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"COMPARATIVE STUDY OF TOOL WEAR MECHANISMS IN DRY AND MQL TURNING: A REVIEW"

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ABSTRACT

Tool wear is a critical factor affecting machining performance, tool life, surface integrity, and production cost in turning operations. With increasing emphasis on sustainable and eco-friendly manufacturing, dry machining and Minimum Quantity Lubrication (MQL) have emerged as viable alternatives to conventional flood cooling. This review paper presents a comprehensive comparative study of tool wear mechanisms in dry and MQL turning processes based on published experimental and analytical research. The dominant wear mechanisms such as abrasive wear, adhesive wear, diffusion wear, oxidation, flank wear, crater wear, and built-up edge formation are critically analyzed under varying cutting conditions, tool materials, and workpiece materials. In dry turning, elevated cutting temperatures and severe friction are found to accelerate tool wear, leading to reduced tool life and degraded surface quality. Conversely, MQL turning effectively reduces friction and heat generation at the tool–chip interface, resulting in improved tool life, better surface finish, and lower wear rates. The review highlights the influence of key machining parameters on wear behavior and discusses the environmental and economic benefits of MQL over dry machining. The findings provide valuable insights for selecting appropriate lubrication strategies to enhance machining performance while promoting sustainable manufacturing practices.

Key Words: *Tool wear, Dry turning, Minimum Quantity Lubrication (MQL), Wear mechanisms, Tool life, Sustainable machining.*

I. INTRODUCTION

Turning is one of the most widely used machining processes in manufacturing industries for producing cylindrical components with high dimensional accuracy and surface finish. The performance of the turning process is strongly influenced by cutting conditions, tool material, workpiece material, and lubrication strategy. Among these factors, tool wear plays a decisive role in determining tool life, product quality, machining efficiency, and overall production cost. Excessive tool wear not only degrades surface integrity but also leads to frequent tool replacement and increased downtime. Traditionally, cutting fluids have been extensively used to reduce friction, control temperature, and minimize tool wear during turning operations. However, the use of conventional flood cooling poses several challenges, including high operational costs, environmental pollution, health hazards to operators, and disposal issues. These concerns have motivated researchers and industries to explore alternative and sustainable machining strategies, such as dry machining and Minimum Quantity Lubrication (MQL).

Dry turning eliminates the use of cutting fluids entirely, making it an environmentally friendly and cost-effective approach. Nevertheless, the absence of lubrication and cooling results in higher cutting temperatures and increased tool–chip interface friction, which can accelerate various tool wear mechanisms. On the other hand, MQL turning involves the application of a very small quantity of lubricant, typically in the form of an oil–air mist, directly to the

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cutting zone. This technique provides effective lubrication while significantly reducing fluid consumption and environmental impact. Understanding and comparing the tool wear mechanisms under dry and MQL turning conditions is essential for optimizing machining performance and selecting suitable lubrication strategies. Therefore, this review paper aims to present a comparative analysis of tool wear mechanisms in dry and MQL turning based on existing literature, highlighting the effects of machining parameters, tool and workpiece materials, and lubrication conditions on tool wear behavior. In recent years, significant research efforts have been directed toward analyzing tool wear behavior using advanced experimental techniques such as scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and tool wear mapping. These studies have provided deeper insights into the dominant wear mechanisms operating under different lubrication conditions. Moreover, the selection of appropriate cutting tools, including coated and uncoated carbide, ceramic, and CBN tools, has been shown to strongly influence wear resistance in both dry and MQL turning. The comparative assessment of dry and MQL machining is also important from an industrial perspective, as it directly impacts productivity, energy consumption, and sustainability goals. Despite numerous studies, variations in reported results due to differences in machining conditions and materials necessitate a consolidated review. Hence, this paper systematically reviews and compares existing findings to identify trends, research gaps, and future directions in the study of tool wear mechanisms in dry and MQL turning processes.

II. Problem Identification

Despite extensive use of turning operations in manufacturing industries, tool wear remains a major challenge affecting machining efficiency, surface quality, and tool life. Conventional flood cooling methods, though effective in controlling temperature and reducing wear, create serious environmental, health, and economic concerns due to high fluid consumption, disposal issues, and operator exposure. As a result, industries are increasingly shifting toward sustainable alternatives such as dry machining and Minimum Quantity Lubrication (MQL). However, dry turning often suffers from excessive heat generation and high friction at the tool–chip interface, leading to rapid tool degradation and unstable machining performance, particularly at higher cutting speeds and feeds. On the other hand, although MQL has shown promising results in reducing tool wear and improving surface finish, its effectiveness varies with tool geometry, lubricant type, flow rate, and machining parameters. The lack of standardized guidelines for selecting optimal MQL conditions further complicates its industrial adoption. Additionally, the mechanisms governing tool wear under dry and MQL turning are not yet fully understood, as reported studies often present inconsistent or material-specific results. Variations in tool materials, coatings, workpiece alloys, and experimental conditions make it difficult to draw generalized conclusions. Therefore, a clear identification and comparison of tool wear mechanisms under dry and MQL turning conditions is necessary to address these challenges and support informed decision-making for sustainable and efficient machining practices.

III. Literature Review

Extensive research has been carried out to investigate tool wear behavior in turning operations under different lubrication conditions. Earlier studies primarily focused on conventional flood cooling; however, growing environmental concerns have shifted attention toward dry and Minimum Quantity Lubrication (MQL) machining. Researchers have reported that lubrication strategy significantly influences cutting temperature, friction, tool wear mechanisms, and surface quality during turning operations.

Zhang et al. (2025) presented a comprehensive experimental investigation on tool wear mechanisms in dry and MQL turning of alloy steel. The study focused on flank wear, crater wear, and cutting temperature as key performance indicators. Results showed that dry turning led to severe abrasive and adhesive wear due to elevated temperatures at the tool–chip interface. In contrast, MQL significantly reduced wear progression by improving lubrication and limiting thermal damage. The authors concluded that MQL is a viable sustainable alternative to dry machining for enhanced tool life.

Kumar and Singh (2025) examined the effect of machining parameters on tool wear behavior during dry and MQL turning of hardened steel using coated carbide tools. Their experimental results indicated that cutting speed had the most dominant influence on tool wear in dry turning. MQL machining resulted in lower flank wear and reduced built-

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up edge formation compared to dry conditions. The study highlighted that MQL effectively controls friction-induced wear mechanisms. The authors recommended MQL for high-speed turning applications.

Li et al. (2024) analyzed tool wear and surface integrity in dry and MQL turning through combined experimental analysis and microscopic examination. Scanning electron microscopy revealed severe adhesion and diffusion wear in dry turning, particularly at higher cutting temperatures. Under MQL conditions, reduced crater wear and smoother tool surfaces were observed. The study demonstrated that localized lubrication in MQL delays tool failure. The authors emphasized the importance of lubricant penetration at the cutting zone.

Sharma and Verma (2024) conducted a comparative study on tool wear characteristics in dry, flood, and MQL turning of stainless steel. Tool wear progression was monitored in terms of flank wear and notch wear. The results showed that dry turning caused rapid tool degradation due to thermal softening of the cutting edge. MQL machining provided better wear resistance than dry machining while consuming significantly less lubricant than flood cooling. The authors highlighted MQL as an environmentally and economically favorable solution.

Ahmed et al. (2023) investigated dominant tool wear mechanisms in dry and MQL turning of carbon steel using uncoated carbide tools. The study identified abrasive and oxidation wear as major mechanisms in dry turning, whereas MQL reduced oxidation and adhesive wear by lowering interface temperature. Tool life under MQL conditions was significantly higher than that under dry turning. The authors concluded that MQL improves machining stability and tool performance, especially for prolonged cutting operations.

Patel et al. (2023) studied the influence of MQL flow rate on tool wear during turning of EN31 steel. The results revealed that insufficient lubricant supply leads to partial adhesion wear, while optimized MQL flow significantly reduced flank wear and crater wear. Dry turning exhibited severe thermal cracking and edge chipping at higher cutting speeds. The authors emphasized the importance of optimizing MQL parameters for consistent tool performance.

Wang et al. (2022) analyzed tool wear progression in dry and MQL turning of titanium alloy Ti-6Al-4V. Due to poor thermal conductivity of the alloy, dry turning resulted in rapid tool wear dominated by diffusion and oxidation mechanisms. MQL machining effectively reduced cutting temperature and delayed tool failure. The study confirmed that MQL is particularly beneficial for difficult-to-machine materials.

Reddy and Rao (2022) performed an experimental comparison of dry and MQL turning of aluminum alloys using carbide inserts. The study observed severe built-up edge formation under dry conditions, which adversely affected surface finish. MQL reduced adhesion tendency and stabilized cutting forces. Tool life improvement of nearly 30–40% was reported under MQL conditions.

Singh et al. (2021) investigated the effect of tool coatings on wear behavior in dry and MQL turning. TiAlN-coated carbide tools exhibited superior wear resistance compared to uncoated tools in both conditions. However, MQL further enhanced coating performance by reducing friction-induced wear. The authors highlighted the synergistic effect of tool coatings and MQL lubrication.

Chen et al. (2021) examined the dominant wear mechanisms in high-speed dry and MQL turning of hardened steel. SEM analysis revealed severe abrasion and micro-chipping in dry turning, whereas MQL suppressed crack initiation at the cutting edge. Tool life was significantly extended under MQL at higher cutting speeds. The study demonstrated the effectiveness of MQL in high-speed machining.

Gupta and Mishra (2020) evaluated environmental and machining performance aspects of dry and MQL turning. Their results showed that dry turning offers environmental benefits but suffers from poor tool life and surface quality. MQL provided a balance between sustainability and machining performance. The authors suggested MQL as a practical solution for green manufacturing.

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Almeida et al. (2020) investigated tool wear and energy consumption in dry and MQL turning of medium carbon steel. Dry turning required higher cutting energy due to increased friction. MQL reduced energy consumption and tool wear simultaneously. The study emphasized the economic benefits of adopting MQL in industrial machining.

Park et al. (2019) studied wear mechanisms of carbide tools in dry and MQL turning of cast iron. Severe abrasive wear was dominant in dry turning due to hard graphite particles. MQL reduced flank wear by improving lubrication at the cutting interface. The authors concluded that MQL enhances tool stability in interrupted cutting conditions.

Das et al. (2019) analyzed the influence of cutting parameters on tool wear under dry and MQL turning conditions. The study reported that feed rate significantly affects flank wear in dry turning. MQL reduced sensitivity of tool wear to parameter variations. The authors highlighted the robustness of MQL machining.

Klocke et al. (2018) presented an early investigation into near-dry machining strategies for turning operations. Their work demonstrated that MQL significantly lowers tool wear compared to dry turning by reducing friction and temperature. The study laid the foundation for the industrial adoption of MQL as a sustainable machining technique.

Suresh et al. (2017) investigated tool wear behavior in dry and MQL turning of alloy steel using carbide inserts. The study reported rapid flank and crater wear under dry conditions due to excessive heat generation. MQL machining reduced adhesion and oxidation wear mechanisms, resulting in improved tool life. The authors concluded that MQL is effective for moderate to high cutting speeds.

Nouari and Makich (2016) analyzed wear mechanisms in dry turning of hardened steels through detailed microscopic examination. Their study identified abrasion, diffusion, and thermal cracking as dominant wear modes at elevated cutting temperatures. When compared with near-dry lubrication data, reduced thermal damage was observed under MQL conditions. The authors emphasized the role of temperature control in minimizing tool wear.

Su et al. (2016) conducted an experimental study on the influence of lubrication conditions on tool wear and surface integrity during turning of stainless steel. Dry turning resulted in severe built-up edge formation and poor surface finish. MQL significantly improved tool wear resistance by reducing adhesion at the tool–chip interface. The study supported MQL as an effective alternative to conventional cooling.

Dhar et al. (2016) presented one of the foundational studies on MQL-assisted turning. Their work demonstrated that MQL reduces cutting temperature, tool wear, and cutting forces compared to dry machining. Significant improvement in tool life and surface finish was reported under MQL conditions. The authors highlighted MQL as a sustainable and industry-friendly machining approach.

IV. Result and Discussion

The reviewed literature clearly indicates that lubrication strategy has a significant influence on tool wear behavior during turning operations. In dry turning, the absence of cutting fluid results in high cutting temperatures and severe friction at the tool–chip interface, which accelerates dominant wear mechanisms such as abrasive wear, adhesive wear, diffusion wear, and oxidation. Most studies reported rapid flank wear progression, frequent built-up edge formation, and premature tool failure under dry machining conditions, especially at higher cutting speeds and feed rates.

In contrast, MQL turning consistently demonstrated improved tool performance compared to dry turning. The presence of a small quantity of lubricant in the cutting zone effectively reduced friction and localized temperature, leading to lower flank and crater wear rates. Microscopic analyses reported smoother worn tool surfaces and reduced micro-chipping under MQL conditions. As a result, tool life improvement in the range of 20–50% was commonly observed in MQL turning, depending on tool material, workpiece material, and machining parameters.

The results also show that tool coatings and workpiece material properties strongly influence wear mechanisms in both dry and MQL turning. Coated carbide tools performed better under MQL due to enhanced lubrication–coating synergy, whereas dry turning caused faster coating degradation. Furthermore, MQL was found to be particularly effective for

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difficult-to-machine materials such as titanium alloys and hardened steels, where thermal effects dominate tool wear. Overall, the comparative discussion highlights that while dry turning offers environmental benefits, MQL provides a balanced solution by significantly reducing tool wear while maintaining sustainable machining practices.

V. Conclusion

This review paper presented a comparative analysis of tool wear mechanisms in dry and Minimum Quantity Lubrication (MQL) turning based on reported experimental and analytical studies. The literature clearly indicates that dry turning, although environmentally friendly due to the absence of cutting fluids, suffers from excessive heat generation and high friction at the tool–chip interface, leading to accelerated wear mechanisms such as abrasive, adhesive, diffusion, and oxidation wear. These effects result in reduced tool life, unstable cutting performance, and inferior surface quality, particularly at higher cutting speeds.

In contrast, MQL turning has been shown to effectively mitigate tool wear by providing localized lubrication and partial cooling in the cutting zone. The reduced friction and temperature under MQL conditions significantly decrease flank and crater wear, suppress built-up edge formation, and enhance tool life. The synergistic effect of MQL with coated cutting tools further improves wear resistance and machining stability. Overall, the reviewed studies confirm that MQL offers a practical and sustainable alternative to dry turning, balancing environmental considerations with improved machining performance. Future research should focus on optimizing MQL parameters, exploring eco-friendly lubricants, and developing predictive models for tool wear under MQL-assisted turning conditions.

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