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INNOVATIVE STRATEGIES IN INDUSTRIAL MACHINERY MAINTENANCE AND REPAIR

Abstract: *Machinery and equipment are the foundations of industrial productivity. However, mechanical failures such as wear, fatigue and corrosion can lead to serious losses. Improving the maintenance and repair processes of machines and their parts has become a critical necessity for businesses in terms of minimizing machine downtime, extending equipment life and reducing costs. Predictive maintenance reduces unplanned downtime and increases operational efficiency by detecting problems before they turn into major failures. While predictive maintenance tools such as vibration and infrared analysis provide early diagnosis, many businesses still struggle with unexpected failures and high repair costs. While modern technologies increase equipment reliability and extend its life, they are not sufficiently integrated into traditional maintenance approaches. Innovative tools, especially Augmented Reality, have the potential to make maintenance and repair processes more efficient and accurate. In this context, it is of great importance to create a comprehensive framework covering sustainability, innovation and failure prevention, and to research innovative strategies to improve machine performance and extend equipment life.*

Keywords: *wear mechanisms, repair, maintenance, augmented reality, soldering, welding, part replacement*

1. Introduction

Tribology is the study of the interaction between surfaces in relative motion. It is the science concerned with the study of boundary-layer interactions between solid bodies, as well as between these bodies and liquids or gases. The field of tribology encompasses all aspects of friction and wear, including lubrication (Kazama, 2017). The goal of tribology is to reduce friction and wear for specific applications. In addition to achieving the desired functionality, this involves minimizing manufacturing, assembly, and maintenance costs, as well as ensuring high efficiency and reliability. Friction and wear turn out within a tribotechnical system (TTS). To define a

TTS, a system is built around the components and materials directly involved in friction and wear, effectively isolating them from the rest of the assembly (Kazama, 2017). The materials involved in friction constitute the elements of the TTS and are characterized by their material properties and geometric shapes (Rabinowicz & Tanner, 1966). A tribotechnical system is characterized by its intended function, input variables (operating conditions), output variables, loss variables, and overall structure (Tarassov & Kolubaev, 1999). The structure of a tribotechnical system (TSS) is determined by the elements involved, their properties, and the interactions between them.

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1.1 Types and mechanisms of wear

Wear processes can be divided into different types according to the nature of the tribological load and the materials involved. Common types of wear include adhesive wear, fatigue wear, abrasive wear, and material corrosion, and these are shown in Figure 1. The main mechanisms that cause wear are important for understanding these processes, with four mechanisms being particularly important (Tsujiimoto et al., 2018):

Surface fatigue: This occurs due to repeated stress cycles that cause cracks to form on the surface and material loss (Al-Samarai & Al-Douri, 2024).

Abrasive wear: This involves the removal of material from the surface by mechanical contact with harder particles or surfaces (Ichida et al., 2005; Shpenev, 2018).

Adhesion: This mechanism involves the transfer of material and the sliding of surfaces against each other as a result of adhesion of surfaces under high pressure (Kinloch, 1980; Mishina & Hase, 2019).

Tribochemical reaction: This involves chemical reactions at the interface of sliding surfaces that can change the properties of the materials and contribute to wear (Nakayama & Martin, 2006).

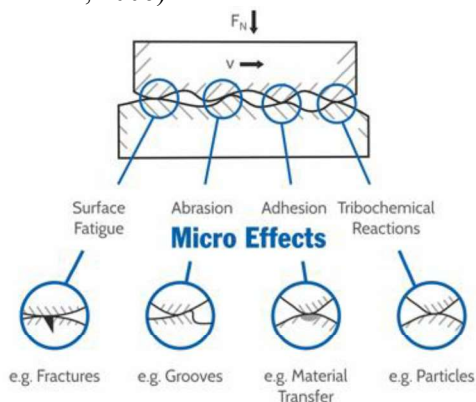


Figure 1. Types of common wear mechanisms

During wear, wear occurs by microcutting (Hutchings & Shipway, 2017). If the protective surface layers are disrupted in adhesion, atomic bonds (microwelds) can form primarily at plastically deformed microcontacts between the base body and the counterbody (Avramova et al., 2024). When the strength of these adhesive bonds exceeds that of the softer friction partner, material can separate from the deformed surface of the softer component and transfer to the harder one. Tribochemical reactions occur when friction activates the near-surface zones of the base body and/or the counterbody, causing chemical reactions with elements of the lubricant or the environment (Chen et al., 2022). The reaction materials often have altered properties compared to the original materials. After these materials reach a certain thickness, they can undergo brittle fracture and exhibit properties that reduce friction and wear. Abrasive wear occurs when a solid body is subjected to a load against particles of a material that is equal to or harder than the material itself (De Mello & Polycarpou, 2010). A major challenge in preventing and controlling abrasive wear is that the term “abrasive wear” does not accurately reflect the complexity of the wear mechanisms involved. In most cases, several wear mechanisms, each exhibiting different characteristics, operate simultaneously. Understanding these mechanisms is essential for developing effective strategies to reduce abrasive wear in various applications.

Various surface defects, including voids, scratches, and cracks, are common during machining, which directly affect the surface integrity and mechanical properties of components, limiting their performance in service.

Although higher feed rates generally improve surface integrity, the effect of cutting speed remains unclear (Kuhlmann et al., 2024). In some cases, increasing speed degrades tool edges, while in others, thermal softening can improve surface roughness. These discrepancies are caused by a variety

of factors, including workpiece and tool materials, machine conditions, and cutting environments (Brown et al., 2022). The presence of deformed layers beneath the machined surface varies throughout the cutting process, with fresh tools producing smoother surfaces than worn tools, leading to increased plastic deformation (Brown et al., 2022). The depth of plastic deformation is influenced by tool wear and cutting parameters.

Residual stresses caused by non-uniform plastic deformation can significantly affect the fatigue life of machined parts. In particular, tensile residual stresses accelerate crack formation and compromise durability (Shokrieh & Akbari, 2021).

Numerous studies have been conducted to improve surface integrity by minimizing tool wear during operations such as turning and milling through optimal machining parameters, tool modification, and innovative cooling methods (Fernandes & Barbosa, 2022). However, the complexity of machining operations requires further optimization, especially for difficult-to-cut materials, which increase tool wear.

Cooling and lubrication methods are increasingly important for controlling heat generated during machining (Fernandes & Barbosa, 2022). Traditional methods may need to be replaced by advanced approaches such as minimum quantity lubrication (MQL) and cryogenic cooling (“Experimental Research on Minimum Quantity Lubrication Surface Grinding With Different Cooling and Lubrication Conditions,” 2020). Hybrid cooling methods can potentially address the limitations of these individual techniques.

2. Overview of current maintenance strategies

2.1 Types of maintenance strategies

Reactive maintenance. Reactive maintenance involves responding to

equipment failures when they occur (Warren, 2016). Although this approach may seem simple, it can result in long downtimes, increased repair costs, and safety concerns (Pighin & Marzona, 2005). This approach lacks preventative measures and can lead to operational disruptions.

Preventive maintenance. Preventive maintenance focuses on scheduled maintenance tasks aimed at preventing equipment failures (Cahyati et al., 2024; Lynwander, 2019). While this strategy can reduce unexpected failures, it may not always reflect the actual condition of the equipment. Excessive maintenance can waste resources, while under-maintenance can cause problems.

Predictive maintenance. Predictive maintenance (PdM) uses data analysis and condition monitoring to predict equipment failures before they occur (Mehta, 2024; Patel & Kalgutkar, 2024). Examples include applications such as vibration analysis and infrared imaging analysis (Huseynzade & Abdullayev, 2024a; (Huseynzade & Abdullayev, 2024b) shown in Figure 2 (a) and (b). This approach uses sensors and data analytics to assess the condition of machines in real time, while also allowing maintenance activities to be performed based on actual wear and tear rather than arbitrary schedules.

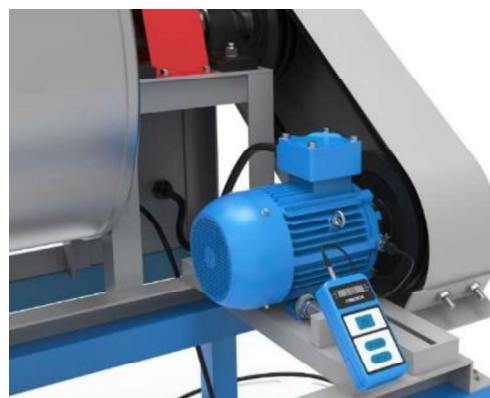


Figure 2 (a). Type of predictive maintenance strategies: Vibration analysis

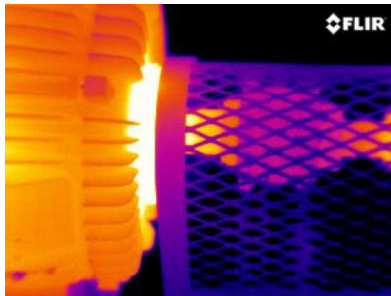


Figure 2 (b). Type of predictive maintenance strategies: Infrared imaging

2.2 Challenges of predictive maintenance

While PdM is essential for modern industry, its adoption faces significant challenges:

1. *1. Financial and organizational constraints:* The implementation of PdM entails significant costs for sensors, data retrieval, model development, and experimentation (Mehta, 2024). The high initial investment and uncertain Return on Investment make it difficult, especially for small enterprises.
2. *2. Data limitations:* Reliable data is essential, but data issues such as poor quality or sensor failure can lead to inaccuracies in forecasts and maintenance times (Li et al., 2017).
3. *3. Machine maintenance limitations:* Maintenance still relies on human intervention, as most industrial machines lack autonomous maintenance capabilities (Sharp & Ersdal, 2021).

These challenges highlight the need for careful planning and investment to maximize the benefits of PdM in industry.

3. WELDING, SOLDERING, AND REPLACEMENT STRATEGIES IN MAINTENANCE AND REPAIR

When it comes to industrial machinery maintenance and repair, welding, soldering,

and replacement strategies each play a critical role in the longevity of the equipment. Each technique has different applications, advantages, and disadvantages based on the materials, durability required, and repair complexity.

3.1 Welding process

Welding is primarily used to repair or join metal components in high-wear applications such as pipelines and heavy machinery. This method involves fusing metal parts using heat, pressure, or both (Lawal et al., 2023). Common welding types include arc welding, Metal Inert Gas (MIG) welding, and Tungsten Inert Gas (TIG) welding. MIG and TIG welding are shown in Figure 3.

The advantages of this method are: it creates strong, durable joints; it is suitable for high-stress and load-bearing applications; it allows for the repair of large, thick metal components.

The disadvantages include: it requires a skilled workforce due to the high temperatures and complex techniques; if not performed properly, it can cause material damage or residual stresses.

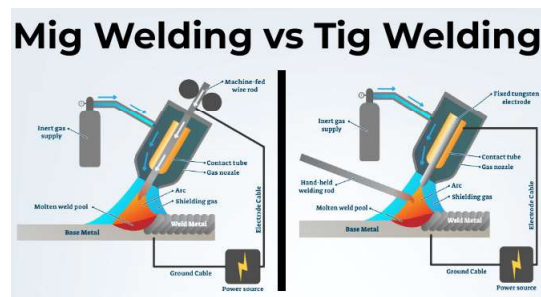


Figure 3. Most common types of welding: MIG and TIG

Table 1 provides techniques suitable for various materials.

Table 1. Appropriate Techniques for Most Commonly Used Materials

Material	Welding techniques	Soldering Techniques
Stainless steel (SS304, SS316)	Gas metal arc welding (GMAW), resistance welding	Maintaining corrosion resistance
Aluminum alloys	Resistance welding, Friction stir welding (FSW), Cold metal transfer (CMT)	Less common, CMT
Titanium alloys	Fusion welding, Diffusion welding	Not typical
Hard chromium/nickel	Laser metal deposition (LMD), Directed light generation (DLF)	Not Typical

3.2 Soldering process

Soldering is used to join smaller, thinner, and heat-sensitive metal components such as electronic components (Judd & Brindley, 1999). Figure 3 shows a schematic of the process of soldering an LED component to a circuit board. Soldering is done by applying molten solder to copper pads to create conductive connections. In this process, the solder melts by heating the solder tip, creating a permanent electrical connection between the copper pad and the LED leg. During the soldering process, care should be taken to prevent overheating of the components and unwanted short circuits during the cooling process. While correct soldering ensures efficient operation of the circuit, incorrect soldering can lead to contact problems or circuit failure.

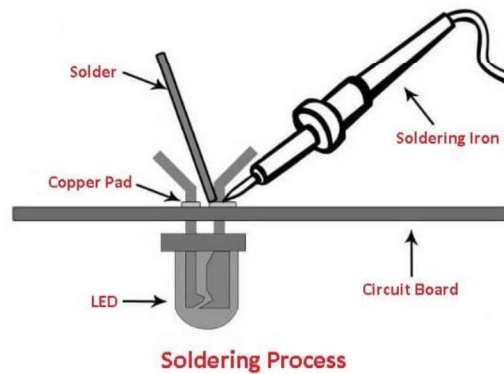


Figure 4. An example of the soldering process and tools

Advantages include: ideal for small, precise joints, especially in electronics; the low heat required minimizes damage to sensitive components.

Disadvantages include: soldered joints are less strong than welded joints and are not suitable for high-load applications.

3.3 Part replacement strategies

Replacement is often the preferred strategy for components that are worn out, beyond repair, or have a high probability of failure. Replacement involves removing the defective part and replacing it with a new one.

Advantages include: ensures reliability by ensuring that the component is new and functional; reduces downtime by using pre-fabricated parts that are ready to be replaced; avoids metal fatigue and wear problems in critical components.

As well as advantages, there are disadvantages. These include: it can be expensive, especially for high-cost components; disposal of replaced parts can create environmental or logistical problems.

3.4 Choosing the right strategy

The choice between welding, soldering, and replacement depends on factors such as the function of the component, the required

strength, cost, and downtime. For example:

1. Welding is often used for high-voltage components.
2. Soldering may be required for precision or heat-sensitive components (e.g. electronics).
3. For worn parts with low repairability, a replacement strategy is the best choice to ensure long-term reliability.

4. RECENT DIRECTIONS IN MAINTENANCE STRATEGIES

4.1 Embracing Smart Technologies

Condition Based Maintenance (CBM): This strategy uses real-time data to determine maintenance needs. By focusing on the actual condition of the equipment, this approach can optimize maintenance schedules, reduce costs, and increase equipment reliability.

Integration of the Internet of Things (IoT) and Artificial Intelligence (AI): IoT and AI are revolutionizing maintenance practices. IoT devices can collect and transmit data on equipment performance, and artificial intelligence algorithms can analyze this data to provide insights into optimal maintenance strategies and predict failures (Singh et al., 2021).

Reliability Centered Maintenance (RCM): RCM is an approach that prioritizes maintenance tasks based on the criticality of the equipment and its potential impact on operations (Braglia et al., 2019). This approach focuses on ensuring that critical components remain reliable while optimizing maintenance efforts for more critical systems.

The industrial machinery maintenance landscape is evolving with the demand for greater efficiency, safety, and cost-effectiveness. Traditional maintenance practices are increasingly inadequate for the complex demands of modern manufacturing

environments. By adopting innovative strategies such as predictive, condition-based, and reliability-based maintenance, business owners can improve operational efficiency and sustainability.

4.2 Augmented Reality applications in manufacturing

Augmented Reality (AR) is a transformative technology based on Virtual Reality (VR) and is designed to enhance the user experience by transferring three-dimensional (3D) computer-generated virtual information (e.g., machine parts and objects) into the real world (Eswaran et al., 2022). This technology allows users to perceive and interact with digital content in their physical environment, thus increasing their understanding and interaction with real-world scenarios.

Figure 5 illustrates the use of Augmented Reality (AR) technology for maintenance and troubleshooting purposes in industry. The operator visualizes digital overlays on the mechanical system in real time via a tablet, increasing the efficiency of inspection and repair processes.



Figure 5. Example of an Augmented Reality-based maintenance process

In the figure, the AR interface provides visual guidance using color-coded indicators, such as red arrows marking critical areas and green arrows indicating relevant connections or flow directions. This technology allows technicians to diagnose problems, access

interactive guides, and follow step-by-step repair instructions without the need for extensive physical documentation.

Assembly support: AR can guide operators through complex assembly processes by superimposing step-by-step instructions on physical components. This visualization helps ensure that tasks are performed accurately and in the correct sequence, reducing the likelihood of errors.

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Maintenance and repair: Technicians can use AR to visualize maintenance procedures by displaying relevant information and instructions directly on the equipment they are servicing. This can include providing guidance on troubleshooting components that need attention, resulting in reduced downtime and increased repair accuracy.

Training and skill development: AR offers immersive training experiences that allow new employees to practice skills in a controlled environment without the risks associated with real machinery. By simulating various scenarios, trainees can gain hands-on experience before working on actual equipment.

Benefits of using Augmented Reality (AR)

First, implementing AR reduces the time required for training and task completion by providing instant access to necessary information, thus facilitating operations. Second, the visual guidance provided by AR helps minimize errors, resulting in higher quality results and less waste. Furthermore, with AR support, operators can make independent decisions, increasing their confidence and capabilities. Hou et al. concluded that context-aware Augmented Reality (AR) based on a field maintenance

procedure for a complex piping system could reduce total work time by 55% and errors by 50% (Hou et al., 2013). Furthermore, time reductions of 15% to 40% demonstrate the transformative potential of AR.

5. Discussion

In the food industry, optimized maintenance methods can help ensure the reliability of critical components such as mixers, cooking, and packaging machines, which leads to the maintenance of product quality and reduced production downtime. These results can also improve the efficiency of technological flow lines used in various stages of the textile industry such as spinning and weaving, reduce downtime caused by mechanical problems. In addition, the application of AR technologies in maintenance and repair processes can simplify operations in both industries, providing real-time guidance to workers to quickly resolve problems. The results are expected to be most useful in the food sector, where compliance with regulatory requirements and product safety are of paramount importance.

6. Conclusion

Finally, adopting optimized maintenance strategies significantly increases the reliability of critical equipment in industries such as food processing and textiles. Implementing predictive maintenance techniques reduces machine downtime, optimizes production processes, and increases overall operational efficiency. Additionally, integrating Augmented Reality technologies into maintenance and repair activities simplifies troubleshooting and improves technical support, leading to increased repair efficiency. Table 2 shows tips for innovative approaches in industrial maintenance.

Table 2. Innovative approaches in industrial maintenance

Recommendation	Description
Expansion of Predictive Maintenance (PdM)	Apply IoT sensors and AI analytics to monitor equipment health and predict failures.
Integration of Augmented Reality (AR) technologies	Use this technique for real-time troubleshooting and technical guidance during maintenance.
Education and skill development	Provide training programs to equip maintenance personnel with modern technology skills.
Regulatory compliance and safety	Ensure that maintenance practices are compliant with industry regulations, particularly regarding food safety.
Continuous development and research	Invest in ongoing R&D to explore innovative maintenance technologies and strategies.

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