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OVERVIEW OF TRIBOLOGY AS AN INTERDISCIPLINARY SCIENCE

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Abstract: *This publication explores the classification of elements in tribology, the science of friction, wear, and lubrication, which plays a crucial role in various industrial applications and engineering solutions. The primary objective of the study is to systematize and analyze the different approaches to classifying tribological systems, emphasizing the impact of materials, design features, and operating conditions on tribological behavior. The research explores the main types of tribological elements, mechanical properties, the chemistry of tribo-surfaces, physical properties, and forms of wear, while also identifying the factors affecting their behavior under diverse conditions. Additionally, innovations in materials and lubricants that enhance the efficiency of tribological systems are discussed. The findings of this research will serve as a foundation for a better understanding of tribological mechanisms and will support the development of new techniques and technologies aimed at optimizing manufacturing processes and prolonging the operational life of mechanical components.*

Keywords: *tribology, friction, wear, lubrication, tribo-surfaces*

1. INTRODUCTION

Tribology is a synergistic, multidisciplinary field that merges materials science with mechanical engineering. It focuses on the science of interacting surfaces in relative motion, incorporating concepts such as wear, friction, and lubrication [1,2,3]. The term "tribology" was first introduced by Professor H. Peter Jost in 1966 [4, 5]. This scientific discipline examines the interactions between the surfaces of materials when they are in relative motion, integrating physics, mechanics, engineering, and materials science to understand and enhance the processes of friction, wear, and lubrication. The term "tribology" derives from the Greek word "tribos," which means "friction," combined with the suffix "-logy," indicating "the study of" or "knowledge about," thus rendering the literal translation as "the science of friction" [1,2,4].

Tribology is recognized in many dictionaries as "the science of interactions between surfaces in relative motion" or "the study of friction, wear, and lubrication, as well as bearing design" [6]. Tribology is often defined as the science of surface interactions in relative motion, focusing on friction, wear, lubrication, and bearing design. The complex interactions between solid surfaces require interdisciplinary knowledge from physics, chemistry, applied mathematics, solid and fluid mechanics, thermodynamics, materials science, and engineering. As technology advances and industry needs evolve, tribology's importance grows, particularly in optimizing friction and wear to improve efficiency, reduce costs, and extend the lifespan of machines.

The study of tribology centers on the mechanics of interacting interfaces, specifically examining mass loss (wear) and energy dissipation (friction). It's crucial to understand that friction and wear result from various experimental parameters and operating conditions, not inherent properties. Differences in wear behaviors among materials are influenced by their unique physical, chemical, mechanical, and adhesive properties [7].

The discipline encompasses specialized areas such as automotive, aerospace, and medical tribology, which address specific applications. Gaining a deeper understanding of friction and wear is pivotal for the design and optimization of mechanical systems, which is essential for enhancing the durability and efficiency of machines.

One of the areas in which it is used and of paramount importance is for the visually impaired and blind. These users use their fingers to read, to explore the world through the tactility of any object where the surface has an effect.

The complexity of tribology increases as it is closely related to numerous practical applications where theoretical formulations may be limited. This is where the need to designate individual units in tribology originates, and this article aims to outline them.

2. TRIBOLOGY

Tribology encompasses all aspects related to lubrication, friction, and wear [2, 8]. Improving the performance of mechanisms such as bearings, slides, roller bearings, gears, etc. requires the optimization of multiple factors, including kinematics, geometry, clearances, lubricants, materials, and surface treatments. Since friction and wear are the main causes of failure in mechanisms, tribology plays a key role in saving energy and materials, extending the life and reliability of mechanisms, as well as in controlling friction. Tribology is an intersection of various disciplines, including solid and fluid mechanics, solid and surface physics, metallurgy, chemistry, etc. [2, 5]. The interrelationship of friction, wear, and lubrication is often described as the tribology triangle, shown in fig. 1 [2].

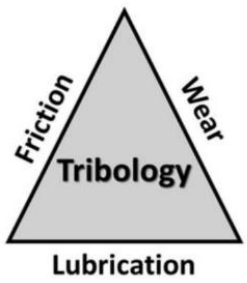

Figure 1. Tribology triangle [2]

2.1 Friction

Friction is a natural phenomenon that plays an important role in our daily lives. In the scientific field of tribology, friction is often considered a major factor contributing to wear and energy loss in sliding systems. The term "friction" was first used in the 16th century and is derived from the Latin word "frictio", meaning "rubbing", and from the Middle French "friction", which is derived from the verb "fricare", meaning "to rub". The initial use of the term "friction" to describe "resistance to motion" is documented in the 17th century [9].

Two main types of friction are distinguished: (1) static friction, which precedes the onset of relative motion between two solid surfaces, and (2) kinetic or dynamic friction, which occurs between two moving surfaces. To distinguish between the two cases, in static friction the force generated between the two solid surfaces is sufficient to resist the motion, while in dynamic friction it is not. In both cases, friction can be quantitatively defined as the force generated between the solid surfaces in the direction opposite to that of the relative motion (for kinetic friction) or potential motion (for static friction).

2.2 Wear

Wear is considered one of the primary causes of material loss and/or surface deformation, which can ultimately result in damage to mechanical components [10]. The term "wear" was first used in the late 13th century in reference to clothing, indicating their gradual deterioration due to extended use. In the realm of tribology, wear is defined as the deformation and gradual removal of material from a solid surface due to mechanical and chemical interactions with the opposing surface [2]. Among the various manifestations of this phenomenon, wear can be defined as "the progressive loss of material from the working surface of a body as a result of relative motion between the surfaces" [11]. Depending on the properties of the surfaces and the operating conditions, different mechanisms of wear may dominate in contacting bodies, including adhesive, abrasive, surface fatigue, impact, friction, erosion, and corrosive wear. From an engineering perspective, wear is generally seen as an undesirable phenomenon, as it is frequently encountered in practical applications. However, this is not always the case. There are many beneficial applications of the wear process. For example, the production and finishing of surfaces through abrasive techniques, as well as the use of pencils or chalk, illustrate instances of desirable wear. Thus, in practice, wear does not always need to be avoided. Since ancient times, efforts have been made to enhance the smoothness of motion of an object across a surface, as well as to minimize wear and control friction [2]. This has resulted in the necessity to introduce substances, fluids, or solid films to reduce contact between moving surfaces.

2.3 Lubrication

Lubrication serves as an effective means to minimize friction and to prevent or manage wear [12]. The term itself was first recorded in the early 19th century and is derived from the Latin word "lubricatus," which is the past participle of "lubricare," translating to "to make slippery" [13]. Given that lubrication can greatly influence the functionality of tribosystems — defined as any system containing tribological components—one commonly accepted definition describes a lubricant as "a substance that can modify the interaction between the surfaces of contacting solid bodies." It is essential to highlight that the term "substance" in this context is not limited solely to liquid oils, as it might initially seem; while liquid oils are indeed frequently used as lubricants in various scenarios, lubrication encompasses other forms as well, including liquid lubrication, grease, solid lubrication, and lubrication utilizing air and gases.

In suitable contexts, any liquid, such as water, can act as a liquid lubricant. In the realm of liquid lubrication, the lubrication regime is dictated by the conditions surrounding the lubricant within the sliding system. The three primary lubrication regimes are liquid film lubrication, boundary lubrication, and mixed lubrication. A key characteristic of lubricants in liquid lubrication is their viscosity.

Grease consists of a stable combination of a liquid lubricant (which can be either mineral or synthetic) and a thickening agent [14]. Additionally, various additives may be incorporated to provide specific properties. Solid lubrication involves placing a soft solid film between sliding surfaces, which can also arise from a chemical reaction between the sliding surfaces and their environment. Furthermore, air or gas has gained popularity as a lubricant in high-speed applications involving bearings in motion.

Across all the described forms of lubrication, the primary goal remains to reduce friction, wear, and surface adhesion. In certain situations, lubrication is introduced into tribosystems to help regulate interfacial temperature. When lubrication fails, the hard surfaces of engineering components may come into contact with one another, leading to increased friction and heat generation. This situation can result in surface damage, including localized welding, material removal, or transfer, and ultimately, the failure of the system.

3. CLASSIFICATION OF TRIBOLOGY ACCORDING TO THE MAIN TYPES OF UNITS

The main types of tribological units include: the importance of tribology, basic principles, applications, general theories, classical methods, forces, coefficients, mechanical properties, chemical properties of tribo-surfaces, physical properties, forms of wear, and factors influencing their behavior under different conditions.

3.1 Importance of tribology

The importance of tribology is the first part, which covers two aspects that are related to economics and production: industrial and financial importance. These two aspects require the study of materials and their interactions, and their results are indicative of progress in production. Tribology has significant financial and industrial benefits [2].

Financial importance - Tribology offers significant financial advantages to businesses and industries, with the main aspects including:

- Material savings: By optimizing friction and choosing the right lubricants, companies can reduce component wear. This not only extends the life of machines but also reduces the need for frequent replacement of parts, leading to savings in production costs.
- Energy savings: Improving the tribological properties of mechanical systems helps reduce energy consumption. When friction is minimized through appropriate technologies and materials, it allows machines to operate more efficiently and with lower energy consumption, which is not only economically beneficial but also environmentally friendly.

Industrial significance - Tribology also has a significant contribution to the industrial sector, which can be summarized in the following aspects:

- Increased uptime: Optimization of friction and wear using tribological studies leads to better machine performance. This means that equipment can operate for longer without failures, and therefore production can be more efficient.
- Reduced maintenance costs: By reducing wear and increasing the reliability of machines, maintenance costs are significantly reduced. Better tribology prevents frequent repairs and replacements, which is beneficial to organizational health and budgets.
- Development of energy-efficient technologies: Tribology is key to innovation and the development of sustainable technologies. The implementation of energy-efficient technologies not only reduces the existing uncontrolled consumption of fuels but also minimizes the negative impact on the environment. This is especially important in the context of global efforts to address climate change and the resource crisis.

3.2 Basic principles, applications, general theories, classical methods, forces, coefficients

Tribology, the science of friction, wear, and lubrication, encompasses a variety of fundamental principles, theories, and methods that are crucial for understanding the mechanical interactions between different materials. The division of tribology into key aspects such as forces, coefficients, theories, and lubrication provides a foundation for its application in industry and the development of effective technologies.

Friction - Friction can be classified into two main categories:

- Dynamic friction: This occurs when two surfaces move relative to each other.
- Static friction: This describes the state in which the surfaces are not moving but still exhibit resistance to motion.

Wear - Controlling friction is critical for minimizing wear, which leads to material loss and deformation of surfaces. The major types of wear include:

- Deformation: Changes in the geometry of the surfaces.
- Surface wear: Material loss that affects the functionality of components.
- Wear resistance number: A measure that evaluates the resistance of materials to wear.
- Pitting wear: Concentrated wear that affects small areas of the surface.
- Peeling wear: Common in materials with lower hardness.
- Oxidative wear: Associated with chemical reactions that lead to material degradation.

Lubrication - Lubrication is essential to minimize friction and wear. In industrial practice, lubricants are classified as: Heavy oils, Medium oils, Light oils. Lubricant characteristics include economic and technical-operational parameters, such as operating speed, temperature, and chemical composition, which affect the provision of effective protection to machinery.

Theories of Friction – Several theories explain the mechanisms of friction:

- The basis of the possibility of welding surfaces: This theory considers how the mechanical interaction of surfaces can lead to integration between them.
- Electrostatic interaction: Interactions between molecules on surfaces can cause significant friction.
- Mechanical engagement of microroughness: The microroughness of surfaces plays a role in the interactions, which is a prerequisite for the main deformations and destruction of microgrowths on surfaces.

Basic principles and theories - The basic principles of tribology, shown in fig. 2 include the determination of force and coefficients of friction, which play an important role in the assessment of friction between surfaces.

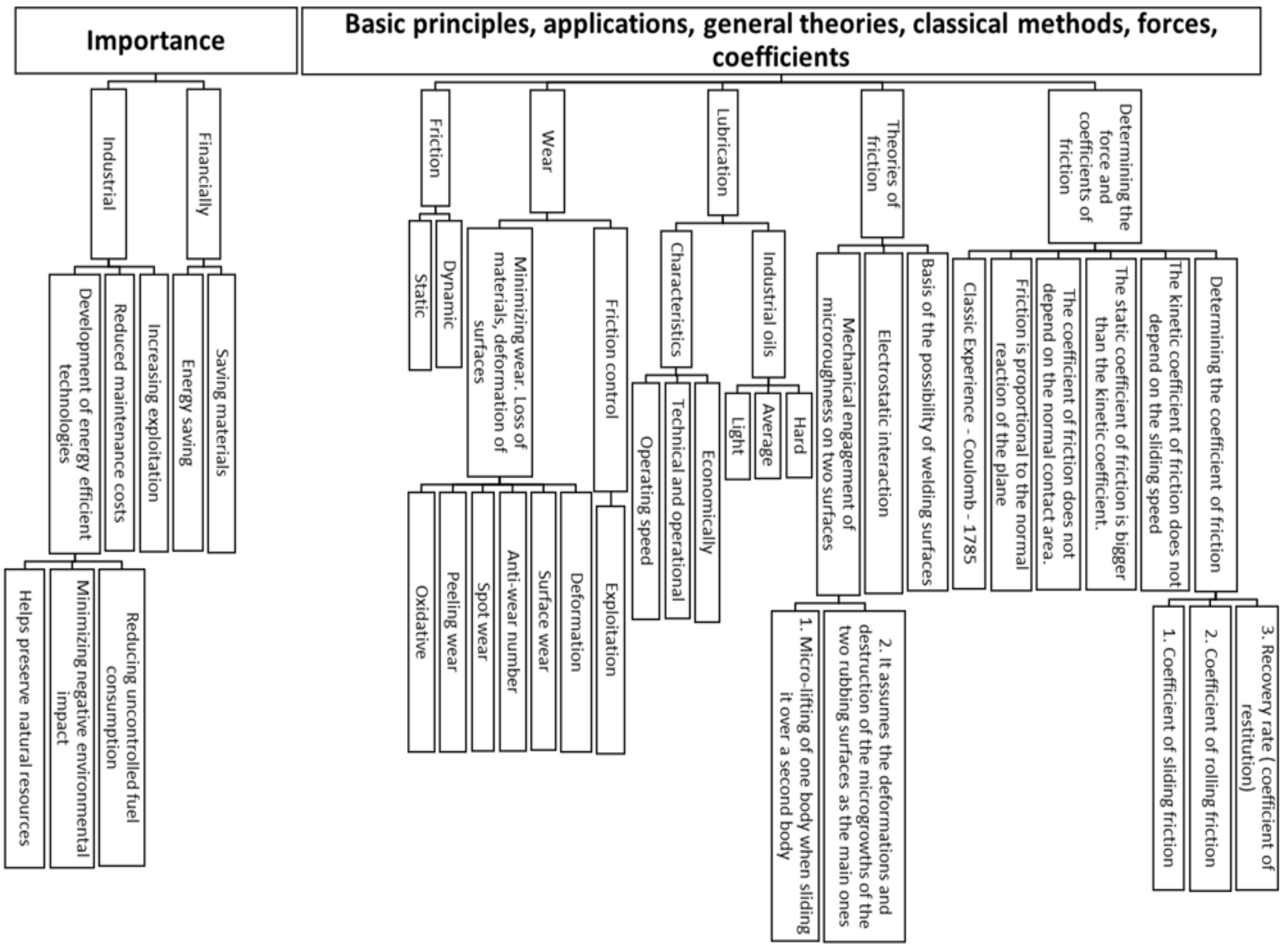

Figure 2. Schemes of Importance and Basic principles

The classic experiment of Coulomb in 1785 is fundamental to the theories of friction and estimates the main parameters affecting the process. The kinetic coefficient of friction does not depend on the sliding speed, which is important for stable dynamic systems. The static coefficient of friction is usually higher than the kinetic one, which indicates that the initial movement of an object is more difficult than maintaining it in motion. In addition, the coefficient of friction does not depend on the normal contact area, but is proportional to the normal reaction of the plane dynamically controlling the friction.

Determination of force and coefficients of friction: The coefficient of friction can be different depending on the conditions and nature of the contacting surfaces.

- Coefficient of sliding friction - This is the main coefficient that determines the friction between two surfaces when one slides over the other.
- Coefficient of rolling friction - This coefficient is significantly lower than that of sliding and is important in dynamic applications where wheels or rollers play a role.
- Coefficient of recovery - The coefficient of recovery (restitution) is used to demonstrate the rate of energy dissipation involving collisions of surfaces, most often a sphere. The recovery rate depends on many elements, such as the geometry of the bodies in contact, the speed of approach, the properties of the material, the duration of the contact, and any friction [15].

3.3 Mechanical properties

Hardness – Hardness is a property of materials that indicates their ability to resist deformation or penetration. In the Handbook of Metals, it is described as the resistance to plastic deformation, typically assessed through indentation. Higher hardness means greater resistance to deformation under applied load. Three main types of hardness are measured: indentation hardness, scratch hardness, and rebound hardness.

- Indentation Hardness - Indentation hardness for metals can be measured by the depth of the indentation. The three most common testing methods are the Brinell hardness test (BH), the Rockwell hardness test (HR), and the Vickers hardness test (HV). Different indenters, such as a diamond pyramid, hardened steel ball, or tungsten carbide ball, may be used depending on the testing method. Conversion tables exist for comparing hardness values across these methods, though their accuracy depends on the precision of the data provided. The Rockwell test can also assess the hardness of ceramic substrates. By applying two different loads (small and large), the difference in indentation depth can be measured, allowing direct hardness readings using conversion tables. For plastics, the Rockwell and Shore hardness tests are commonly employed, providing empirical hardness values that may not correlate with other properties. Shore D is often used for "hard" polymers, while Shore A is used for "soft" rubber. Indentation hardness is particularly relevant for tribological applications due to its similarity to the geometries involved in surface interactions. While hardness is a key parameter for material selection against abrasive wear, the relationship between hardness and abrasion resistance is not straightforward, as abrasion depends on various external factors. For materials with surface hardening or specific phase compositions, hardness may vary with depth, making both surface and bulk hardness considerations important in tribological applications.
- Scratch Hardness - The scratch hardness test is primarily used to study single-cycle deformation processes in a material due to friction from a point (the stylus tip) and how these processes depend on various material parameters. The test involves pressing the stylus against a flat sample

with a specific normal load and moving either the stylus or the sample. The resulting groove depth or imprint size is used to calculate scratch hardness (HSp) or to characterize wear resistance. Generally, scratch hardness is a more suitable measure of a material's abrasion resistance than static hardness values. Additionally, a pendulum apparatus can be used by attaching the stylus or a single abrasive grain. When released with a certain energy, the stylus or grain penetrates the sample to a specific depth, creating a groove.

Deformation

- Elastic Deformation - Elastic deformation is a recoverable change in shape of a material that occurs under normal loading and disappears once the load is removed. It is governed by Young's modulus (E). If the load exceeds a certain threshold, plastic deformation may occur. In a typical tensile test, stress is calculated as the applied force divided by the cross-sectional area, while strain is the extension divided by the original length [2].
- Creep Deformation - Creep deformation refers to the time-dependent behavior of materials. Unlike instantaneous elastic or plastic deformation, creep deformation accumulates over time under constant load, defined as "progressive deformation of a material under constant stress." Creep can lead to failure during testing, as the deformation continues until damage occurs. The "creep rupture strength" is time-dependent and relates to both stress and time [2]. Additionally, cyclic loading at elevated temperatures can exacerbate material degradation due to the creep-fatigue interaction. This interaction describes how creep damage occurs at weak points in a material's internal structure, like grain boundaries, reducing its plasticity and accelerating crack growth. Physical mechanisms causing creep damage in solids include atomic diffusion and dislocation movement over time. Creep typically exhibits three stages on a time-deformation curve: the transient stage (immediate elastic and possible plastic deformation), the steady-state stage (gradual accumulation of creep deformation), and the unstable stage (accelerating deformation leading to rupture). Creep is often expected in materials with low hardness and strength, such as polymers, due to weak bonding between molecular chains. In crystalline materials like metals, creep becomes significant at high temperatures, particularly between 0.3 and 0.6 times their absolute melting temperatures [2]. Amorphous materials like glasses exhibit more complex creep behavior; at low temperatures (below the glass transition temperature), creep involves molecular chain movement and may recover after stress removal. Above the glass transition temperature, creep behaves like a viscous flow and is generally irreversible.

Fatigue - Fatigue analysis is crucial for the design and operation of engineering parts or components, with over 80% of mechanical service failures attributed to this phenomenon [2]. Awareness of fatigue began in the early 1800s when European researchers observed cracking in bridge and railway components under cyclic loads.

- Fatigue Failure - In components subjected to cyclic (or variable) loading, fatigue cracks may initially appear on the surface at a micrometer scale, followed by crack propagation that grows with each load cycle until reaching a critical size, ultimately leading to fatigue failure [2]. These cracks often initiate early in a component's service life or may preexist due to manufacturing processes. Fatigue damage can occur at stress levels significantly lower than the material's tensile strength measured under single-cycle loading. Additionally, repeated heating and cooling can induce cyclic thermal stresses, known as thermal fatigue. In fatigue situations, fracture mechanics is commonly used to analyze fatigue issues. Predicting and preventing fatigue failure is essential in the design of machinery and structures exposed to cyclic loads or vibrations, requiring a thorough understanding of the mechanisms governing fatigue crack initiation and growth, as well as their dependence on operating conditions and the environment.

- Fatigue Life - Fatigue endurance is typically divided into two stages: (1) crack initiation and (2) crack propagation. In the crack initiation stage, microcracking may occur, which is often too small to observe. During the crack propagation stage, the crack grows slowly but steadily, followed by rapid expansion leading to complete failure [2]. It is important to note that the mechanisms governing crack initiation and propagation can differ, necessitating separate treatment of these stages.
- Stress-Life Curve -The stress-life curve, also known as an S-N curve, is a graphical representation used to describe the relationship between the cyclic stress amplitude (S) and the number of cycles to failure (N) for a given material. It is constructed from experimental data obtained through fatigue testing. The curve typically shows that as the applied cyclic stress increases, the number of cycles to failure decreases. The S-N curve is essential for predicting the fatigue life of materials and for the design of components subjected to cyclic loading [2].
- Fretting Fatigue - Fretting fatigue is a specific type of fatigue that occurs at the contact surfaces of two materials that experience small relative motion or oscillation under load. This small movement can lead to the formation of wear debris and surface damage, which can initiate cracks at the interface. Fretting fatigue is particularly relevant in situations where tight-fit joint interfaces are subjected to vibrational or cyclical loads, such as in bolted connections or bearing surfaces.
- Surface Fatigue - Surface fatigue refers to the fatigue damage that occurs primarily at the surface of a material, often due to the repetitive contact stresses experienced during operating conditions. It typically manifests as cracks or pitting that form at or near the surface, which can propagate inward over time. Surface fatigue is a critical consideration in applications involving bearings, gears, and other components that experience high surface contact pressures. Prevention measures, such as surface hardening, lubrication, and the use of appropriate materials, are essential to mitigate surface fatigue.

3.4 Chemistry of Tribo-Surfaces

The chemistry of tribo-surfaces, shown in fig. 3 involves the study of processes occurring between contacting surfaces, including reactions with the environment, such as liquids, gases and vacuum. Various phenomena take place at tribo-surfaces, including adsorption, diffusion, adhesion, surface forces, and chemical reactions. Surface chemistry, or reactivity, is an external property that makes material surfaces and interfaces conducive to chemical processes [16]. The term reactivity encompasses both kinetic and thermodynamic factors that influence the rate and ability of chemical reactions, which can vary with temperature. Surface chemistry typically occurs at the molecular level, where surface atoms exhibit different chemical behavior compared to bulk material, often showing a high propensity for chemical reactions. Adsorption is often recommended as one of the steps in these reaction mechanisms.

Adsorption - Adsorption is the process by which atoms, ions, or molecules adhere to the surface of a material, known as the adsorbent, contrasting with "absorption," where particles penetrate the bulk phase of the material. It can be classified into two types based on the strength of interaction between the tribosurface and the environment: physical adsorption (physisorption), which involves weak van der Waals forces, and chemical adsorption (chemisorption), which occurs through chemical bonds between the adsorbent and the adsorbate. In lubrication technology, particularly in boundary lubrication, adsorption on tribo-surfaces and the subsequent changes in surface chemistry are crucial for the performance of lubricants and surface additives [14], [17].

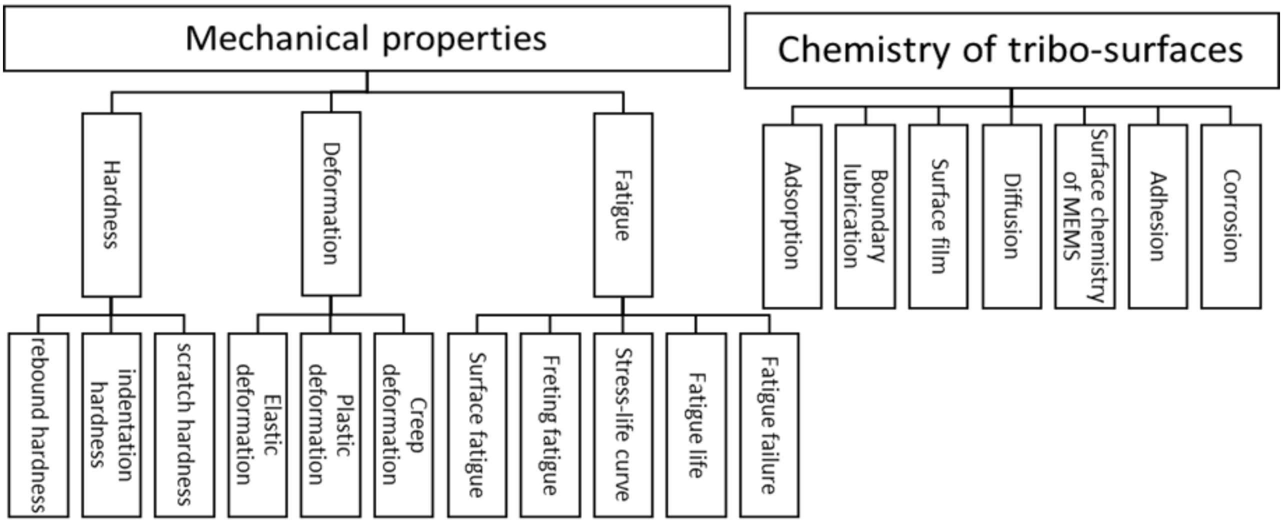

Figure 3. Schemes of Mechanical properties and Chemistry of tribo-surfaces

Boundary Lubrication - Boundary lubrication is considered one of the most extreme conditions in tribology and poses challenges for tribochemists. The primary mechanism for the formation of boundary films is the process of adsorption, which occurs under high loads and/or low speeds, where the thickness of the lubricating film is minimal. In boundary lubrication, chemical reactivity influences the formation of the lubricating film by preventing direct contact between surfaces through adsorbed molecules [12]. Monolayers of molecules reduce friction and protect surfaces. The reactivity of lubricant molecules may indicate potential corrosion, and not all lubricant formulations have the same tribological effect. Additives are commonly used in lubricating materials to facilitate the formation of boundary films, with polar additives bonding to the surface to achieve low friction. The molecular weight of the additives significantly affects their tribological characteristics, as higher molecular weights generally increase the load-carrying capacity. Recently, biodegradable nanoparticles, such as those from boric acid, have shown promising results in significantly reducing friction and wear losses.

Surface Film - Almost all metals and alloys form a natural oxide film when exposed to air, and may also develop sulfide, nitride, and chloride films depending on environmental conditions and alloy elements. These films are typically nanometer-thick, varying by metal due to the chemical reactivity at the metal-environment boundary. For example, a typical natural oxide film on stainless steel surfaces in air is only a few nanometers thick. Such films significantly affect interactions between surfaces based on their chemical and mechanical properties. A beneficial tribological effect can occur with the formation of a soft adhering film that acts as a lubricating layer, separating contact surfaces, while hard, brittle films are less effective as they tend to crack during operation. According to Quinn's theory, oxidation is enhanced by locally high contact temperatures from frictional heating, leading to wear when the hard, brittle oxide layer exceeds a critical thickness and cracks. Recent studies by Merz et al. investigate the formation mechanisms of the oxide film on steel surfaces and its tribological behavior in various environmental conditions, suggesting that thick oxide films formed during sliding due to high contact temperatures can grow to micrometer thickness, contrasting the nanometer oxide layer developed under atmospheric conditions. Results support the theory that contact with local roughness enhances surface oxidation [2, 12].

Diffusion - In chemistry, diffusion refers to the movement of fluid molecules within solid materials, typically porous solids. Diffusion occurs when the likelihood of molecules colliding with each other is greater than colliding with pore walls. In tribology, diffusion treatment (or diffusion annealing) involves modifying surface properties by introducing interstitial or substitutive atoms from an external source. Sometimes, diffusion annealing is required to further adjust the microstructure and properties of treated materials, involving heating to temperatures above the recrystallization point followed by slow cooling. For steels, heating temperatures range from 1050 to 1300°C, allowing for long diffusion paths that may require several hours [2]. During this process, atoms diffuse to move the material toward its equilibrium state. The diffusion rate is influenced by concentration gradients, temperature, treatment duration, and the diffusion coefficient of the base material. Atomic movement leads to the removal and redistribution of dislocations in metals, which increases ductility. Surface modifications through diffusion are often applied in tribological applications where wear and corrosion resistance are needed. Techniques like nitriding, carburizing, and boronizing enhance surface hardness and wear resistance. However, boronizing may lead to cracking due to inconsistencies between the phases formed. Post-boron diffusion annealing is proposed to achieve a single-phase structure, enhancing mechanical and tribological properties. A key drawback of diffusion annealing is grain coarsening due to high processing temperatures and slow cooling, requiring subsequent treatments like normalizing to refine the structure for engineering applications.

Surface Chemistry of MEMS - The surface properties of micro-electromechanical systems (MEMS) are critical due to their high surface-to-volume ratio [2]. Controlling surface forces, particularly adhesion between contacting surfaces, is a major challenge in the operation and maintenance of MEMS. Adhesive forces can arise during device operation, potentially causing system failure. To enhance performance, various surface treatments have been applied to modify the surface chemistry of MEMS, significantly reducing adhesion based on surface functionality and roughness. Treatment examples include: (a) plasma deposition of fluorocarbon films; (b) textured surfaces; (c) hydrogen passivation using HF or NH_4F; and (d) formation of self-assembled monolayers (SAM) on contact surfaces. Additionally, humidity significantly impacts surface properties and the reliability of MEMS devices. Adsorbed water can act as a lubricant in magnetic tape systems, while the friction behavior of silicon plates can be greatly influenced by water presence. Conversely, liquid films may lead to high static friction and adhesion between MEMS surfaces, creating both beneficial and detrimental effects on tribological characteristics depending on the surface properties and sliding conditions.

Adhesion - Adhesion is the ability of one substance to stick to another and occurs between solid surfaces when two surfaces slide over each other or are pressed together. Interactive forces (metallic, covalent, hydrogen, ionic, and van der Waals) create adhesive bonds at the atomic level. To separate two adhered surfaces, a certain force (adhesive force) must be applied in the desired direction, which may lead to the formation of unwanted wear fragments.

Corrosion - Corrosion is a chemical process in which materials, typically metals, deteriorate due to interactions with their environment, particularly moisture and oxygen. This phenomenon can result in significant structural damage, making it crucial to consider during the design and maintenance of structures and mechanisms.

3.5 Physical properties

The coefficient of adhesion (fa) is defined as the ratio of the adhesive force (Fa) required to separate two bonded surfaces—this can be either normal tensile or shear force—compared to the initially applied normal compressive force (Fc) that keeps the two surfaces together. The physical properties are shown in fig. 4. It is often directly proportional to the duration of static contact and the rate of separation. The adhesive force is also proportional to the actual contact area, which is influenced by the surface roughness and the mechanical properties of the interacting bodies, as well as external loading conditions. Generally, an increase in normal load results in a larger actual contact area, thereby enhancing the adhesive strength. Mathematically, the adhesion coefficient is expressed by the following formula [2]:

$$\mathrm{f_a} = \frac{\mathrm{F_a}}{\mathrm{F_c}} \tag{1}$$

Additionally, when a shear force is applied alongside the normal load, plastic flow resulting from the combined stress will further increase the real contact area, leading to enhanced adhesion. Temperature significantly affects adhesion, with higher temperatures typically resulting in stronger adhesion due to the softening, increased flow, plasticity, and solubility of solid surfaces, especially in polymers. For metals, adhesive behavior can also be influenced by intrinsic material properties such as crystal structure, crystallographic orientation, chemical reactivity, and contact interface conditions, including charge separation, contact duration, and separation rate (Bhushan, 2013a).

Surface energy (γ)- is a key factor that influences adhesion, with lower values of this energy leading to reduced adhesion. Additionally, the presence of oxides, lubricants, or contaminants on contact surfaces typically lowers surface energy and exacerbates adhesion issues. Surface energy of materials is defined as the work required to create a new unit area (in J/m²). The theory of adhesion, developed by Bradley (1932) and Bailey (1961), incorporates the concept of "free surface energy [2]." According to their work, the adhesion work (Wad) between two materials per unit area is described by Dupre's formula:

$$\mathrm{w_{ad}} = \Delta\gamma = \gamma_1 + \gamma_2 - \gamma_{12} \tag{2}$$

where γ_1 and γ_2 are the surface energies of the two materials, and γ_12 is the surface energy of the interface.

Wettability - is a physical property that describes a droplet's ability to either adhere to or spread on a solid surface, typically expressed through the contact angle (θ), as shown in Figure 1.5. The contact angle is defined as the angle between the tangent to the liquid surface at the point of contact and the solid surface at equilibrium conditions. This relationship can be described by Young's theory (Young, 1805)[2]:

$$\cos\theta = \frac{\gamma_{\mathrm{sv}} - \gamma_{\mathrm{sl}}}{\gamma_{\mathrm{l}\,v}} \tag{3}$$

where γ_sv, γ_sl, and γ_lv represent the interfacial tension of gas-solid, solid-liquid, and gas-liquid interfaces, respectively.

The contact angle can be used to determine whether a surface is wettable (highly hydrophilic, 0° < θ ≤ 45°) or not (highly hydrophobic, 90° < θ ≤ 180°) [2]. Various experimental methods have been developed to measure the contact angle. However, in some situations it is practically difficult to measure or predict the contact angle (e.g. for a very small droplet at the nanoscale and with the necessary other techniques, including a simulation method, to quantitatively predict the wettability properties) (Blanck et al., 2020; Yuan & Lee, 2013).

In theory, the degree of wettability is the result of the balance between two forces:

a) the force of adhesion of the liquid to the surface

b) the force of adhesion of the liquid to the liquid.

Bertrand, Blake, and Coninck (2009) introduce theoretical models to describe the wetting dynamics of a liquid droplet.

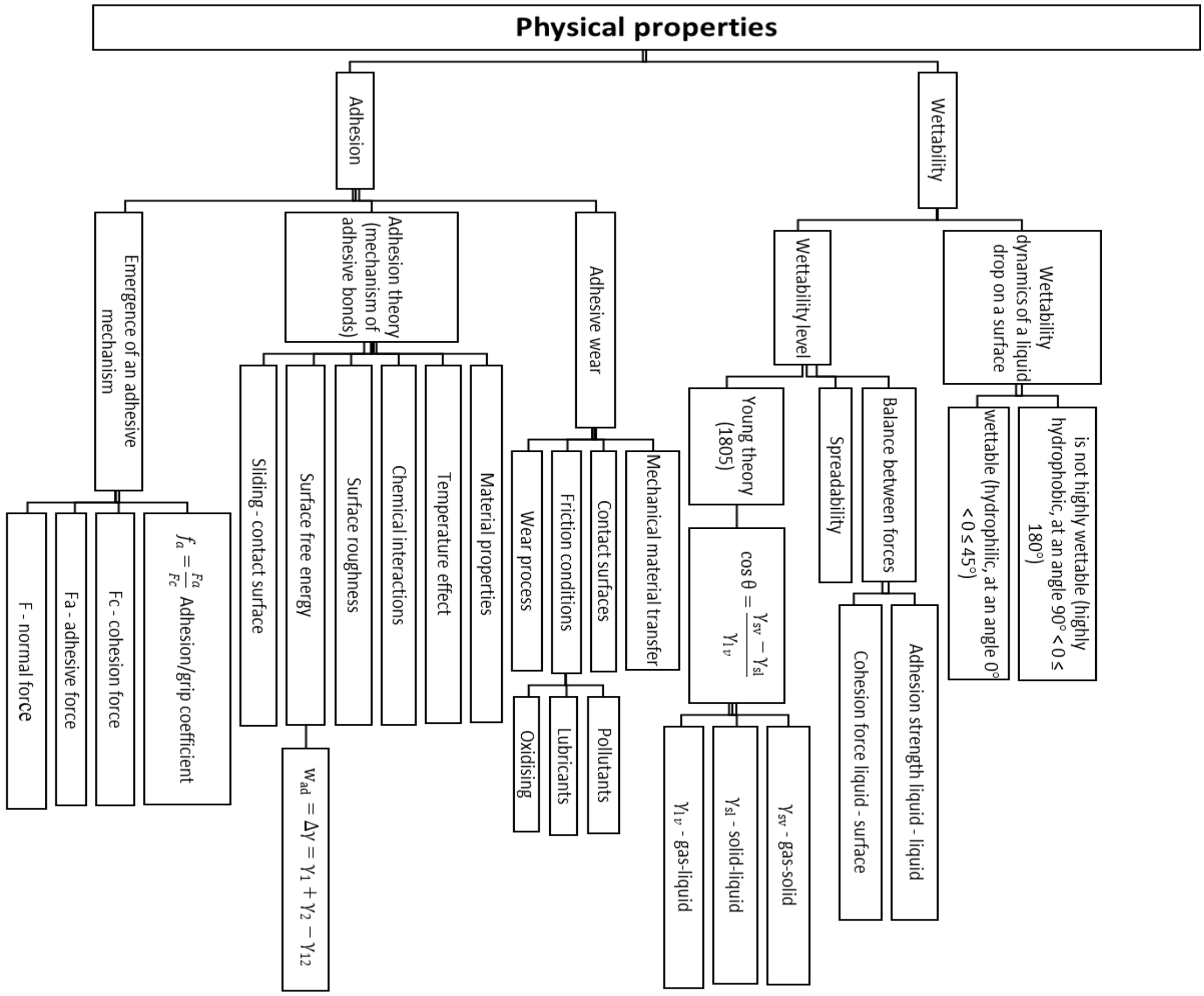

Figure 4. Scheme of Physical properties

3.6 Forms of Wear: Abrasive, Erosive, and Cavitation

Wear can occur through abrasive and erosive processes, both resulting from the interaction between particles and solid materials. Abrasive wear involves material loss due to solid particles moving across a surface, while erosive wear is caused by particles impacting a hard surface. Cavitation, on the other hand, occurs when a localized liquid force acts on a surface during bubble collapse [17, 19]. A scheme of Forms of wear is shown in fig. 5.

Both abrasion and erosion are rapid and severe forms of wear that can lead to significant costs if not properly managed. Although these wear types share similarities, they differ fundamentally; for instance, liquid particles can cause erosion but cannot abrade. These distinctions are crucial when selecting materials for wear resistance, as the microscopic mechanisms of wear differ for abrasion, erosion, and cavitation.

Abrasive Wear - Abrasive wear occurs when a hard object interacts with particles of equal or greater hardness. A common example is the wear of excavator blades. The extent of this wear is often underestimated, as even soft materials can cause abrasive wear if hard particles are present. For instance, organic materials like sugarcane can lead to wear in cutters due to the silica content in the fibers. One challenge in managing abrasive wear is that the term doesn't accurately reflect the various wear mechanisms at play, which often operate simultaneously and have distinct characteristics. Initially, abrasive wear was thought to resemble cutting with metalworking tools, but microscopic studies show that other mechanisms, such as micro-cutting, micro-fracturing, or material pull-out, also contribute significantly. These processes can lead to accelerated fatigue from repeated deformations [10, 18, 19].

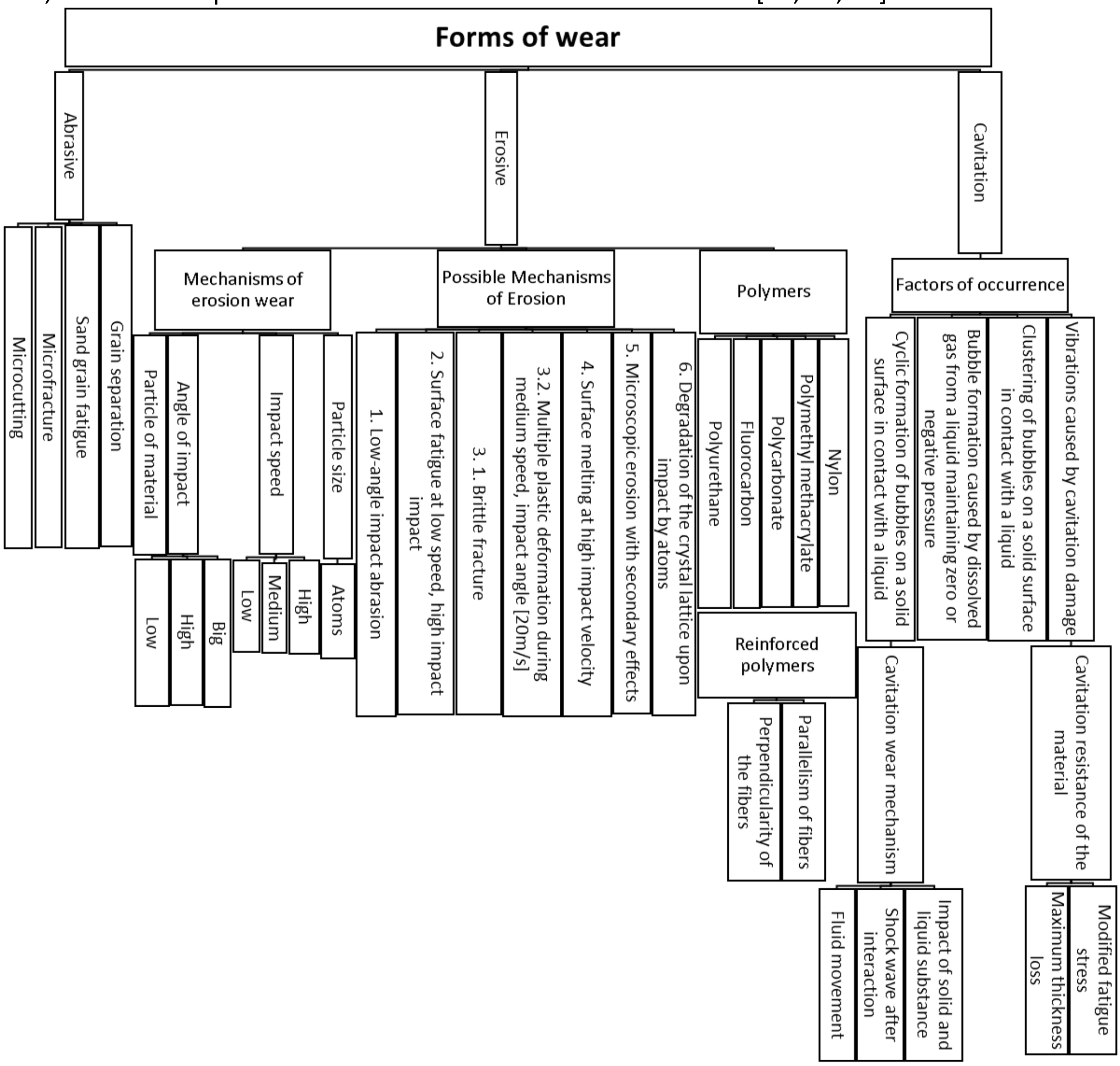

Figure 5. Scheme of Forms of wear

Erosive Wear - Erosive wear occurs when solid particles or liquids impact the surface of an object. It is commonly seen in various machines, such as damage to gas turbine blades when aircraft fly through dusty clouds and wear on pump impellers in mineral slurry processing systems. Unlike other wear forms, mechanical strength does not ensure resistance to erosion, necessitating specific material characteristics to minimize wear. The properties of the eroding particles are also increasingly recognized as crucial factors in managing this type of wear [10,19,20].

- Mechanisms of Erosive Wear - Erosive wear encompasses various wear mechanisms influenced by particle material, impact angle, impact speed, and particle size. Hard and rigid particles can lead to abrasive-like wear. When liquid particles are involved, abrasion does not occur; instead, wear results from repeated impact loads. The term "erosive wear" refers to a range of wear mechanisms that occur when relatively small particles strike mechanical components. This definition is empirical, focusing more on practical implications than on fundamental understanding.

Erosive Wear Resistance of Polymers - Polymers are increasingly recognized as effective erosion-resistant materials, especially in applications where metals are unsuitable, such as when transparency to visible light or other radiation is required.

Cavitation Wear - Cavitation wear is known to damage equipment such as propellers, turbine blades operating in wet steam, and valve seats. This wear progresses by creating a series of holes or pits on the surfaces exposed to cavitation, potentially leading to the complete failure of the component. Equipment performance, like that of propellers, is often hindered by severe vibrations resulting from cavitation damage [19].

- Cavitation Wear Mechanism - Cavitation is characterized by the cyclic formation and collapse of bubbles on a solid surface in contact with a liquid. Bubbles form when dissolved gas is released from the liquid, often occurring in regions of negative pressure, such as when fluid flows from a narrow to a wider pipe. Surfaces downstream of sharp objects, like propellers, are particularly vulnerable to cavitation. The ideal way to prevent it is to avoid negative pressures near surfaces, but this is often impractical.

4. CONCLUSION

From the overview and analysis of tribology as an interdisciplinary science at significant levels it affects, it becomes clear that its importance emphasizes the critical role it plays in modern industry, economy, and lifestyle, especially with the visually impaired. The focus of tribology on financial and industrial benefits provides a basis for improving production processes, sustainable use of resources, and reducing negative impacts on the environment. Investments in tribological research and technology will continue to pay off many times over as the world strives for more environmentally friendly and cost-effective innovative solutions.

The classification of tribology by basic principles, applications, theories, mechanical properties, chemical interactions of tribo-surfaces, physical properties and phenomena, understanding the forms of wear, provides an important basis for optimizing production systems. The study of forces and friction coefficients can improve the efficiency of many operations in modern industry, reduce maintenance costs, and develop innovations that will ensure a sustainable and economically viable future.

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