

# A Comprehensive Review of Wear Mechanisms and Mitigation Strategies for Tribological Systems

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## ABSTRACT

*Abrasive wear is characterized by material loss, while adhesive wear results from high stresses inducing material transfer. Corrosion wear arises from chemical reactions, whereas erosive wear occurs due to particle impact. Fatigue wear, including contact fatigue, is attributed to cyclic stress and misalignment. Effective wear mitigation strategies, such as material selection, surface texturing, and lubrication optimization, are explored. Additionally, the influence of surface roughness and structural integrity on wear rates is highlighted. This review comprehensively examines the primary wear mechanisms in tribological systems, including abrasion, adhesion, erosion, corrosion, and fatigue. The novelty of this review lies in integrating recent advancements in wear-resistant materials, nanostructured coatings, and smart lubrication techniques. Emerging trends and challenges, including the role of artificial intelligence in predictive maintenance and sustainable tribological solutions, are also discussed, providing insights into future research directions.*

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## 1. INTRODUCTION

In tribo-technical systems (TTS), friction and wear are observed between specific components. We draw “system boundary” around parts and materials directly involved in these processes, separating them from the rest of the system for clearly defining TTS. The components that subject to friction and wear are the main elements of TTS, described by their material properties. System can be understood by considering several factors

such as tasks which must perform (function), input factors (operating conditions), output results, losses (wear), and overall structure of a system. Fig. 1 provides detailed description of this system (TTS). The structure of this system is formed by components’ unique characteristics and their mutual interactions. Each TTS has a basic structure that includes four main elements: the base body, counter-body, interface medium, and ambient medium.

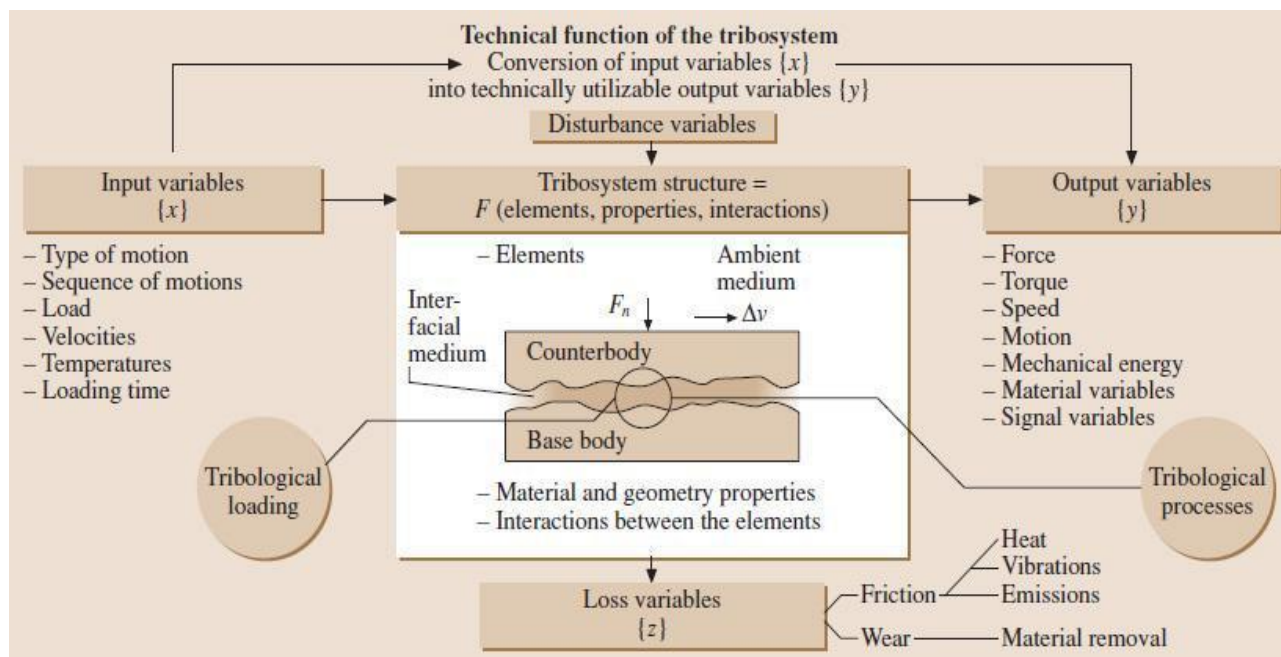


Fig.1. Detailed explanation of TTS [1].

Base body is one of the main surfaces involved in the friction process. Counter-body is a surface that interacts with the base body, creates friction. Interface medium can be a lubricant, or any substance present between the base body and the counter body, affecting friction and wear. Ambient is the surrounding medium, such as air or any external medium that can affect system.

Table 1 shows examples of different TTS configurations with various elements. Although each TTS has a base body and counter body, the interface medium and even surrounding medium can sometimes be absent, for example, in vacuum conditions.

While many existing studies focus on specific materials, applications, or systems, there remains a significant lack of integrative

analyses that comprehensively examine wear mechanisms and mitigation strategies in different tribological contexts. Such a broader perspective is essential to facilitate interdisciplinary comparisons, allowing researchers and engineers to identify universal principles that transcend individual systems, as well as transferable solutions that can be adapted across industries. By synthesizing knowledge from different tribosystems, these integrative reviews can also highlight critical knowledge gaps and promote innovation through cross-pollination of ideas. The present paper aims to address this gap by providing a comparative overview of the main wear mechanisms and associated mitigation techniques applicable to a range of tribosystems, focusing on both common and system-specific issues.

Table 1. Some tribological systems and their properties [1].

System type	Base body	Counter body	Interfacial medium	Ambient medium	Configuration
Turning Tool	Cutting Edge	Workpiece	Cutting lubricant	Air	Open
Sliding Bearing	Journal	Bearing Bush	Oil	Air	Closed
Mechanical Face Seal	Seal Head	Seat	Liquid or gas	Air	Closed
Wheel/Rail	Wheel	Rail	Moisture, dust, grease	Air	Open
Conveyor system	Conveyor Belt	Rollers	Dust, grease	Air	Open
Electric motor bear	Rotor shaft	Bearing	Grease	Air	Closed
Industrial mixer	Agitator Shaft	Sealing Surface	Process fluid	Air	Closed

## 2. WEAR MECHANISMS

Wear is the complex process which occurs between contacting surfaces and often results in the loss of material from one of the surfaces. Typically, this material removal occurs as the result of mechanical forces applied by the opposing surface [2]. During this process we observe small particles are separated from contact areas. Therefore, it is necessary for engineers to have a comprehensive understanding of these mechanisms because in this way they can find ways minimizing wear on bearing surfaces. One way to classify the different wear mechanisms is by the methods by which materials are removed from the surfaces. More specifically, wear mechanisms can be classified

based on the mechanical processes that cause material loss. In this context, five main wear mechanisms are identified: abrasion, adhesion, erosion, corrosion, and fatigue [3].

Figure 2 shows a notable increase in publication trends related to the tribological system for wear mechanism and mitigation strategies.

Over the years, several theoretical models have been developed to explain and quantify wear behavior under various operating conditions. Among these, Archard's wear law, Reye's hypothesis, Khrushchov and Babichev's wear model are widely recognized for their contributions to understanding wear mechanisms.

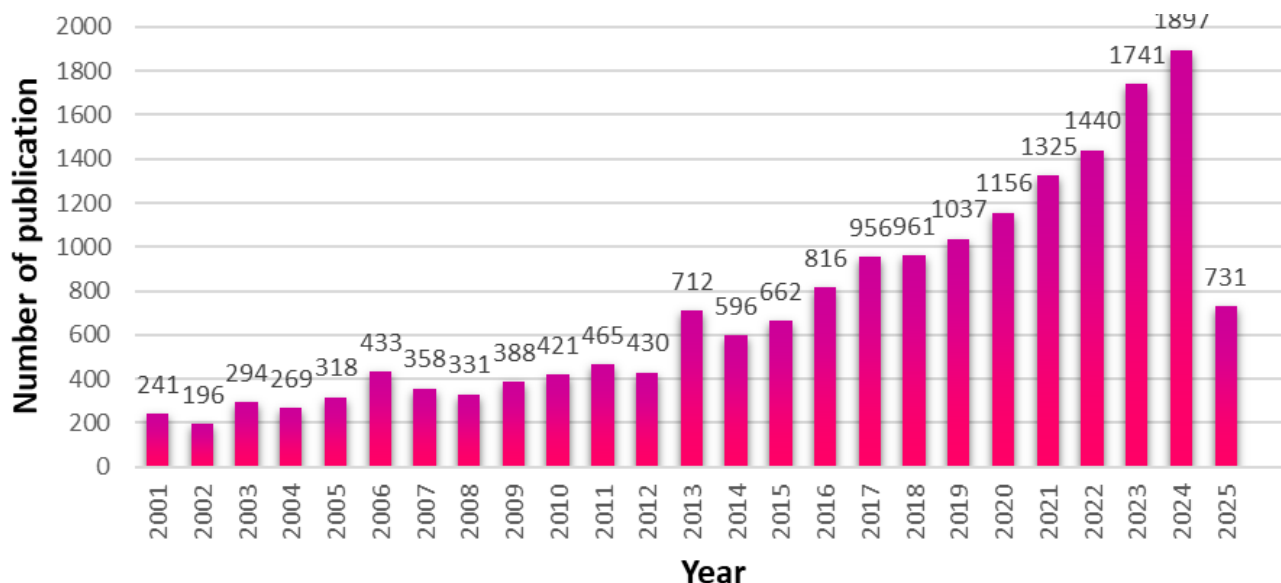


Fig. 2. Current publication trends in "Wear Mechanisms and Mitigation Strategies for Tribological Systems" from 2001 to 2025 (Data retrieved from ScienceDirect using keywords: "tribology, wear mechanisms").

**Archard's wear law.** Archard's equation is widely used to quantify wear volume based on contact conditions, as shown in equation (1):

$$V = \frac{KWL}{H} \tag{1}$$

where V is the wear volume, K is the wear coefficient, W is the applied load, L is the sliding distance, and H is the material hardness.

**Reye's hypothesis.** The energy-based wear model proposed by Reye indicates that the volume of wear is directly proportional to the frictional work performed per unit area. The model states, as shown in equation (2):

$$V \propto \int F \cdot ds \tag{2}$$

where F is the frictional force and ds is the sliding distance. This hypothesis is instrumental in the analysis of abrasive wear, emphasizing the significance of energy dissipation in the process of material loss.

**Khrushchov and Babichev's wear model.** The model proposed by Khrushchov and Babichev highlights the significance of material hardness and microstructural features in determining wear resistance. A relationship for wear rate is established based on the hardness ratios of the interacting surfaces. The formula is as in equation (3):

$$I = \left(\frac{H_1}{H_2}\right)^n \tag{3}$$

In this context,  $I$  denotes the intensity of wear, while  $H_1$  and  $H_2$  signify the hardness values of the contacting surfaces. The variable  $n$  is defined as an empirical constant. This model plays a crucial role in the analysis of two-body abrasive wear, particularly in how variations in material hardness affect wear rates.

## 2.1 Abrasive wear

Abrasive wear is the most common, damages bearing surfaces and producing large amounts of wear debris. This often occurs when a rough, hard surface slides against a softer counterpart [3]. In such cases, numerous small peaks or ridges on the harder surface act as cutting tools and remove material from the softer surface [4]. Hard particles can be mixed with lubricants, which act as abrasives or hard protrusions on the contact surfaces. When these particles move relative to the surface, they cause wear known as abrasive wear [5-7]. Rough abrasive particles can create cutting effect on the working surface of bearing under load, causing scratches or indentations. In addition, the crushing of brittle particles or inclusion of small particles has an abrasive effect on the bearing surface, even contributing to wear. Some abrasive particles can also be generated by debris that peels off the bearing surfaces due to contact fatigue. Overall, abrasive wear arises from many synergistic wear mechanisms.

**Modes of abrasive wear.** Types of abrasive wears depend on how the abrasive particles move on the worn surface. There are two main modes of abrasive wear mostly described in literatures: two-body and three-body abrasive wear.

Two-body abrasive wear is like the action of sandpaper on a surface. Here, solid particles act as cutting tools, breaking the surface. On the other hand, three-body abrasive wear occurs when the abrasive particles are not fixed in place, they can both roll and slide along the surface, causing wear in a different way. These two modes of abrasive wear are shown in Fig. 3.

Until recently, these two abrasive wear modes were thought to be similar. However, some key differences have been identified [8]. It has been found that three-body abrasive wear is approximately ten times slower than two-body wear [9]. Factors such as the hardness of the

counterface that presses the abrasive particles to the surface are important for three-body wear, but not so important for two-body wear.

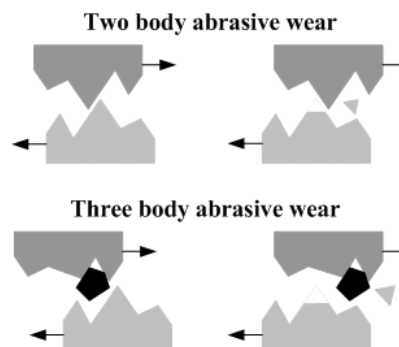


Fig. 3. Two body and three body abrasive wear.

In two-body abrasive wear, the material removal process resembles the action of a cutting tool, whereas in three-body abrasive wear, the material is removed more slowly, and the exact mechanisms of this process are not yet fully understood [10]. Unlike two-body wear, in which material is removed from the surface in the form of scratches, in three-body wear, the material is gradually removed, which creates a more chaotic surface texture, since the abrasive particles repeatedly contact the surface [11].

Small hard particles that are formed because of two-body wear can act as cutting elements between the two contacting surfaces, leaving noticeable scratches on the bearing surfaces. In such situations, three-body abrasive wear develops, which can cause serious damage.

Based on the empirical equation describing volume loss due to wear developed by Rabinowicz et al. [12], Huang and Liang [13] proposed an optimized version of this equation (4):

$$V_{\text{wear-abrasion}} = K_{\text{abrasion}} \times K \left( \frac{P_a^{n-1}}{P_t} \right) V_c w V B \bar{\sigma} \Delta t \quad (4)$$

Where  $V_{\text{wear-abrasion}}$  is the loss of tool volume due to abrasive wear over a given period,  $P_a$  is the hardness of the abrasive particle,  $P_t$  is the hardness of the tool, and  $n$  and  $K$  are the known function of the ratio  $P_t/P_a$  or  $\Gamma$ ,  $K_{\text{abrasion}}$  is the dimensionless abrasive wear coefficient and is generally considered constant,  $VB$  is the wear length or wear area of the flanks. This equation provides model for predicting the wear volume by considering various parameters (of course related to abrasive wear).

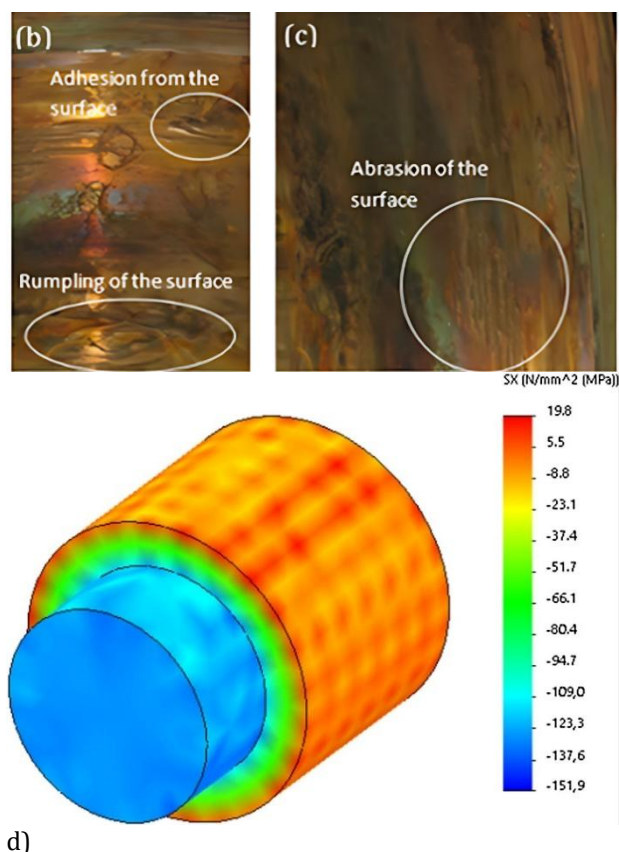
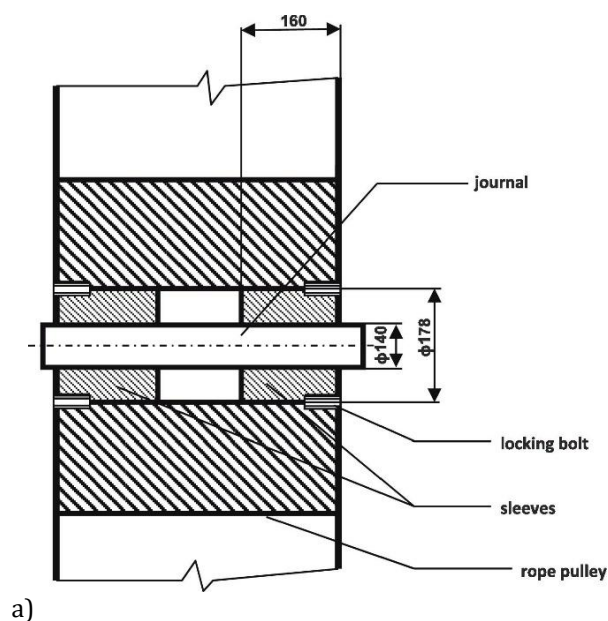
To solve abrasion problems, it is important to consider both two-body and three-body wear mechanisms. McKellop [4] suggested that well-polished surfaces, which reduce the number of asperities, can lower the wear rate caused by two-body abrasive wear. For three-body wear, hard materials (like ceramic) are better at resisting damage from abrasive particles [14]. Another way to reduce wear is surface texturing [15]. This can reduce the damage caused by three-body abrasion. The authors believe that, mentioned methods may be the best approach to minimize impact of abrasive wear.

## 2.2 Adhesive wear

Adhesive wear is one of common issues in parts, occurs when the contact stress between two bearing surfaces becomes too high. Stewart [16] found that artificial joints experience forces three times greater than our body weight. This phenomenon is not unique to biomedical applications; similar conditions are observed in many industrial systems. For example, mechanical components such as bearings, gears are often subjected to dynamic loads that significantly exceed their static loads due to impacts, vibrations, and cyclic motions. Just as artificial joints must withstand repetitive high loads while maintaining low wear and high reliability, industrial components must operate under loading and wear conditions. In these conditions, the two surfaces can fuse together, caused by asperities on the harder surface penetrating the softer one. As the joint surfaces move in opposite directions, these fused areas can break apart.

Peterka et al. [17] investigated the cause of failure in the sliding bearing of a rope pulley. The structural diagram of bearing can be seen in Fig. 4 (a).

During their investigation, they found that the bushing material was stuck in the journal as shown in Fig. 4 (b) and 4 (c). The inner surface of bushing displayed wrinkles and peeling, signs that aligned with the wear failure of the bearing. Simulation analysis revealed that this problem was caused by bearing's manufacturing tolerances not meeting required standards, resulting in a bearing clearance that was too small (Fig. 4 (d)).



**Fig. 4.** (a) Schematic representation of sliding bearing, (b) images depicting adhesion and surface rumpling, (c) evidence of abrasion on the inner, (d) simulation illustrating the tension distribution in the bearing contact zone.

The mandrel's thermal expansion, combined with insufficient lubrication, caused the tin in the bushing material to reach its melting point. This caused the material to melt and stick to other components. As a result, the adhesive worn out.

To prevent adhesive wear, the following actions are recommended:

- Use heat- and wear-resistant materials,
- Apply lubricants with strong oil film properties and monitor lubricant conditions,
- Ensure the bearings are manufactured with precise accuracy and the correct clearance,
- Apply the correct preload to avoid unnecessary stress on the bearing.

This process leads to material transfer from the softer polymer surface to harder materials like ceramics or metal alloys [18]. Additionally, adhesive wear generates large quantities of bioactive particles, often smaller than a micron [19].

To reduce the damage caused by adhesive wear, one approach is to weaken the adhesive bonding force between the moving surfaces [4]. Wang et al. [20] studied the impact of the actual contact area on the wear rate of joints and found that as the contact area increased beyond a critical point, the material loss from the softer surface significantly rose. This occurs because larger contact areas strengthen the adhesive bond. Typically, this increase in contact area is linked to smoother surfaces.

In terms of reducing adhesive wear, increasing surface roughness seems beneficial. However, this contrasts with the approach used to reduce abrasive wear, so other methods should be explored to combat adhesion, rather than making the surface rougher. Several researchers [21-23] have demonstrated that well-designed surface textures can help by increasing the hydrodynamic effect, which thickens the lubricating film. These films help to separate the two surfaces, reducing the contact area. We also believe that material composition plays a major role in adhesion between surfaces. However, original research on how different material compositions affect adhesive wear is limited, and more work is needed in this area.

### 2.3 Erosive wear

Erosive wear occurs when particles impact a surface, it is influenced by factors like impact angle, velocity, and the properties of the particles themselves [24,25]. This type of wear happens

when the momentum from these particles causes material to detach from the surface. As shown in Fig. 5, when hard particles hit the surface at a certain angle, they damage it through a process called micro-cutting.

Of all the factors that affect erosive wear rates, the impact angle has the most significant influence [24-27]. Wang et al. [27] studied how different impact angles affect erosive wear and divided them into two categories.

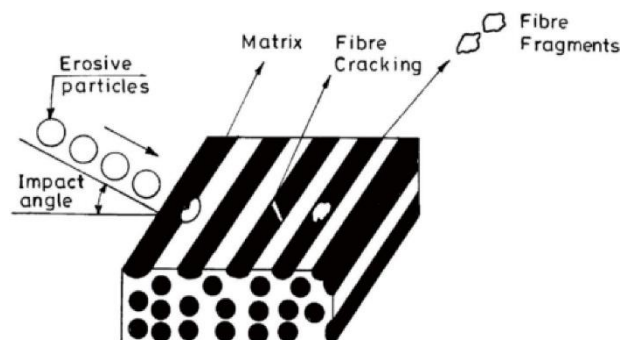


Fig. 5. Explanation of erosive wear [26].

When the impact angle is close to  $90^\circ$  (normal impact), micro-cracking and plastic deformation are the main mechanisms causing damage. But when the impact angle is less than  $90^\circ$ , the dominant processes are micro-cutting and micro-plowing (see Fig. 5). If the impact angle is very shallow, the erosion starts to resemble three-body abrasive wear [28]. In order to reduce erosive wear, two key approaches should be considered. The main one is that it is important to choose the right material. It is considered more appropriate to use materials that are more resistant to particles. For example, CoCrMo alloys have better wear resistance than stainless steel [29]. A second approach is to minimize the number of hard particles between the bearing surfaces. Reducing the wear caused by wear and tear is very important because it leads to fewer wear particles near the man-made joints.

Tian et al. [30] suggested that the use of mesh or porous structures in materials can increase their adhesion strength, while Alkaline-Calcium-Heat-Water (A Ca HW) treatments can strengthen the bond between cells and the implant. Other techniques such as hydroxyapatite (HA) coatings and heat surface treatment may also be useful [31]. Furthermore, introducing surface textures in specific areas to trap debris can significantly contribute to reducing erosive damage.

## 2.4 Corrosive wear

Corrosion is more common when active metal alloys are used in machine parts. This process occurs during metal surfaces encounter fluids. Corrosion failure in pads refers to the chemical or electrochemical reactions that occur between surface material of the pad and its environment, it causes damage. Corrosion can impair the proper functioning of bearings and may even lead to more severe failures [32–34]. Corrosion can take many forms, including both uniform and localized types. Localized corrosion includes more specific issues such as pitting corrosion, corrosion fatigue and hydrogen embrittlement.

Uniform corrosion is one of the most common forms and often appears as oxidative corrosion or rusting [35]. This leads to gradual thinning of metal components of the bearing. Because such failures occur on the surface, they are relatively easy to detect and prevent, making them more manageable. On the other hand, localized corrosion is more damaging and more difficult to detect. Locally corroded areas can be the starting point of fractures, making it a more dangerous and hidden hazard.

Moreover, the debris from this process is often harder than the original material, meaning it can cause both abrasive and erosive wear [36]. Komori and others [37] also concluded that wear and corrosion can accelerate each other, thereby creating a feedback loop of damage. Due to the potential for serious damage, it is very important to prefer materials with better corrosion resistance for joints [36-38].

Sinnett-Jones and others [36] recommend using materials that can quickly form an oxidizing layer. Zhang et al. [38] investigated the effect of coatings in reducing abrasive wear, finding diamond-like carbon (DLC) to be particularly effective. Finally, ceramic-based materials are completely resistance to corrosion.

**Uniform corrosion.** In bearings, it is caused by rust, usually caused by water or moisture seeping into the bearing through damaged seals. The reason is the chemical reaction between the carrier material and the sulfuric acid formed by the sulfides in the lubricants. Bearings made of materials such as babbitt

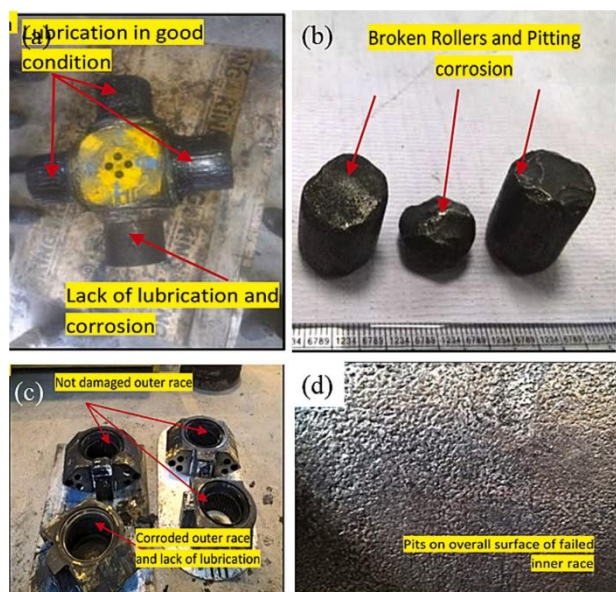
alloys containing tin and copper are particularly sensitive to these chemical reactions with acidic environments [34,39].

X-ray diffraction (XRD) analysis showed that the black corrosion product was copper sulfide, which formed because of the sulfuric acid in the lubricating oil reacting with the copper in the bearing material [39]. Factors such as temperature and sulfuric acid can lead to this type of corrosion, but it can be prevented by changing the lubricant regularly or using sulfur-free alternatives.

Ensuring proper sealing, regular maintenance, and selecting the right lubricants can help reduce the risk of uniform corrosion. In addition, attention should be paid to storage conditions and measures should be taken to prevent rusting when the machine is not in use.

**Pitting corrosion.** It is particularly dangerous and hidden type of damage. It develops in isolated hot spots on the metal surface and gradually penetrates inside, forming small pits [32]. This type of corrosion not only reduces the precision and smoothness of the bearing surface but can also cause serious damage. In Fig. 6, a study of pitting corrosion on a universal joint crosspiece of a hot rolling mill [32] demonstrates this problem. The crosspiece, which connects the transmission shafts and regulates the angle of force transmission, consists of four cylindrical roller bearings mounted crosswise. Pitting corrosion was found in only one of the bearings (Fig. 6 (a)). The main cause was the assembly errors of the seals, which led to their premature wear. As a result, water entered the bearing during operation, which worsened its lubricating properties. Significant pitting was found on the outer and inner rings, as well as on the rollers and seals, and it formed over the entire surface (Fig. 6 (b) - 6 (d)). This destruction was further aggravated by insufficient or no lubrication.

The same measures are necessary to prevent pitting corrosion as for general corrosion protection. It is very important to ensure reliable sealing and to use corrosion-resistant materials in the manufacture of bearings. In addition, during transportation, the bearing surfaces must be clean and protected from acidic or salt solutions to prevent damage.



**Fig. 6.** Pitting corrosion in a universal joint cylindrical roller bearing caused by seal failure [32]. (a) illustration of the damaged bearing inner ring; (b) image of the bearing roller; (c) image of the bearing outer ring; and (d) close-up of pits on the inner ring surface.

**Fretting corrosion.** Most frequently, fretting damage may take three forms namely fretting corrosion [40,41], fretting wear [42,43] and fretting fatigue [44,45]. It could happen in different positions of a bearing, between the ring and the axis or base, within a rolling element-ring contact area, between cage and cage pin [42,43]. It is commonly found in the case of a loose fit or some direction relative motion (for example vibration between surfaces in contact) when fretting occurs [41].

Fretting corrosion, particularly, creates pits or grooves on the surface where the bearing contacts the metal, often accompanied by reddish-brown or black metal oxides [40]. This form is often caused by both corrosion and wear. Fretting wear and corrosion are not entirely separate processes. Instead, they work in tandem, with oxidation and wear occurring in cycles. The oxidized particles that are released act as abrasives, further accelerating the wear process.

## 2.5 Fatigue wear

Fatigue wear, also known as surface or contact fatigue wear, is a common failure mode that sits between wear and fatigue failure.

This type of wear occurs due to surface fatigue damage, which is driven by cyclic contact stress during friction. Over time, this stress leads to two types of surface failure: pitting and cracking. Similar to general fatigue, microcracks and spalling are observed; however, in this case, surface friction plays a critical role in accelerating the damage process. Surface fatigue wear is closely tied to contact fatigue. Another variation of this is fretting wear, which results from small, repetitive vibrations at the contact surface of tightly fitted components. Fretting damage is often linked to fatigue as well.

**Contact fatigue.** This is divided into two types depending on the place of origin: surface (pitting) and subsurface (chipping) [46]. Pitting develops at points of stress concentration on the bearing surface [47,48]. The cracks formed during the tensile test propagate through the material at an angle of 20–40°, twist and turn into secondary cracks, and eventually these cracks reach the surface [47]. As the cracks grow, numerous twists create a step-like structure, and friction in the cracks generates free particles. The branching of secondary cracks further weakens materials, leads to micro-pits formation. Chipping, on the other hand, often begins with subsurface defects such as inclusions or carbides [41,43,49–51]. Pits caused by impact loads are usually shallow but large, and the released particles have a convex shape. These loose particles act as abrasives, increasing local stresses at the contact surfaces and causing larger spalls [52,53]. This process can be extensive, sometimes resulting in poor material removal and, in severe cases, leading to the formation of fatigue cracks.

Premature development of contact fatigue is influenced by various factors, such as insufficient lubrication or overloading, which can accelerate material failure due to fatigue [51,54]. Bearing misalignment can also cause uneven load distribution, which further accelerates fatigue [53,55,56]. Many bearings that fail due to contact fatigue exhibit the characteristic appearance of large white etching cracks (WECs) beneath the surface. These cracks are formed due to frictional changes in the structure along the crack surfaces under cyclic loading. Although WECs usually occur near the end of the fatigue cycle and are associated with failure, most researchers believe that they are a consequence of failure rather than a cause [57,58]. This means that WECs do not cause failure - instead, they occur because the material has already failed.

**Fretting fatigue.** This type of fatigue occurs when small relative sliding movements occur between the contacting surfaces of bearings. Bearings operate under complex loading conditions, often subjected to alternating mechanical stresses, repetitive vibrations, and external effects. Fretting fatigue is characterized by a reduction in fatigue strength or early cracking caused by a combination of fretting wear and cyclic loading. Damage caused by fretting wear on the bearing surface creates areas where fatigue cracks begin to initiate, which, under the influence of cyclic stresses, can eventually lead to failure [44,45]. Under fretting fatigue conditions, the strength of the material is significantly weakened, allowing fatigue cracks to form even at low stress levels. Because fretting fatigue occurs at contact surfaces, it may go undetected until the damage has become severe.

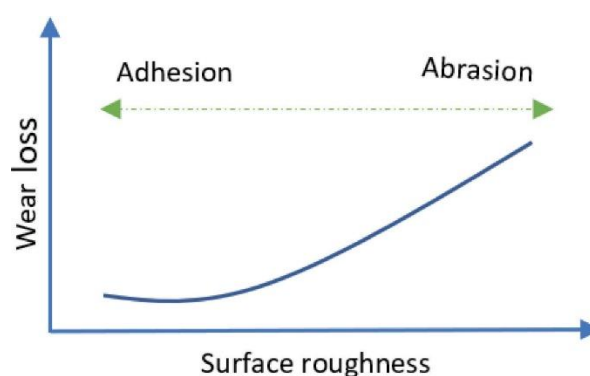
Fatigue can be prevented by doing the following measures: (1) ensure proper interval distance between the contact surfaces, (2) maintain sufficient tension, (3) use proper preload, and (4) improve machining accuracy to prevent excessive shape deviations.

### 3. SURFACE ROUGHNESS

In tribological systems, surface roughness is a universally significant factor influencing friction and wear behavior across various material pairings and applications. This section aims to summarize and compare recent research findings on how surface roughness affects tribological performance in different systems, such as metallic components, polymer-metal combinations.

Surface roughness is a critical factor for machinery as it plays a key role in the tribological performance of bearing surfaces. According to Persson et al. [59], surface roughness directly influences contact mechanisms, which in turn influences the wear rate of mating surfaces in machinery. Numerous parameters can describe surface finish, with the arithmetic mean deviation ( $R_a$ ) being the most used. However, recent studies have shown a growing interest in studying the relationship between the tribological behavior of mating surfaces and other roughness parameters such as  $S_{sk}$  (Skewness of height distribution) and  $S_{ku}$  (Kurtosis of height distribution) [60].

During two rough bearing surfaces slide against each other or when a rough surface moves against a smooth surface, abrasive wear tends to dominate between the two mating surfaces. Kovalchenko et al. [61] noted that a smooth surface can help reduce wear losses during the running-in period, thereby slowing down the surface degradation process. In addition, bearing surfaces with significant defects, primarily caused by three-component abrasive wear, tend to have higher roughness, which in turn reduces the service life of such joints [62]. If both mating surfaces are exceptionally smooth, another wear mechanism known as adhesive wear will become the main factor contributing to the mass loss and surface topography changes of artificial joints (see Fig. 7).

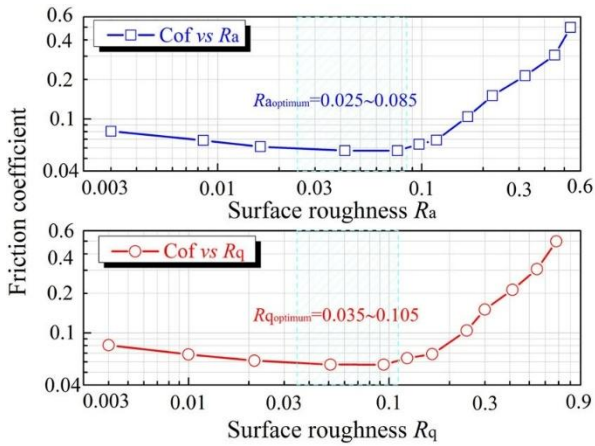


**Fig. 7.** Adhesion and abrasion at different levels of surface roughness [63].

Currently, the relationship between surface roughness ( $R_a$ ) and wear rate shows proportionality. It means decreasing surface roughness results in decreasing wear rate.

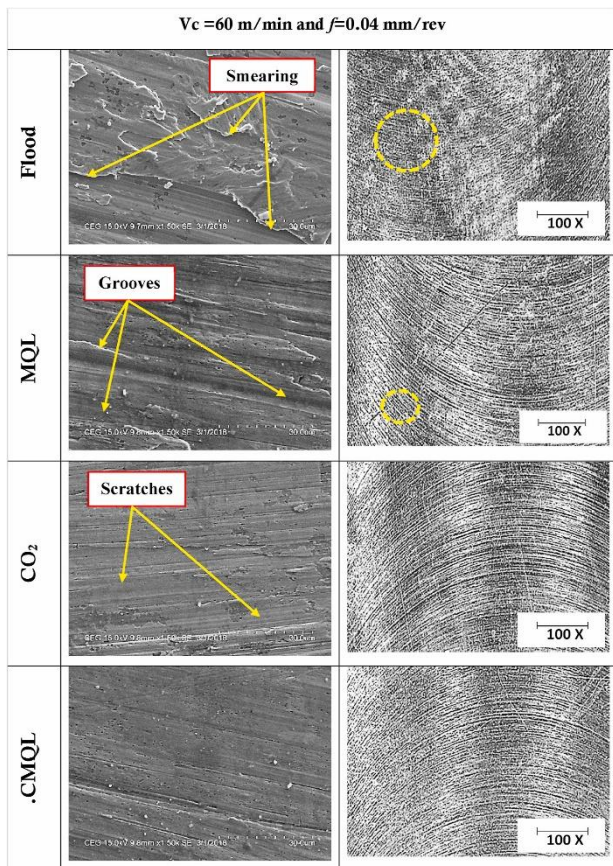
However, Yuan et al. [64] suggested that if the surface roughness falls below a certain critical value, the wear rate may increase again, although they could not determine this critical value for the stainless steel-UHMWPE composite. Recent studies have made progress. As we can see from the research by Feng et al., (Fig. 8) the critical surface roughness ( $R_a$  optimum) for steel-rubber composites is approximately  $0.04 \mu\text{m}$  [65].

Foster et al. [66] also determined a critical value for the steel-steel combination, noting that this transition point is primarily since adhesive forces become stronger than abrasive forces when the surface is extremely smooth. Further research is needed to determine critical values for different material combinations in joints.

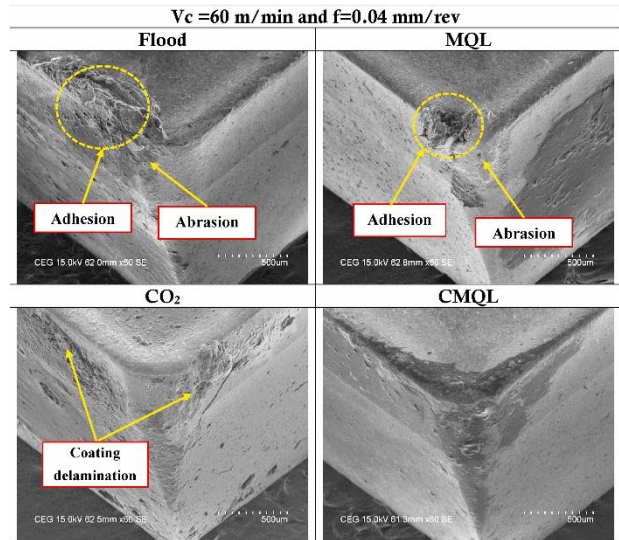


**Fig. 8.** The friction coefficient for the steel-rubber pairing under varying surface roughness conditions [65].

Ross et al. [67], who studied the tool wear and surface condition of machined Nimonic 80A under different cooling and lubrication conditions, investigated the surface defects on the machined workpieces. Their study showed that smearing, grooves and scratches were the major surface defects on the machined surfaces as shown in Fig. 9. Additionally, Fig. 10 illustrates tool wear comparison under different cooling methods.



**Fig. 9.** Surface images of machined parts under different cooling/lubrication conditions (Scale bar = 300  $\mu\text{m}$ ) [67].



**Fig. 10.** Scanning Electron Microscope (SEM) images of tool wear under different cooling conditions (Scale bar = 500  $\mu\text{m}$ ) [67].

The presence of cracks, grooves, and scratches is indicative of the dominant wear mechanisms. Table 2 provides an overview and explanation of various surface defects documented during the processing of super alloys.

**Table 2.** Different surface defects and materials.

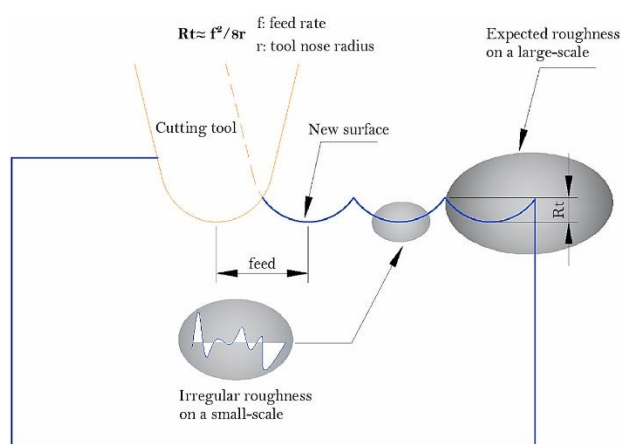
Surface defect	Machined materials	Explanation
Grooves	Inconel X750 [68]; Nimonic 80A [67]; Ti-6Al-4V [69,70]; Inconel 718 [71,72]	Grooves form when abrasive particles get trapped between the cutting tool and the workpiece, leading to displacement of material on the surface.
Scratches	Ti-6Al-4V [70,73]; Nimonic 80A [67]; Ti-1023 [74]; Inconel 718 [75,76]	Scratches, often appearing as shallow grooves, occur when hard particles or debris become trapped between the tool and chip.
Cracks	Ti-6Al-4V [77]; Inconel 718 [72,78];	Cracks develop on the machined surface due to residual stresses, thermal fatigue, or rapid temperature fluctuations.

As shown in Fig. 11, while the surface roughness ( $R_t$ ) is theoretically a function of feed rate ( $f$ ) and insert radius ( $r$ ) according to the well-known equation (Eq. 5), it has also been observed that other factors such as cutting speed and depth of cut affect the surface roughness in machining processes [79].

$$R_t = f^2 / 32r \quad (5)$$

Overall, surface roughness is a critical parameter for mechanical joints.

Achieving perfect surfaces helps reduce friction and wear, but there are still some challenges. First, achieving a low surface roughness on soft materials like UHMWPE poses several machining difficulties [80,81]. Additionally, if surface roughness falls below a critical value, friction may increase again, causing the wear rate to rise. Finally, producing products with superior surfaces can be quite expensive for professionals. This raises the question of whether manufacturing ultra-smooth surfaces is the best approach to enhancing the tribological performance of mechanical joints [81].



**Fig. 11.** Surface roughness formation on machined surfaces [68].

Overall, surface roughness is a critical parameter for mechanical joints.

**Surface texture.** Surface texturing has been recognized as one of the most effective methods for reducing wear rates and friction in tribological components. Hamilton et al. [82] were among the first to study the effect of surface texture on lubrication regimes. Since then, numerous researchers have investigated how various texture parameters – shape, size, and area fraction – affect the tribological performance of friction components. Texture technology has found applications in many industrial sectors, including piston rings [83], bearings [84], and other mechanical components.

It is clear that while reducing surface roughness generally reduces wear rates, the optimal roughness values and dominant wear mechanisms vary significantly between tribological systems, especially in metal- and polymer-based contacts.

#### 4. ENHANCEMENTS IN SURFACE INTEGRITY AND TOOL WEAR

This section forms part of a comparative analysis of wear mechanisms and mitigation strategies for various tribosystems presented in this paper. In particular, it examines methods for enhancing surface integrity and reducing tool wear in machining processes for various materials. By comparing the effectiveness of various machining optimization strategies, cutting tool modifications, and cooling techniques, this section highlights both universally applicable approaches and material-specific considerations that are important for improving tribological performance and extending tool life.

With the development of machining as a key manufacturing process, focusing on improving surface integrity and reducing tool wear has become a priority for industry and researchers worldwide. To improve these indicators, machining optimization can be achieved through three main strategies: 1) Selecting the optimal machining parameters that provide the best result in each specific case using strategies such as ANOVA (Analysis of Variance) and Taguchi method [85]. In modern times, researchers have also successfully applied artificial intelligence tools to optimize surface integrity. 2) Development of cutting tool modifications, including new materials, coatings, and advanced solutions such as changes in tool geometry. 3) Implementation of alternative cooling methods that not only preserve surface integrity and reduce tool wear, but also reduce operating costs. Recent developments in each of these strategies are reviewed, assessing their contribution to improving surface integrity and extending tool life.

**Optimization through processing settings.** As in other manufacturing processes, metal cutting is always a search for optimization techniques to improve product quality, increase productivity, reduce costs, and increase process durability [86]. Metal cutting, which is the basis of the mechanism, is a complex process involving deformation, friction, heat generation and microstructural changes or chemical reactions depending on the workpiece and tool materials. Factors such as machine tool characteristics, workpiece characteristics, cutting tool parameters, and machining parameters are

known to have significant effects on surface integrity and tool wear [87-89]. Because the workpiece material is usually determined by customer or project requirements and the machine tool selection is limited to the equipment available in the shop, tool material and geometry are often selected from a supplier catalog based on compatibility with the machine tool and workpiece material.

When used, the most available way to optimize surface integrity and tool life is to determine optimal machining parameters. These parameters typically include cutting speed and depth of cut, although their set may vary depending on the machining process. The simplicity of this approach is quite complex in practice, without experimental data, it is difficult to predict the results (surface integrity and tool wear) for a given process.

It is clear that the more experimental data there is, processes can be understood and optimized better. However, collecting large data sets can be time-consuming and expensive. To address this problem, design of experiments (DoE) have been developed to obtain sufficient data to determine optimal processing parameters with minimal resource expenditure. Some studies investigated the effect of cutting parameters in turning operations [90,91], but did not use mathematical models to analyze the data, limited to comparing the results. Although this approach may solve a specific problem, it is not sufficient to select the best machining parameters in the future, as it provides limited information about the impact of each input parameter on surface integrity and tool wear.

The effect of mechanical and thermal parameters on surface residual stresses during hard turning of 18MnCr5 steel was investigated by Gunnberg et al. [92]. However, large-scale modeling methods, such as finite element analysis (FEA), require experimental data. An analytical model for predicting residual shear stresses was developed by Huang & Yang [93], which provides valuable information for understanding and predicting such accidents. The usefulness of using FEA to simulate machining processes has been reviewed in a study by Watmon et al. [94]. Here, it is possible to demonstrate how accurate FEA is in predicting parameters such as tool wear, residual stresses, cutting forces, cutting

temperature, and microstructural changes. However, although FEA is quite accurate in some cases, these models are limited by fundamental assumptions, so each case must be examined individually.

In complex situations, especially when working with difficult-to-machine materials, optimizing cutting parameters alone may not be effective in ensuring adequate surface integrity. In these cases, alternative strategies such as changing the tool or implementing more effective cooling methods are more necessary. However, each optimization method presents its own limitations, real-time control of cutting parameters offers clear advantages over other approaches. For example, Denkena et al developed a system that adjusts the feed rate in real time to compensate for tool deviations, minimize variations during milling, and prevent system failures [95].

According to [96], flank wear and cutting edge radius are the most analyzed outputs in tool wear studies. Excessive flank wear not only leads to poor surface finish but also accelerates tool failure, reducing tool life and increasing production costs. Real-time monitoring methods like spindle acceleration and machine vision are being explored [97]. However, universal tool wear prediction models are lacking. Integrated monitoring and AI-driven systems are needed for reliable micro-milling.

Although long-time efforts in this field, there is still no universal solution or theoretical model that can be applied to all machining processes. Nevertheless, state-of-the art technologies and experience allow us to select the most appropriate parameters not only to improve surface integrity, but also to reduce tool wear. The combination of these methods provides comprehensive and strong approaches than the application of a single optimization method.

## **5. DISCUSSION**

The development of new materials, advanced testing techniques, and environmentally friendly engineering solutions has led to a rapid advancement in wear mitigation in tribological systems. New materials and coatings, like alloys with high entropy (HEAs) and ceramic/cermet

coatings like the carbide tungsten (WC) and titanium diboride ( $TiB_2$ ), offer superior resistance to wear in high-stress applications [98]. For their ultra-low friction, graphene and other two-dimensional (2D) materials are popular, and self-healing coatings with embedded microcapsules can repair wear-induced damage and extend component life. To minimize wear by reducing surface adhesion and friction, biomimetic and bioinspired materials like lotus leaf-inspired superhydrophobic coatings are being studied. These material advances and tribological testing and monitoring are improving real-time wear prediction and mitigation. Precision measurements of wear progression are made possible by in-situ and real-time wear monitoring technologies that use laser interferometry, atomic force microscopy, and embedded sensors. Meanwhile, finite element analysis (FEA) and machine learning (ML)-powered high-fidelity computational models simulate complex wear behaviours under a variety of operating conditions, negating the need for expensive experimental testing. Artificial Intelligence (AI) is evaluating tribological data to predict component failure and improve maintenance plans, changing wear mitigation. Nanoscale tribometry is also helping build ultra-thin protective coatings by improving molecular knowledge of friction and wear. Due to global sustainability concerns, biodegradable and bio-derived lubricants made from vegetable oils are becoming more popular. They perform similarly or better than petroleum-based lubricants while reducing environmental impact. Non-toxic, water-based wear-resistant coatings are also becoming more popular, helping companies meet stringent environmental laws. By designing and manufacturing complicated, wear-optimized geometries with minimum material waste, additive manufacturing (3D printing) is revolutionizing wear mitigation. Additionally, triboelectric nanogenerators (TEENGs) can reduce energy losses in tribological systems by harvesting electrical energy from friction [99]. Tribology sustainability is improved by circular economy initiatives including surface reconditioning and component recycling. The lack of standardized testing procedures for precisely comparing tribological performance across different applications, the high cost and scalability issues associated with novel materials and coatings, and the requirement for improved material compatibility to integrate advanced

coatings and alloys into existing systems are just a few of the significant obstacles and future directions that still exist despite these encouraging developments. Furthermore, the creation of sustainable tribological solutions without sacrificing durability or performance is required by stricter environmental requirements. By utilizing developments in artificial intelligence, nanotechnology, and green chemistry, materials scientists, mechanical engineers, and data analysts will need to work together across disciplinary boundaries to overcome these obstacles and create the next generation of wear-resistant materials and predictive maintenance techniques.

The results of this study show that while the basic wear mechanisms such as abrasion, adhesion, and fatigue are common to most tribosystems, the effects of factors such as surface roughness, lubrication, and tool wear reduction vary significantly between material types and applications. Metal tribosystems typically require more stringent control of surface defects and texture, while polymer-based systems require a balanced approach to surface smoothness and the risk of adhesive wear. These comparative insights support the value of integrative analyses and suggest areas where focused, system-specific research can further optimize tribological performance.

## 6. CONCLUSION AND RECOMMENDATIONS

A comprehensive and integrated approach is necessary to address wear and corrosion challenges in materials effectively. Controlling the identified wear mechanisms can significantly enhance the performance and longevity of mechanical components. Strategies such as surface polishing to minimize roughness, surface texturing to prevent abrasive damage, and appropriate material selection combined with systematic maintenance offer optimal wear resistance. For instance, adhesive wear can be mitigated through the selection of wear-resistant materials like  $TiB_2$  and WC, the use of lubricants with strong oil film properties, and precise bearing design to limit material transfer. Similarly, erosive wear reduction necessitates selecting materials such as CoCrMo alloys and minimizing the presence of abrasive particles between bearing surfaces.

Corrosion-related wear requires the correct selection of materials and maintenance strategies, ensuring adequate surface protection through techniques like hydroxyapatite (HA) coatings and heat surface treatments. Additionally, fretting corrosion arising from the combined effects of wear and corrosion can be controlled by maintaining optimal clearance, interference fit, preload, and machining accuracy. Surface roughness plays a crucial role in tribological performance, requiring a balance between friction reduction and preventing excessive wear. While ultra-smooth surfaces like UHMWPE can reduce wear, their high cost and manufacturing complexity necessitate alternative approaches.

Future research should focus on bridging existing research gaps and advancing novel strategies beyond currently explored concepts. While high-entropy alloys, advanced ceramic coatings, and self-healing materials offer promising solutions for superior wear resistance, further investigations into their long-term performance and scalability are required. Similarly, emerging technologies such as biomimetic coatings, real-time wear monitoring, and AI-driven predictive maintenance are reshaping tribology; however, their adaptability across diverse industrial applications needs further validation.

While this review article covers a broad range of tribosystems to provide a comprehensive understanding of wear mechanisms and mitigation approaches, future research could focus on individual material classes or application sectors to explore system-specific behaviors in more depth. A particularly critical area requiring additional research is the wear reduction in food industry machinery, where safety and regulatory compliance are paramount. Investigating specialized coatings, food-grade lubricants, and innovative material designs to enhance wear resistance without compromising hygiene standards is essential. Future studies should also explore sustainable solutions, including biodegradable lubricants and eco-friendly tribological modifications, to align wear mitigation strategies with global sustainability goals. By addressing these research gaps and leveraging technological advancements, the field of wear mitigation can progress toward more efficient, cost-effective, and environmentally responsible solutions.

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