die forging to guarantee that the die cavity is filled. For instance, it permits the metal to also be drawn into the space between the rolls during rolling. However, in some other forming applications, such as extrusion, a low level of friction may be desired to maintain a low forming pressure. It is evident from these examples that metal forming requires friction to be both low and high. The forming conditions and the load (energy) must be balanced at the ideal friction level [14].

The formation of various tribolayers has a significant impact on wear and friction during metal forming operations. The impact of high-temperature tribolayers has been the subject of more research in recent years. Jiang and co. proposed a model to illustrate the formation of tribolayers. They suggested that wear debris can be by the same token caught inside the notches brought about by wear or be eliminated from the tribosystem. The tribological response will then be altered by the trapped debris. Abrading can occur as a result of the debris acting as free-moving particles if it is hard. During the sliding process, the particles may also be compressed to form wear-protective layers. The chemical sintering effect that occurs between the particles in an oxidational environment also helps to facilitate the consolidation of these layer [14].

2.6 Tribology in Relation to Lubrication

In the home, sliding surfaces are frequently oiled to prevent squeaking or to extend their lifespan. Machine bearings are greased to avoid seizure and to extend their lifespan. Friction reduction has received less attention in the 20th century than seizure or wear, but it was crucial in the 18th and 19th centuries as railroads were being built and when animal power also was commonly used. It has gained importance once more as a result of the increase in gasoline prices, a trend that started in the early 1970s. The requirements for a bearing are commonly stated in terms of its stiffness, dynamic behavior, and load carrying capability. While many of these characteristics can be defined, excellent design also takes into account a number of nonmathematical factors, such as how lubrication is applied, how to account for misalignment, and how to handle starting and halting a bearing [8].

2.7 Industrial Application of Tribology

Car engines, cutting tools, cams, and bearings are some of the common industrial tribological components.

2.7.1 Tribology of Bearings

Bearings are employed within mechanical systems to support the numerous rotating components, such as shafts, etc. The cylindrical rotating shafts are supported by journal bearings. Journal bearings have the unique property of only making metal-to-metal contact under two circumstances: first, at the beginning and second, at the end of rotation [1]. Only under these two circumstances can journal bearings begin to wear out. At all other times, a pressurized fluid that we provided externally creates a hydrostatic lift between the shaft and bearing. By hydrostatic lift, the shaft spins at a small elevation from its initial position without coming into contact with the bearing, preventing bearing wear. However, there is significant wear at the beginning and conclusion of rotation, therefore we must identify its causes. Because we need to conserve energy in today's world, it is crucial to prevent this wear. By doing so, we may save energy [1]. The low turning speed is the primary cause of this type of wear at start-up and shutdown. Various analysis and observations shows that there is a very thin lubricant film at low turning speed. At low turning speeds, there is an extremely thin lubrication film, according to various analyses and observations. The thin film causes wear. Thus, raising speed can improve film thickness while decreasing wear. Lift pump systems are sometimes employed to provide hydrostatic support, which enhances the thickness of the lubricating film. But even with this lift pump mechanism, wear is still possible. When the film thickness is less than ten times the surface finish, wear always occurs. If there is debris in the lubricant, wear might happen even in thick films. Therefore, we need to enhance oil thickness and decrease lubricant contamination to lessen wear at startup. The rapid rise in temperature of the bearing pads during startup is another factor in wear because it results in pad deflection and fractures in the oil film. Preheating the pads will help you prevent this. Research has shown that fluid film starts to develop quickly upon startup. The friction coefficient for bronze bearings remains steady between 0.16 and 0.20 [1].

2.7.2 Tribology in automobile engines

In automobiles, the engine is the most crucial tribological component. It's because the engine loses the greatest quantity of fuel energy. Friction causes the fuel energy to be lost in part. Mechanical losses account for over 15% of the fuel energy lost. The fuel consumption of cars has been observed to decrease by 1.5% when mechanical losses are minimized by 10%. The tribological analysis of the materials used and the application of effective lubrication can both increase mechanical efficiency [1]. Petroleum-based lubricants make up the majority of the lubrication used today. These lubricants are to blame for the pollution of the environment and the release of dangerous compounds. Studies have been conducted on using environmentally friendly and biodegradable lubricant in place of mineral. Mineral oils can now be replaced by vegetable oils as effective lubricants. Vegetable oils contain all the necessary qualities to function as lubricants and are 90–98% bio-degradable [1].

2.7.3 Tribology in gears

Gears are utilized in a wide variety of applications and are crucial for transferring a shaft's power to another. Therefore, it is necessary to look into various tribological elements of gear, such as causes of failure and mitigation strategies. Since the teeth of the gears are what transmit power, we are aware that maximal gear deterioration occurs there. So, in order to partially prevent gear failure, we must make certain surface adjustments [1]. Failure of the gear occurs when the teeth lose their form. Friction, scuffing, or scratching, and rust are the main reasons of gear failure. We can utilize different thin films of some tougher materials on gearing profiles to stop these failures on surfaces. One of them is a coating made of diamond-like carbon (DLC). We can incorporate tungsten into these coatings to improve their wear resistance. It was discovered that WC coated gears offer good wear resistant capabilities whenever you compare the WC/C coating gear lubricated with low viscous oil to the case-carburized gears lubricated with standard gear oil. Carburized gear failure occurs when two mating faces come into touch with one another, which causes scratching or wear[1].

However, failure in WC covered gears occurs as a result of coating thinning rather than wear. This demonstrates how WC coating enhances the tribological characteristics of gears. WC coatings were reported to lower the surface roughness of gears by 40% compared to uncoated gears, according to numerous trials. Additionally, the temperature of the lubrication fluid used in tungsten-coated gears was lower than that of oil used in uncoated gears, indicating that coated gears have less friction. Gear surfaces experience micro pitting, or the creation of pits, as a result of extreme surface roughness and inadequate lubrication [1]. If tension is placed on the pit or scratch, it may result in the surface fracturing at the scratch, which ultimately results in gear failure. Utilizing WC coatings reduces surface roughness while also preventing micro pitting, a factor in gear failure prevention. Polymer gears can be utilized to convey power in accurate applications with high levels of safety. An injection-molded polymer gear is a roller with teeth on its surfaces that is constructed of a polymer material. Polymer gears can be used without additional lubrication because they are self-lubricating gears. They have a poor life because to heavy surface wear at high temperatures, which can arise in high-power transmission applications. Their lifespan can be extended by lowering the gears' operating temperature and reducing friction with some solid lubricant coating [1]. Molybdenum disulphide (MoS_2), graphite flake, boron nitride, and polytetrafluoroethylene are a few coatings that can be employed (PTFE). By lowering the operating temperature to 30 degrees celsius and reducing wear by up to 90%, PTFE offers the greatest gain in life. Pitch line fracture is less likely to occur as temperature drops near the pitch line of the gear surface [1].

2.7.4 Tribology in metal cutting fluids

In various cutting operations like turning, machining, and grinding, In order to offer lubricating and cooling effects, metalworking fluids are used. If the metal working fluids are not employed, the interacting surfaces will wear out and operations will fail. Vegetable oils may also be employed as MWFs, according to recent studies. The stability of vegetable oils against oxidation has restricted their application. Vegetable oils' oxidation stability has been enhanced either chemically altering the oils or by introducing antioxidants to the oils [1].

2.7.5 Tribology in cams

Cam and Follower is a key component in internal combustion engines. As they maintain constant contact with one another, they carry out the desired tasks. Therefore, there is a high likelihood of surface wear as a result of this constant contact, which causes cams and followers to fail earlier than expected. We need to examine the numerous root causes and contributing variables for these kinds of failure. This form of wear can be attributed to a number of factors. The following list of failure modes for cams and followers includes some of them: 1) Increasing wear 2) Rubbing No. 3 Pitting No. 4: Polishing [15]. All of these failure causes are primarily influenced by the component's metallurgy, or the materials used in its construction. The geometry of the components and the characteristics of the lubricating oil are other elements that influence these wears. Unalloyed cast iron, alloy steels cast iron, toughened and case-carburized steel, medium carbon steel, and alloyed steels are frequently used materials in the production of camshafts. These materials significantly affect the wear-resistant qualities. Hardened cast irons are chosen over nodular graphite irons because they offer better pitting resistance. Additionally, hardened steel is resistant to scuffing but prone to pitting, whereas cold iron is very prone to trying to pit but well resistant to scuffing. As a result, materials are chosen in accordance with the kind of applications, such as high- or low-speed applications [1]. Due to the deformation of cast iron, which is extremely prone to pitting because pitting is a mechanism of fatigue, cast iron is susceptible to fatigue. Some unique surface treatments can enhance the propensity of various materials to have wear-resistant qualities. Some type of phosphating is the better surface treatment for enhancing wear-resistant qualities. Phosphating involves layering phosphate crystals on the surface of the metal [15]. By altering the shape and size of the phosphate crystals, different wear resistance qualities can be obtained, with fine-grained coatings offering the best wear resistance. Utilizing soft-nitriding processes like Tufftriding can improve scuff resistance. Rotational speeds, temperature, the viscosity of the oil, and operating circumstances are other elements that influence the wear on the cams and followers. When it comes to cast iron cam and follower, the tensile stress that develops in the surface at the point of contact exceeds the material's tensile strength, leading to surface rupture. With all of these considerations in mind, grey pearlite low alloyed cast iron with elements like Mo, Ni, and Cu, which improve cast iron's hardness for cams, and surface-hardened, toughened, and ionitrided steel, which has a huge abrasive wear opposition to tribological wear, provides the most suitable materials for cams and followers [1].

2.7.6 Tribology in Internal combustion engines

Studies on friction and wear are expanding quickly for a variety of machine parts used in internal combustion engines, and this is a direct result of the automotive industry's increasingly stringent requirements for fuel economy, pollution, safety, and overall vehicle durability[7]. Since piston assemblies, valve train parts, and internal bearings are the main frictional components of vehicle engines, engine tribology research has undergone particularly remarkable improvements during the past ten years. The piston assembly, which makes up the majority of these friction sources, is responsible for almost 45% of all frictional losses in a typical engine [7].

The braking thermal efficiency of an engine can be greatly increased by reducing such frictional losses. in order to enhance engine performance. In order to improve engine performance, a lot of study was required to comprehend the tribological characteristics of the piston ring's contact with the cylinder liner. Contrary to engine bearings, the cylinder liners and piston rings' mechanism calls for a wide range of service speed during an operating cycle.

At the bottom dead center (BDC) and top dead center (TDC) of the stroke, the piston ring's speed is practically nil for a brief moment (TDC). There is essentially no chance that the lubricant will make contact under these circumstances. A boundary lubrication regime is therefore more important at BDC and TDC [7].
However, at the middle of the stroke, when the speed is the maximum, the fluid-film lubrication or hydrodynamic condition predominates. Squeeze film lubrication and elastohydrodynamic conditions of lubrication are anticipated to have a larger role in engine tribology at dead centers where there is little velocity. Engine tribology essentially includes all lubrication regimes.
The tribological testing of a piston ring assembly is intrinsically difficult. To analyze the frictional characteristics of piston rings, for instance, floating liners have been used2, but such application-oriented test setups require a unique design for every kind of engine. These specialized test apparatuses are not only expensive but also unable to accommodate conventional test specimens. The range of applications for data obtained from such carefully built test techniques is also constrained. As a result, such data cannot be successfully compared from one test to another and lacks universal application.
A cylinder liner and piston ring may now be subjected to standard tests3 thanks to advancements in technology. The most sophisticated mechanical testers on the market today can be set up for these tests and have the capability of comparing test results to one another. Such comparison testing can be used to create affordable engine lubricants and perform quality control on these oils, in addition to helping to enhance engine components. A UMT TriboLabTM (Bruker Nano Surfaces, San Jose, California) was used to conduct high-speed reciprocating tests for the comparative research detailed in this article. According to ASTM G181 document3, these were carried out by observing and documenting the tribological features of piston rings against a segment of cylinder lining [7]. With different combinations of test variables, including stroke, load, and frequency under lubricated circumstances.
Engine tribology is essential to the study, creation, and quality assurance of several machine components used in internal combustion engines. The most advantageous activity to increase an automobile's energy efficiency is thought to be the tribological evaluation of cylinder liner and piston ring components while they are lubricated because piston assemblies are the main cause of frictional losses in an engine [7].

2.7.7 Robotics, tribology, and human-machine interaction

The tribological components at the contact, such as body friction and wear problems, are what connect wearables with human-machine interaction. Robot joint problems involving friction, wear, and lubrication must be overcome to stop vibrations and allow for exact alignment. [5].

2.7.8 Joint Replacement

Wear and its effects continue to be a major factor in implant failure in prosthetic hips. Millions of wear debris can travel to the periprosthetic tissues every year, where they might cause osteoclast activity and localized systemic inflammatory close to the implant. This process, osteolysis, is well examined and may eventually lead to implant failure and loosening. [16].

Due to the biological effects of wear debris produced by prosthetic joints, it is crucial to develop accurate and concentrated wear reduction techniques. We may move beyond the old trial-and-error techniques and reduce hazards for the patient by understanding the multifactorial nature of wear and accurately simulating in vivo settings in the laboratory [16].

Therefore, it is essential to check surfaces. that have been worn under real "working conditions" in order to understand the system's affecting elements and successfully recreate them in a bench test [16].

This covers the primary aspects of tribology that relate to the articulating surfaces of hip prostheses. The first step is to define the various terms used to describe tribological systems, with an emphasis on the various wear mechanisms, wear modes, and lubrication regimes. Thus, the hip bearing is referred to as a tribological system with different lubrication regimes, material loss, heat, and even sound outputs. It is discussed how bearing material and form effect how hip bearing couples wear [16]. Following is a part on wear testing procedures that covers hip bearing thorough tests in simulators and material screening testing. A summary of current challenges and future directions in relation to hip wear is provided at the end of the chapter. Improvements to the wear of metal-on-metal bearings, some of them include the creation of brand-new coating materials for bearing surfaces, improvements to how prosthetic hip joints are tested for wear, and the creation of virtual wear testing to supplement the actual wear testing [16].

2.7.9 Gas turbine Tribology

With service, turbine surfaces experience significant degradation as a result of this harsh operating environment. Modern technological developments in the design and manufacture of gas path turbomachinery components have only increased the significance of comprehending the effects of flow path degradation on gas turbine operation.

Mineral oils are widely used as lubricants. It has a few positive highlights, for example, simple accessibility and moderately minimal expense. Mineral oils, on the other hand, also suffer from a number of serious flaws, include the oxidation and loss of viscosity at extreme temps, combustion or explosion in the presence of potent oxidizing agents, and solidification at cold temperatures. Even if there are instances when very low temperatures must be maintained, these effects are too much to handle in gas turbine engines where a lubricant with high temperatures is necessary.

Synthetic lubricants were developed to address some of the drawbacks of mineral oils. Countries without a consistent supply of mineral oil were the first to introduce synthetic lubricants at the beginning of this century. These lubricants were expensive and did not initially gain widespread acceptance. Synthetic oils saw a gradual rise in use, particularly in more specialized applications where mineral oils were insufficient. Lubricant with a low vapour pressure is required in other applications like vacuum pumps and jet engines; Lubricant with low toxicity is needed in the pharmaceutical and food processing industries, among other places. High-performance lubricants, especially those used in aviation with high-performance gas turbine engines, have seen the greatest demand in recent years. A crucial mechanism in any machine with rotating parts is the gearing of power transmission.[17].

2.8 Tribology in Manufacturing Industry

Another crucial area of tribological research is tribology in the manufacturing industry. The study of hot metal forming (friction and heat transmission), while the significance is mentioned in that fluids have decreased [18]. The Minimum Quantity Lubrication (MQL), a practical method for applying cutting fluids by reducing their amount, is important in today's machining processes because it is affordable and environmentally friendly. Tribology may aid in the growth of additive manufacturing by conducting tribological analyses on newly printed goods to learn more about their surface mechanical properties (friction, wear, lubricant interaction). Direct integration of sensors and actuators into machine components is possible with additive manufacturing [18].

2.9 Engineering Technologies, Materials, and Trigonometry

Without a doubt, research in nano- and micro-tribology, polymer and ceramic tribology, and nanotechnology has aided in the development of cutting-edge techniques and materials, including the fabrication of 2D materials like graphene and the investigation of nanoparticles to boost material resistance. The toxicity of the new materials and their structures must be considered. Biomimetics can be useful in this situation because it is aware of which substances and nanostructures in live nature are not hazardous [18].

2.10 Tribology and Big Data

Numerous connections exist between the idea of big data and tribology. There are already tribological networks and libraries of tribological data (such as data on wear or friction coefficient). Particularly in transient tribological experimental procedures, a significant amount of data from various equipment and sensors is collected. Often, data is stored on magnetic storage systems, which have tribological issues [5].

2.11 Tribology in Maintenance, Monitoring, and Diagnostics

It is commonly known that tribology plays a crucial role in maintenance engineering and It is crucial to identify potential issues with a machine as soon as they arise while it is in operation in order to minimize downtime and associated costs [7]. Improvements in the life prediction of components, such as rolling bearings, research on failure mechanisms, diagnostic analysis, and prognostic forecasts, and maintenance of working machinery are all impacted by tribology [4].
Rolling bearings have been designed with embedded sensors detecting torque, force, vibrations, and temperatures. Another option is a combination of sensors, power, diagnostics, and communications within the bearings for a full condition monitoring system [4].

For lubricated components to last longer in equipment, online monitoring of lubricants is crucial. Real-time measurements of wear debris in the lubricant are carried out, but vibration analysis is frequently used to diagnose faults in machinery that contains rolling bearings and gears, whether in conjunction with wear debris analysis or not [4], [18]. Several strategies for tribological condition monitoring are described. For space applications, maintenance-free mechanical assemblies are necessary, and the study of tribological interactions is crucial for space applications that are applicable to industry [7].

2.12 Contribution

The development of tribology is thoroughly discussed in this paper in the context of the research, demonstrating how it has progressed over time through the use of engineering improvements, materials science, and energy conservation.

It discussed how improved lubrication in machine parts reduces friction, which reduces energy consumption and offers further benefits economically by reducing costs associated with routine maintenance, part replacement, and lubricant costs. Additionally, it improves mechanical efficiency and results in a reduction in personnel.

This research elaborated on how one-third of the energy being wasted can be redirected and used efficiently by the rate of friction reduction in light of the improvements in tribology about energy consumption. The study discussed how the use of fluid film bearings might lower energy consumption in moving parts such as engines, machinery, and metalworking by advancing tribology. In circumstances like internal combustion energy, where tribological developments have reduced the emission of toxic gases from the exhaust system of the various machines, this also aids in the decrease of the heat created by machine parts contacting one another.

This essay also discussed the advancements made in the fields of materials, tribology, and erosive wear reduction in areas like pipes, as well as the replacement of typical cast iron surfaces with rubber-coated ones. It also unwrapped the idea that coating surfaces like tools and machine parts with a special coating can slow down the rate of wear on those components.

Nanotechnology and advances in tribology are being used to reduce friction in both its power and colloidal form. The mechanical characteristics of metals are improved by its use in nanofluids, which are additions in metals.

Conclusions

The relative motion of media in contact is the cause of friction, a dissipative process. In order to maintain this relative motion, an ongoing supply of energy is required. This motion can typically be described as a combination of rolling (angular displacement with respect to a tangential axis), sliding (linear displacement tangential to the contact plane), and spin (angular displacement with respect to the normal axis).

Frequently, the effort put in to combat friction is redundant; that is, it offers nothing to the functioning of the machine of which the bodies are a part, and eventually should be disseminated as waste intensity since it opposes the free movement of parts in a machine leading to loss of useful energy which could be used to do useful work. As a result, the goal of tribology is to keep these frictional forces as low as possible in the majority of tribological designs. All machine surfaces are rough and, surprisingly, the most finely pre-arranged surfaces will show abrasiveness when in contact with other surfaces in contact. A lot of very small regions of contact make up the actual area of contact. Asperities or junctions of contact are the names given to these regions where contact between atoms takes place.

The main aim of tribology has been to curb the effect of friction between bodies in contact. This is due to several factors which have potentially led to energy losses in the past. Therefore, the term lubrication has been infused into the depths of tribology, as it looks for highly effective methods to tackle friction. All liquids offer some form of lubrication, but some are much better than others. Frequently, the success or failure of a machine is determined by the difference between two lubricating materials. Lubricants play vital roles in contact surfaces of machines which include; Lubrication, cooling, cleaning, and suspending. Among these, as is protecting metal surfaces from corrosive damage. A base fluid and an additive package make up lubricant. The essential capability of the base liquid is to grease up and go about as a transporter of added substances. Either adding a new property to the base fluid or improving an existing one are the two goals of additives. Added substances are synthetic mixtures added to greasing up oils to give explicit properties to the completed oils. The lubricant gains new and useful properties from some additives; Some act to improve properties that are already present, while others act to slow the rate at which unfavorable changes occur in the product over its lifespan. In terms of enhancing the performance characteristics of lubricating oils, additives have significantly contributed to the improvement of industrial machinery and prime movers.

The world today has morphed into a reservoir of greenhouse gasses consistently given off as waste that are harmful to the atmosphere. This has been due to the ever-existing production sector, which has resulted to several harmful effects such as global warming, climate change, etc. It has given a subtle reminder to reduce the adverse effects of waste on our environment. In industrial processes, the concept of lubrication cannot be overemphasized, as it forms a foundation on which mechanical machines operate. In light of its importance, parts of mechanical machines need to overcome friction to work efficiently. The failure to curb friction, most times leads to the emission of greenhouse gasses to the environment by the machine, especially in combustion engines. Also, the lubricants have to be environmentally friendly to ensure the use of these lubricants do not harm the environment when emissions occur due to the depletion or during disposal of these lubricants. Tribology has always looked for a way to tackle the problem of harmful fluid emissions to the environment either directly or indirectly.

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