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REVIEW ARTICLE

A comprehensive exploration of minimum quantity lubrication in machining process

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ABSTRACT - Minimal Quantity Lubrication (MQL) has received a lot of interest in the machining processes because of its potential and environmental benefits. Transitioning from traditional flood cooling technologies to MQL has various advantages, including lower heat generation and better chip evacuation. The MQL approach has shown to be effective since it conforms with “green machining” criteria. The current study reviews significant research publications on the usage of cutting fluids and fluids based on nanofluids, as well as mineral and vegetable oils for various machining operations, including drilling, turning, milling and grinding. The suitability of the MQL technique has been demonstrated as it aligns with the requirements of environmentally friendly machining. The paper elucidates the mechanism behind the MQL technique and systematically explores its impact on the performance parameters of diverse machining processes. The study gives a detailed investigation of MQL in terms of its impact on cutting performance, tool life, and surface finish. Numerous experimental studies indicate that employing MQL results in surface quality superior to dry machining and comparable to that achieved with wet machining. Furthermore, the application of MQL reduces cutting forces, cutting zone temperature, tool wear, and friction coefficient when compared to both dry and wet machining. Consequently, the MQL technique has demonstrated its viability as a feasible alternative to flood lubrication under similar performance parameters.

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1. INTRODUCTION

Metal cutting operations are associated with huge amount of energy consumption. Significant portion of energy is converted into heat at tool-chip interface and tool-workpiece interface leading to tool wear, which ultimately reduces tool life and causes changes in material properties [1]. Lubricants play a critical role in taking away heat from heat zone areas. In past, many traditional machining processes used different types of lubricants and cutting fluids in order to reduce friction, dissipate heat and enhance machining processes [2]. These lubricants often contained chemicals and compounds and they were applied in many forms including oils, emulsions and pastes [3]. Although theses lubricants served the purpose of aiding the machining, they also had some negative consequences for workers and the environment. Moreover, the conventional lubrication technique was associated with large dose of fluids which in turn causes high costs to the process [4]. Using cutting fluids improperly has adverse impact on both human health and the environment. Due to concerns about the economy and the environment, industrial companies are searching for a method that minimises the use of lubricants during the metal cutting process. Protecting environmental instability through socioeconomic precondition is the primary goal of the ISO 14000 standards [5, 6]. In order to enhance cooling techniques and reduce environment associated problems, traditional flood cooling was replaced by MQL technique. MQL is an environmental friendly lubrication method that involves directly applying lubricant to the cutting zone in a minimal amount, typically 500 mLh-1 or less, which is around 10000 times less than that of standard cutting fluids [7]. The objective of this study is to examine how the utilization of various nano-fluids and traditional cutting fluids in diverse machining processes impacts the outcome.

MQL, also known as "Micro Lubrication" or "Small Quantity Lubrication," is the best way to apply cutting fluid to the tool-workpiece interface [8-11]. Several researchers have proposed MQL theory for dealing with biological safety problems. One aspect of biological safety concerns in machining is the potential health risks associated with exposure to cutting fluids, which often contain hazardous chemicals. These fluids can generate mists or aerosols during machining operations, which can be inhaled by workers, leading to respiratory issues or skin irritations. Additionally, the disposal of large volumes of used cutting fluids can pose environmental hazards if not managed properly [12]. Wet cooling is less effective than MQL technique due to improved evaporative and convective heat transfer. In a study it was found that at high-velocity, the fluid droplets pierced the vapour blanket, reached the tool-workpiece interface and increases heat transmission as compared to moist lubrication. Actually, the oil droplets reduce the amount of friction between the tool

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and the chip, and compressed air clears the cutting zone of metal chips [13]. Another investigation revealed that due to low penetrability, aerosols did not provide boundary lubrication at the tool-workpiece contact. In addition, because of minor droplet evaporation, the cooling effect is quite low. However, the MQL technology creates a molecular coating on the machined zone, enhances Rebinder effect, causes reduction in ductility and hardness of workpiece [14, 15].

The lubricant supply system (see Figure 1) is the core of a MQL system in which the cutting fluid or lubricant is stored and delivered to the machining process. It generally comprises of a reservoir or container for storing the lubricant, as well as pumps or pressure regulators to manage the lubricant flow. The nozzle or applicator, is responsible for accurately delivering the lubricant to the cutting zone. The nozzle is placed near to the cutting tool and the workpiece to ensure that the lubrication is delivered where it is most needed. Compressed air is employed in many MQL systems to assist atomize the lubricant into a thin mist or aerosol. A compressor and air lines are commonly used in an air supply system to provide compressed air to the nozzle [16-18]. The mist produced by the mixture of air and lubricant is directed to the cutting zone. MQL systems have control mechanisms for regulating lubricant flow rate and controlling air pressure. These controls enable operators to modify lubrication levels to the needs of the machining process, material, and tool. Maintaining the quality of the lubricant is critical for ensuring maximum performance and preventing nozzle blockages. As a result, MQL systems frequently contain filters or filtering systems to remove impurities from the lubricant before it reaches the nozzle [19-21]. Some modern MQL systems include sensors and monitoring devices that offer real-time input on the lubrication process. This assists operators in ensuring that the appropriate amount of lubrication is administered and allows for modifications as needed [22-26].

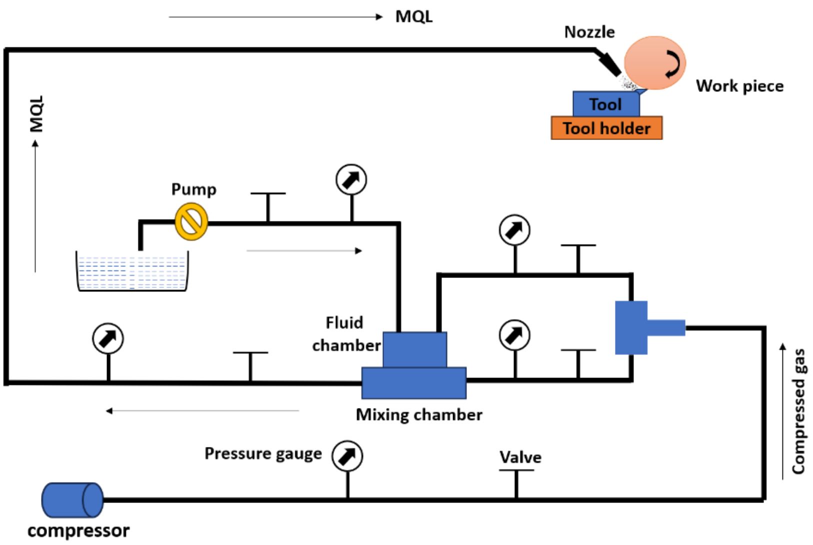


Figure 1. Scheme of MQL system

Internal delivery and exterior delivery are the two main types of delivery systems employed in MQL technology. In an internal delivery system, shown in Figure 2, a specifically constructed single or dual channel are used to spray the mixture of air and lubricant that was created inside the nozzle [27]. The design of an atomization-based cutting fluid spray system for exterior delivery on the other hand use an atomizer to prepare aerosol and disperse it outside to the machining zone. The two types of nozzles used in this system are ejector and standard nozzles, shown in Figure 3 [28].

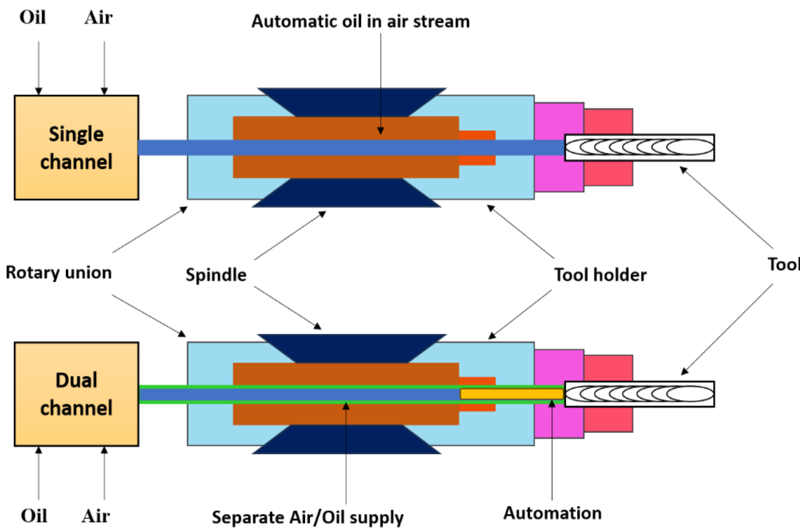


Figure 2. Internal delivery system of MQL technology

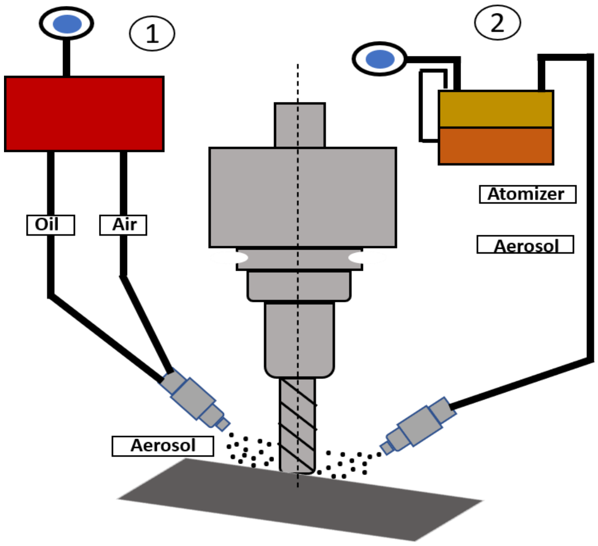


Figure 3. External delivery system of MQL technology: 1. Ejector nozzle, 2. Conventional [28]

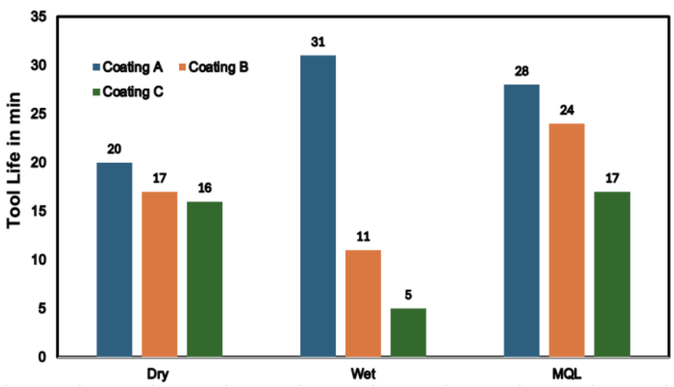
The MQL systems allow for the selection of a wide variety of settings, including cutting fluid type, nozzle design, volume rate, and pressure. Therefore, it is difficult to forecast the outcomes. A model was created to address this issue and anticipate the outcomes when employing MQL systems. It was obtained under dry machining using Jawahir's tool wear prediction, and it comprises both the cooling system and the cutting parameters, (refer to Eq. (1)) [29].

$$T = TR \times \left(\frac{km}{f^{n_1} \times d^{n_2}}\right) \times \left(\frac{V^R}{V}\right)^{(1/N_c)} \times \left(\frac{1}{N_{NDM}}\right) \tag{1}$$

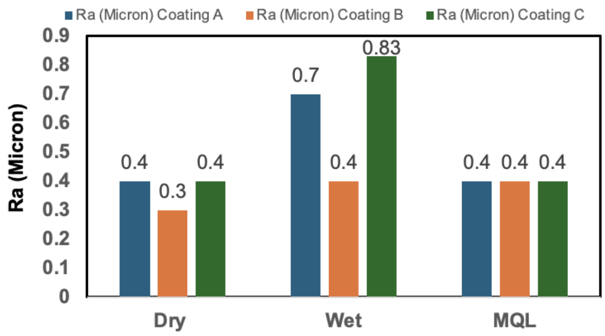
where, T represents tool life (how long the tool lasts), TR represents the one-minute reference tool life in machining, The variables K, n_1, and n_2 are experimental constants, while M is a constant specific to the machining process, F stands for the feed rate, and D represents the depth of cut, VR signifies the reference cutting speed for a one-minute tool life, and V is the actual cutting speed, N_c is the coating impact variable, and NNDM denotes the influence of the cooling system during operation.

2. COMPARISON BETWEEN DRY, MQL AND FLOODED LUBRICATION

MQL may effectively reduce the cutting temperature in contrast to the dry condition, enhancing tool chip contact and keeping cutting tool sharpness. However, the cooling effect caused by the MQL system was not as good as observed in conventional flooded lubrication condition, however MQL outperforms in terms of cost and energy use [31-33]. Surface roughness was greatly reduced by MQL, and the value produced by MQL was similar to flood lubrication but significantly better than dry machining conditions. The literature claims that MQL technology can also improve dimensional accuracy and reduce tool wear [33]. In a study, it was discovered that Inconel 718 could be turned at high speeds while employing a variety of coated tools by applying the MQL approach [34]. The tool life and surface polish of the dry, wet, and MQL techniques are compared in Figure 4 below. The surface finish and tool life acquired using MQL for cutting tools with different coatings were discovered to be superior to those obtained through wet and dry machining. Figure 5 shows a comparison of the corner wears of three different coated tools used in dry, MQL and wet cutting conditions at 1.0 m/s.



(a)



(b)

Figure 4. (a) Tool life and (b) surface finish for three types of machining conditions: dry, wet, and MQL [34]

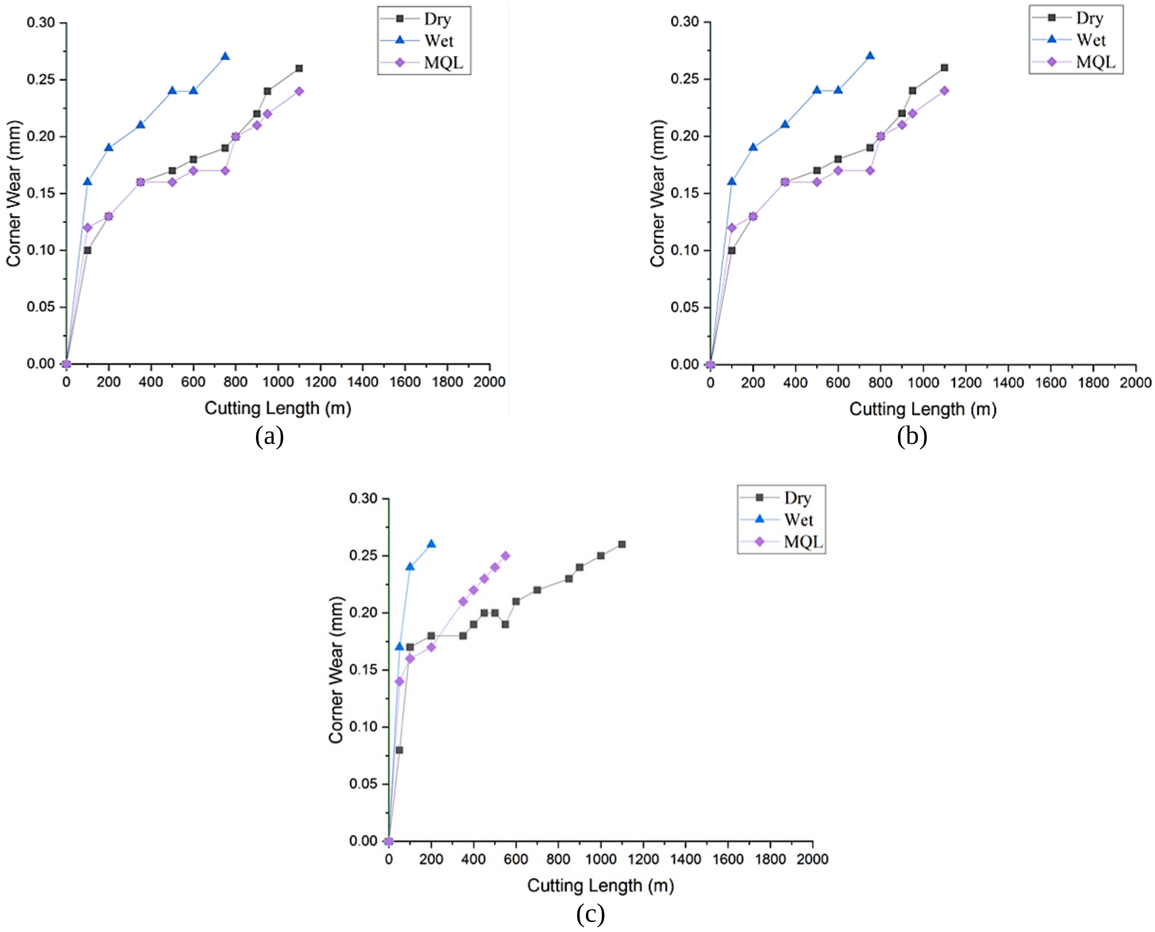


Figure 5. Development of wear under for three types of machining conditions: (a) Dry, (b) Wet, and (c) MQL [34]

Few years ago, a researcher created a fishbone diagram, shown in Figure 6 depicts the likely machining operation parameters and MQL circumstances that influence the results of MQL aided machining process [35].

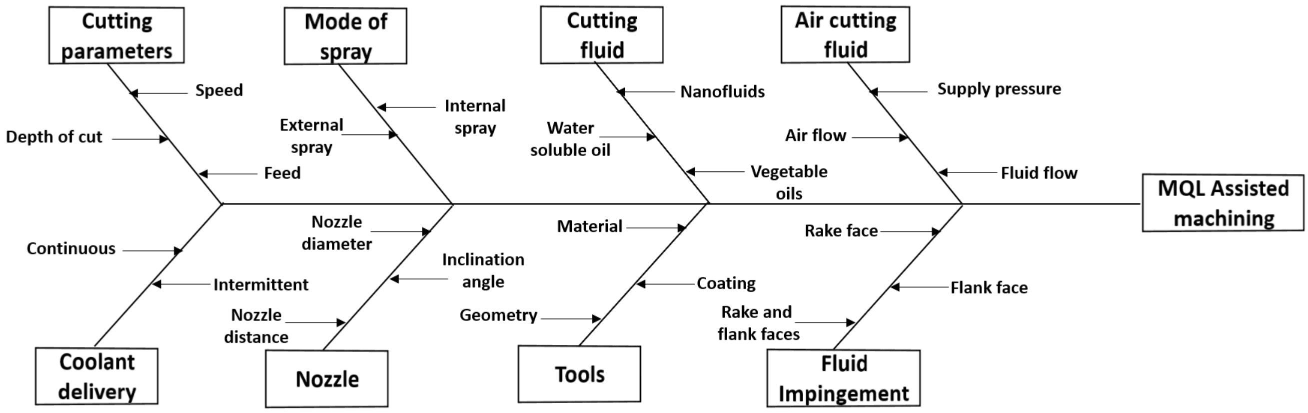


Figure 6. Fishbone like structure displaying MQL assisted machining parameters and conditions [35]

3. SURVEY ON MQL ASSISTED MACHINING

A lot of study has been done on MQL technology to determine how it affects machining performance. Based on the literature that is currently available, the use of MQL lubricating technique and its impact on cutting response parameters in different machining operations, like turning, drilling, grinding, and milling, is comprehensively discussed in this section.

3.1 Survey on MQL Assisted Turning

Table 1 presents summarizes key findings from existing literature, highlighting various studies that have investigated the effectiveness of MQL techniques in turning processes. Hard turning of AISI4340 with P30 or a comparable substrate and coatings of TiC, TiN, and TiCN was studied using MQL. The study employed a lubricating fluid with a high coolant concentration (60%) and minimal additives. This fluid was administe-red at a rate of 2 ml per minute, under an injection pressure of 20 MPa, and with a frequency of 600 pulses per minute. Comparative analysis against both dry and flood cooling methods revealed several benefits of this approach. Specifically, it resulted in reduced cutting force, shorter tool chip contact length, and lower cutting te-mperatures. Moreover, the utilization of this method improved cutting efficiency, extended tool lifespan, and provided better control over chip formation. The fragmentation of the cutting fluid into small droplets, which travel at a fast speed through the blanket of vapors to the cutting zone, is said to improve machinability. The convective and evaporative modes of heat transfer also made cooling more efficient [13, 37, 38].

Table 1. Summary of previously published literature on MQL assisting turning

Citation-Year	Cutting Fluid	Workpiece Material	Mode of Lubrication	Findings
[39]-2024	Blasocut 2000 universal	EN24 steel	Dry, MQL	With the introduction of MQL, flank wear decreased by 76%, surface roughness decreased by 74.1% and cutting temperature decreased by 53% while machining with Diamond coated tool.
[40]-2024	Garlic oil based MQL	EN24 steel	Dry, MQL	When comparing to dry machining, MQL-based turning produces superior results due to a decrease in cuting temperature and surface roughness When comparing to dry machining, garlic oil achieved a 43.8% reduction in flank wear, a 69.3% decrease in cutting temperatures, and an impressive 79.3% improvement in surface finish.
[41]-2019	Emulsion-based coolant mixed in the water	Precipitated hardened stainless steel (PH SS)	MQL	Significant reduction in surface roughness and tool wear when MQL flow rate increased.
[42]-(2013)	Commercially available lubricant	AISI 4340 Alloy steel	Dry, MQL, wet	Decreasing the cutting temperature by 36%, 30% improvement in surface finish was achieved. Additionally, a significant reduction (about 40%) in cutting force was observed.
[43]-(2009)	Vegetable oil	Alloy steel AISI 9310	Dry, MQL, wet	10% drop in cutting temperature and prevents BUE formation.
[44]-(2006)	*	AISI 1040 steel	Dry, MQL, wet	A significant reduction in cutting temperature was achieved, also metallic coloured chips were generated, and the dimensional deviation was reduced.
[45]-(2011)	Mineral oil	C45 AISI 1045 steel	Dry, MQL, Emulsion	Improved outcomes in terms of cutting forces and surface finish.
[46]-(2006)	*	AISI 4340 steel	Dry, MQL, wet	Enhanced tool life, decreased tool wear, and reduction of surface roughness was observed.
[47]-(2014)	Extra-critical CO_2	Inconel 750	MQL, wet	Improved in MRR by about 40% and improvement in tool life was observed.
[48]-(2010)	*	AISI 1045 steel	MQL, wet	MQL assisted machining machining was observed more beneficial in terms of machining response than wet.
[49]-(2014)	Mineral oil	AISI 4340 steel	Dry, MQL	Decreased cutting forces by 17.07% while raising tool-tip temperature by 6.72%.
[50]-(2007)	Mobil Cut-102	AISI 1045 steel	Dry, MQL	Reduction in flank wear was observed by approximately 10%. Also significant reduction in flank wear was observed.
[51]-(2006)	Vegetable oil	AISI 420B steel	Dry, MQL, wet	Regarding flank wear and surface quality, MQL was unable to provide any advantages over dry machining.
[52]-(2006)	Synthetic eater (mono carboxylic acid and polyalcohol) with rapeseed oil	Aluminium silicon Alloy AISI	Dry, MQL, wet	MQL with ester exhibit more advantages as a lubricant than MQL with rapeseed oil.
[53]-(2013)	Ester oil	AISI 4140 steel	Dry, MQL, wet	Improved surface quality and decreased cutting force.
[54]-(2007)	Emulsion oil	Commercially available brass ($CuZn_39Pb_3$)	MQL, wet	For MQL and wet machining, there isn't much variance in surface roughness or cutting forces.

* represents cutting fluids which are not mentioned in the study

In a different study, researchers compared the performance of two nitride coated tools, TiCN and ZrN, in the process of hard turning AISI4340 with minimal fluid application. They used a statistical design of experiments to analyze various factors. The results showed that exit pressure, depth of cut, and feed were the critical factors affecting cutting force, while the type of coating had no significant impact. Increasing nozzle pressure led to higher cutting fluid exit velocity, which resulted in better penetration and reduced cutting force. Cutting temperature was primarily influenced by cutting velocity, followed by the quantity of cutting fluid, nozzle pressure, and pulse frequency. Surface roughness depended mainly on the feed rate, followed by nozzle pressure, coating type, and the volume of cutting fluid used [38].

3.2 MQL Assisted Milling

Table 2 reviews various studies that have investigated the use of MQL in milling operations, highlighting their experimental conditions, key findings, and contributions to the field. Cutting fluid is not commonly used in milling processes due to the ease with which cracks propagate in the tool as a result of temperature variations. These thermal variations lead the cutting insert to fail catastrophically. As a result, dry machining has been given preference more. However, during the milling process the high temperature rise occurs in the cutting zone due to which it becomes difficult to cut materials at higher speeds. The elevated temperature significantly hinders the machining process by causing various challenges, including poor machinability, adhesion, heightened abrasion, and increased chemical reactivity between the tool and workpiece materials. To address these issues, near-dry machining techniques, such as MQL, are widely recognized as the most efficient method for intermittent operations. In the milling of $AlSi_9Cu_4Mg$, the effectiveness of nozzle placement was investigated, specifically at 45° and 135° positions. The evaluation of flank wear revealed that wear at 45° was notably severe, attributed to reduced fluid accessibility in the tool-chip contact zone [55]. The impact of oil consumption of 0.04 cm^3/min and 0.06 cm^3/min was also insignificant on the wear. Also, at a rate of 0.04 cm^3/min, substantial adherence of aluminium particles was observed on the tool surface [56]. Except for Liao et al., who claimed that MQL was successful at 250 m/min, several writers have concluded that MQL is efficient at the low cutting velocity. In high-speed milling of an aluminium alloy, milling under dry, MQL, and flooded lubrication conditions has been investigated and resulted in reduction of cutting forces under MQL and flood lubrication. Also, it could be attributed to lower adhesion and friction in presence of fluid [59-62].

Table 2. Literature survey on MQL assisted milling

Citation-Year	Cutting Fluid	Workpiece Material	Mode of Lubrication	Findings
[61]-2022	*	EN-31 steel	MQL	The value of the flank wear is reduced by 2.10% at the ideal MQL parametric parameters.
[62]-2021	Castor and palm oil	Inconel 690	MQL	A comparison investigation revealed that the optimal castor-palm volume fraction reduced surface roughness by 8.262 and 16.146%, reduced specific cutting energy by 5.459 and 7.971%, and reduced tool wear by 2.445 and 3.155% when compared to castor and palm oil medium, respectively.
[63]-2020	*	Ti-6Al-4V alloy	MQL	Utilizing graphite-infused cutting fluid in Minimum Quantity Lubrication (MQL) conditions successfully led to a notable decrease in surface roughness, demonstrating its effectiveness.
[64]-2018	*	Inconel 718 alloy	Dry, flood and MQL	According to the results MQL performed better in terms of tool wear than dry and flooded lubrication condition.
[65]-2016	*	SS304	Dry, MQL	MQL assisted machining improved tool life. Also diminished surface roughness and cutting forces by introducing an additional protective oxide layer near the tool-chip interface, as opposed to MQL-assisted milling.
[66]-2014	*	Titanium alloy	MQL	MQL assisted machining effectively enhanced machining performance than flood and dry lubrication condition. Particularly MQL machining was improved with a simple system configuration. Additionally, the combination of MQL with cryogenic lubrication and cooling lowered cutting force and tool wear. MQL and cryogenic techniques can be a sustainable option for energy usage.
[67]-(2010)	Vegetable oil	SKD 61 steels	Dry, MQL	MQL decreased burr formation and flank wear by around 60%.
[68]-(2005)	*	BM2000	Dry, MQL, flood	Results concluded that chip morphology was not affected by any three types of lubrication, although among the three types of lubrication, MQL reduced flank wear the most.

Table 2. (cont.)

Citation-Year	Cutting Fluid	Workpiece Material	Mode of Lubrication	Findings
[69]-(2011)	Lubri max-oil	Aluminium alloy	Dry, MQL, flood	Comparable outcomes were obtained with MQL in terms of cutting power and surface roughness.
[70]-(2012)	Vegetable oil (synthetic Bescut 173)	Iconel 718	Dry, MQL	When compared to dry milling, MQL enhanced tool life by around 1.57 times and reduced cutting forces.
[71]-(2010)	Solution of Boron oil-water	Aluminium alloy	Conventional cooling, MQL	Utilizing a less viscous cutting fluid in MQL resulted in enhanced surface quality and improved surface finish, even under higher spindle speeds.
[72]-(2008)	Synthetic polyol ester	Aluminium alloy	Dry, wet air, MQL	The application of MQL assisted machining achieved better surface finish at feed rate (0.09 mm/tooth) and cutting speeds (63 m/min).
[73]-(2007)	Castrol Carecut ES3, Ester	Hardened steel	Dry, MQL	MQL led to improved surface quality and lower cutting forces, although it wasn't recommended for extremely high-speed milling.
[74]-(2007)	Castrol Carecut ES3, Ester	Hardened die steel (NAK 80)	Dry, MQL, flood	The utilization of MQL resulted in an improved surface texture and was recommended for high-velocity milling.
[75]-(2008)	*	Cold worked die steel (AISI D2)	Dry, MQL, flood	During high-speed end milling, MQL milling demonstrated exceptional cutting performance, exhibiting the least flank wear compared to the other three lubrication conditions.
[76]-(2011)	Vegetable oil	AISI 1047 steel	MQL, flood, less flow rate	When machining medium carbon steel using MQL, it led to a reduced MRV and machining length. Notably, the MRV achieved through the MQL approach was the most minimal among the reported values.
[77]-2010)	*Cyclomethicone* and liquid paraffin (1:13) solution	Stainless steel (AISI 420)	Mist, flood	MQL improved the surface texture and led to the least amount of flank wear.

* represents cutting fluids which are not mentioned in the study.

3.3 MQL Assisted Drilling

Table 3 explores the impact of MQL on drilling performance, addressing environmental, economic, and safety concerns and highlighting its potential for research-driven manufacturing advancements. Coated drills have gained popularity in the context of deep hole drilling within aluminum alloy applications. Research has demonstrated favorable outcomes when utilizing H_2O/MQL conditions. The application of aluminum alloy EN AC-46000 for manufacturing automotive engine and gearbox housing components was studied. It specifically investigates two approaches to improve deep hole drilling performance through MQL: the implementation of a high-feed process guiding method and the utilization of innovative radial spindle compensation techniques. The research shows that increased feed values can significantly reduce heat input and energy consumption, resulting in better performance and time savings [80, 81]. Drilling has been found to be a challenging process due to its high strength and hardness. The tests indicate that using MQL can achieve similar performance to flood-lubricated conditions with proper selection of cutting parameters [80]. Another study tested tool life and cutting performance for various coatings on aluminum alloy using MQL machining. The study evaluated the practical application of a technology for cost-effective machining of B319 aluminum alloy, revealing factors influencing cutting performance, including coating hardness, tribological properties, and residual stresses [81]. In an investigation, the performance of uncoated carbide drills was contrasted with diamond-coated ones in the context of drilling aluminum-silicon alloys (A356). The drilling conditions involved minimal lubrication along with ample soluble oil as a cooling and lubricating agent. The findings revealed uneven wear on the surface of the diamond-coated drill, leading to a decline in hole quality when compared to the uncoated drill. However, the study found that MQL performance in drilling aluminum-silicon alloys was comparable to high soluble oil application, for both drills with coatings and those without coatings, highlighting the significant potential of MQL in this application [82].

Table 3. Literature survey on MQL assisted drilling

Citation-Year	Cutting Fluid	Workpiece Material	Mode of Lubrication	Findings
[86]-2023	Commercial MQL oil and used cooking oil	AISI 304 Stainless steel	MQL	Tool wear significantly impacts drilling quality in MQL applications, affecting thrust and radial forces. The study compared commercial MQL oil and recycled cooking oil and found that used cooking oil offers better drilling process consistency due to its enhanced viscosity and superior wettability properties.
[87]-2022	*	AISI 304 Stainless steel	MQL, dry, flood	A novel flank wear measurement method accurately measures drill flank wear, revealing surface integrity issues for high-speed machining. MQL improves machining performance, surpassing flood lubrication.
[88]-2021	Vegetable-oil-based cutting fluid	AISI 321 stainless steel	MQL, dry, flood, and nanofluid MQL	The studies discovered that employing nanofluid Minimum Quantity Lubrication (MQL) in conjunction with Al_2O_3-mixed vegetable oil-infused cutting fluid to drill AISI 321 stainless steel produced the best results in superior drilling performance, including decreased thrust force, reduced torque requirements, improved surface roughness, lower drill tip temperatures, and reduced tool wear compared to other cooling strategies.
[89]-2020	Castor and sunflower oil	Aluminium alloy	MQL, dry, flood cooling	MQL derived from vegetables improves drilling performance by lowering torque and thrust force, enhancing surface smoothness, and decreasing surface roughness, making it a viable alternative to flood cooling.
[90]-2021	*	CFRP/Ti6Al4V stack material	MQL	MQL had a positive effect on tool wear progression during low-frequency vibration-assisted drilling.
[91]-2019	*	composite-titanium CFRP/Ti6Al4V stack	MQL, dry	MQL conditions increase thrust forces and delamination damage at the drill-chip interface, affecting CFRP/Ti6Al4V stacks. Dry machining reduces thrust forces and delamination extents, while MQL fails to prevent premature drill bit failures.
[92]-2019	*	Compacted graphite iron	MQL, dry	Tool wear was measured after five drilling experiments. This paper investigates drilling machinability of CGI under various lubrication conditions, revealing that drilling with compressed air and MQL 5 mL/h is feasible, resulting in longer tool life and lower tool wear.
[93]-2012	*	$AlSi_9Cu_3$	MQL	MQL, with 14 bar pressure, was chosen over MQL with 6 bar pressure due to its superior lubrication and cooling performance.
[94]-2011	Palm oil & Synthetic ester	Inconel 718	MQL	MQL lubricated with palm oil outperformed MQL lubricated with synthetic ester lubricant in the testing.
[95]-2011	Distilled water	Alloy of Magnesium	MQL, dry, flood	MQL effectively reduced drill wear by limiting temperature increase and minimizing magnesium (Mg) adhesion to the cutting tool.
[96]-2010	Bio based coolant and distilled water	Alloy of Magnesium	MQL, dry	Increased surface quality and tool life.
[97]-2008	Distilled water	Alloy of Magnesium	MQL, dry	When compared to dry drilling, the MQL-water drilling method needed less torque and thrust force, as well as less aluminum adhesion to the drill bit, covering a lesser proportion of the drill-flute surface.
[98]-2008	Oil emulsion	Stainless Steel	MQL, air, emulsion	MQL drilling requires greater force and torque than wet drilling but less torque than dry drilling.
[99]-2006	Ester with water	Plain carbon steel	MQL, dry	In the context of tool longevity, a consistent Minimum Quantity Lubrication (MQL) delivery mechanism demonstrated superior performance compared to a MQL supply system that operated intermittently.

* represents cutting fluids which are not mentioned in the study

Existing studies on austempered ductile iron (ADI) drilling found that MQL is advantageous due to its superior machining performance across various parameters such as torque, surface roughness, thrust force, and flank wear width.

The research paper explores the impact of MQL on cutting forces, surface roughness, and tool wear in the drilling process of newly manufactured tungsten carbide tools with a TiAlN coating on ADI [83]. The study evaluated drilling temperatures in Ti6Al4V under MQL application. Results showed that drilling temperatures with MQL applied internally, When using MQL with an external nozzle in comparison to other drilling circumstances, tool wear was shown to be 50% lower. Moreover, the highest temperature was recorded in the workpiece drilled with an uncoated drill. No significant variations were found for different coatings. The study highlights the potential of MQL in drilling applications [84]. The study explores the use of palm oil as a substitute for synthetic ester in MQL for high-speed drilling on Ti-6Al-4V. Under dry cutting conditions, the tools exhibited the shortest lifespan, primarily attributed to severe chipping. It finds palm oil's ability to create a thin film for boundary lubrication [85].

3.4 MQL Assisted Grinding

Table 4 provides a summary of the literature survey on MQL techniques that assist with grinding processes. The tool life increased thrice during the micro grinding experiment when compared to dry grinding. The optimal surface finish was achieved using the MQL approach, specifically with a specific combination of 1.88 ml/h oil flow rate and 25 l/min air flow rate. However, an insufficient combination of oil flow and air had a negative impact on surface finish [100]. The experiments were carried out to explore how specific MQL characteristics, including nozzle distance and orientation, impact various grinding performance parameters. They discovered that angularly pointing the nozzle at the grinding wheel produced the best results, as illustrated in Figure 7 [101].

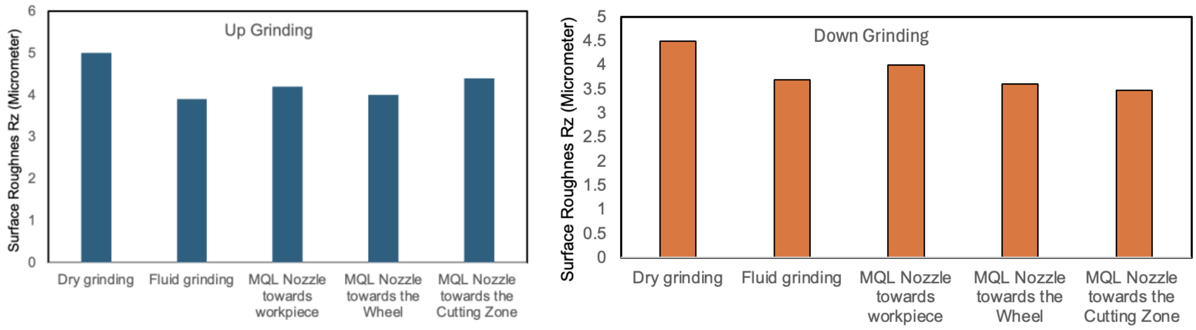


Figure 7. Effect of nozzle orientation on surface roughness [101]

Table 4. Literature survey on MQL assisting grinding

Citation-Year	Cutting Fluid	Workpiece Material	Mode of Lubrication	Findings
[102]-2020	*	Alumina ceramic	MQL, dry	The study utilized 3D roughness data, 3D plots, and SEM pictures to identify ultra-precision aerostatic grinding (UAG) as a method that reduces fracture tendencies, increases material removal, and improves surface quality.
[103]-2018	*	AISI D2 steel	MQL, dry, flood	MQL demonstrated superior performance in surface grinding in both dry and wet conditions due to its superior penetration capabilities and enhanced heat dissipation performance.
[104]-2022	*	AISI 1060 steel	MQL	With a fluid flow rate of 75 ml/h, an infeed of 10 m, and workpiece material hardness ranging from 40 to 45 HRC, excellent output responses were obtained. A fluid flow rate of 75 ml/h produced the best surface finish, while a workpiece material hardness of 40 HRC produced the lowest machining temperature.
[100]- 2012	Vegetable oil based cutting fluid	Plain steel	MQL, dry	MQL significantly extended tool life and surface finish quality, outperforming dry grinding and air cooling methods by seven times and five times, respectively.
[105]-2010	5% Castrol Hysol XF	Tool steel, mild steel, bearing steel	MQL, dry, flood	MQL is better suited for machining softer materials.
[106]-2011	Mineral oil & eater oil based cutting fluid	Hardened steel (100Cr6)	MQL, dry, flood, air jet	When employing mineral hydrocracked oil as an oil alternative, MQL lowered grinding forces and minimized surface damage, excelling in producing excellent surface quality.

Table 4. (cont.)

Citation-Year	Cutting Fluid	Workpiece Material	Mode of Lubrication	Findings
[101]- 2010	HAKUFORM 20e30 MQL oil	Hardened steel (100Cr6)	MQL, dry, flood	Optimizing MQL nozzle placement reduces surface roughness and tangential grinding forces, while increasing nozzle distance enhances surface quality, improving the overall grinding process.
[107]-2009	LB8000 MQL oil	Soft steel (42CrMo4), Hardened steel (100Cr6)	MQL, dry, flood	Efficiently grinding hardened steel materials results in decreased specific energy consumption and a diminished coefficient of friction for both soft and hardened steel materials.
[108]- 2012	Castrol Carecut ES1 oil	AISI stainless steel	MQL, dry, flood	The study tested Castrol Carecut ES1 oil on common steels such as M2, EN8, and EN31 under MQL settings and discovered that MQL is better for working with softer materials.
[109]- 2009	Synthetic oil and vegetable oil	Tie6Ale4V titanium alloy	MQL, flood	The synthetic oil resulted in higher tangential forces and surface roughness when compared to vegetable oil.
[110]-2012	Mineral oil-water emulsion 50 vol. %	AISI 52100 steel	MQL, dry, flood	Pure oil MQL lubrication significantly reduced tangential grinding force and improved surface finish in AISI 52100 Steel machining methods compared to MQL water-oil lubrication.
[111]-2013	Synthetic ester oil and vegetable oil	Hardened steel (UNSS34700) and Aluminium alloy 6061	MQL, dry, flood	MQL (Minimum Quantity Lubrication) demonstrated improvements in surface smoothness, grinding force reduction, and enhanced cooling when compared to both dry and wet grinding methods. However, it did not outperform the conventional wet grinding in terms of overall performance.
[112]-2015	Castrol Carecut ES1 oil	Nickel based alloy	MQL, dry	The study found that when examining the machining of BS 534A99 steel and nickel alloy 718 using Castrol Carecut ES1 oil under MQL and dry conditions, it was observed that introducing oscillations to the workpiece during grinding led to a reduction in the normal force.
[113]- 2010	Vegetable oil, based cutting fluid	AISI 4140 low alloy steel	MQL, dry, flood	Reduction of both normal and tangential forces during the machining process.
[114]- 2012	Synthetic oil Castrol Carecut ES1	AISI stainless steel	MQL, dry, flood	MQL resulted in notably lower grinding temperatures and achieved lower surface roughness values compared to other machining methods.
[115]- 2013	Cimtech D14 MQL oil	Inconel 751 superalloy	MQL	The application of MQL oil flow rate and air pressure can significantly reduce grinding forces, temperature, and surface roughness, achieving minimum grinding force.
[116]-2014	Synthetic oil, mineral oil, vegetable oil, hydrocracked oil	Al2O3 engineering ceramic	MQL	The MQL method, which uses synthetic oil for rough turning, reduces specific energy consumption, while hydrocracked oil improves surface finish in finish grinding operations.
[117]- 2013	Mineral oil	Aluminium based ceramic	MQL	Employing a carefully crafted Minimum Quantity Lubrication (MQL) system during grinding processes led to a decrease in both tangential and normal grinding forces, while simultaneously improving surface roughness.
[118]-2015	RS1642 Behran oil	Low carbon steel	MQL, dry, flood	MQL significantly reduces tangential forces and friction coefficient during grinding processes, especially beneficial for hard steel grinding.

* represents cutting fluids which are not mentioned in the study

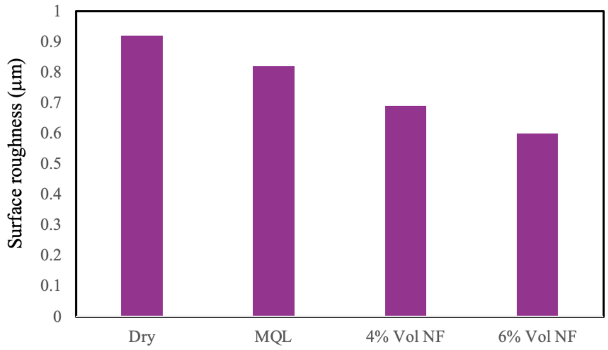
4. MQL MACHINING WITH NANO FLUIDS

Nanoparticles, a type of nanofluid, are a type of fluid with nanometer-sized diameters, typically with diameters in the nanometer range (1-100 nanometers) dispersed within a base fluid like oil or water. These are made from Metals, oxides, and carbon-based materials. When nanofluids are used in MQL machining, they provide several benefits like increased tool life, improved surface finish, enhanced lubrication, efficient cooling effect, environment effects etc. The literature review on MQL machining with a nanofluid system, covering processes like turning, milling, drilling, and grinding, provides a comprehensive overview.

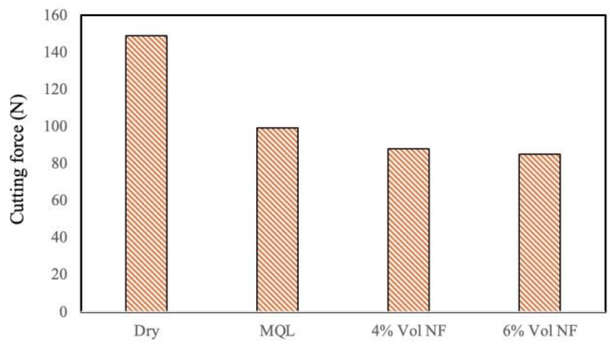
4.1 Turning

The research aimed to enhance ultra-precision turning processes by employing a cutting-edge approach involving a low-viscosity cutting fluid with nano-sized droplets. In order to achieve this, a closed-loop treatment system was utilized to atomize the cutting fluid, resulting in a notable reduction in viscosity. Additionally, the viscosity could be fine-tuned by incorporating water into the mixture [119]. In a separate investigation focusing on high-speed turning of AISI steel, a nanofluid incorporating 1% multi-walled carbon nanotubes (MWCNT) and 3% alumina was employed, accompanied by a compact lubrication system. The integration of MWCNT contributed to a reduction in cutting forces, underscoring the influence of process parameters on high-speed turning dynamics [120]. Another study explored the application of nano-molybdenum disulfide, nano-graphite, and oil-based cutting fluids in MQL scenarios. These fluids, comprising 0.3% nanoparticle content, were dispensed at a rate of 10 milliliters per minute. The evaluation encompassed considerations such as surface roughness, cutting forces, tool wear, and cutting temperature throughout each turning operation [121]. Furthermore, an investigation delved into the performance of SiO_2 nanofluid in turning hardened steel AISI 4140 under Minimum Quantity Lubrication conditions. Fuzzy logic was employed for the analysis of tool wear and surface roughness, while response analysis gauged the statistical significance of various process factors. Optimal surface integrity and tool wear characteristics were attained with a SiO_2 concentration of 0.5% wt, 30° nozzle angles, and low air pressure [122].

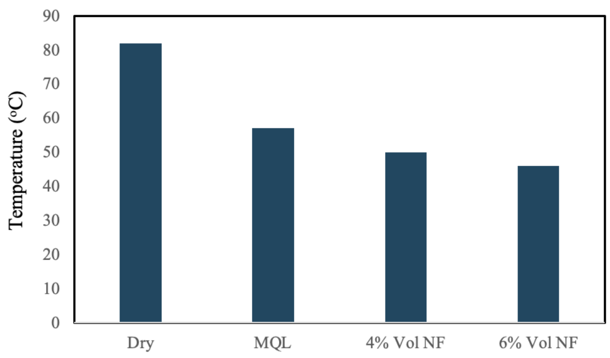
A research investigation emphasized the significance of advancements in nanotechnology for the creation of innovative products and their application in industries. One notable development involved the formulation of a cooling and lubricating fluid utilizing nanoparticles. This fluid, compatible with vegetable-based counterparts, seamlessly integrated with diverse material processing technologies. The tribological characteristics of these nanofluids played a pivotal role in minimizing friction between chip surfaces and tooling, showcasing their adaptability to various processing methods [123]. In a study by Hegab et al. [124], efforts were made to enhance the cooling efficiency of MQL during titanium alloy machining. Nano-additives, particularly MWCNT, were introduced to assess their impact on the base fluid. The outcomes indicated that a 2% concentration of MWCNT nanofluid resulted in an 11% reduction in power consumption and a 45% decrease in flank wear. Another investigation conducted by [125] focused on the development of cutting fluids enriched with vegetable oil nanofluids for machining applications. This study aimed to enhance hard turning on high-strength-low-alloy AISI 4340 steel. Four nanofluid compositions were explored using the MQL approach, with technological performance criteria used to evaluate the machinability of hardened steel.



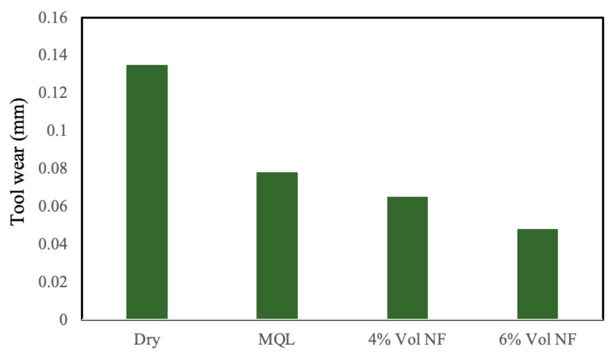
(a) Surface roughness



(b) Cuting force



(c) Temperature



(d) Tool wear

Figure 8. Response charts at ideal parameters [128]

In 2020, Mohammad et al. [126] delved into the thermophysical characteristics of CuO water-based nanofluids. Their findings revealed that larger particle sizes contributed to improved thermal conductivity, while smaller particle sizes increased viscosity. The Nusselt number, a gauge of heat transfer efficiency, was influenced by flow rate and nanoparticle volume percentage. The study highlighted the significant impact of CuO/water nanofluids on heat transfer rates, but also underscored the need for further research to address associated concerns and challenges. In a study focusing on AISI 310S austenitic stainless steel, a hybrid nanofluid-assisted MQL approach was employed. A comparison between dry cutting and nanofluid fortified with Nano Graphene Particles demonstrated that nanofluid reduced cutting force, surface roughness, total carbon emissions, and machining cost in contrast to dry cutting [127]. Taguchi optimization results indicated that employing MQL in combination with Al_2O_3 nanoparticles improved surface roughness, tool tip temperature, cutting forces, and tool wear compared to dry machining and conventional MQL conditions. Additionally, MQL with Al_2O_3 nanoparticles led to superior chip formation in comparison to dry machining and plain MQL conditions. However, the response charts at ideal parameters were depicted in Figure 8 [128].

4.2 Milling

In an experiment, SiO_2 nano solid particles were blended with mineral oil at a concentration of 0.2% by weight. To ensure the effective integration of the nanoparticles with the base fluid, a sonication technique was employed. The results of this research indicated notable benefits, including significant power savings, reduced oil consumption, and a decrease in pollution [129]. A study on Al6061-T6 milling operations used optimized SiO_2 nano lubrication parameters. Factors like nozzle angle, air carrier pressure, and nano lubricant concentration were considered. The study used a Standard Orthogonal Array L16 design and Taguchi optimization method. Signal-to-noise ratios assessed cutting force and surface roughness, and variance analysis confirmed the statistical significance of the parameters [130]. A study was conducted by Sayuti et al. [131] to investigate the use of carbon onion nanoparticles in CNC end-milling of Duralumin AL-2017-T4. The major goal of this study was to see how different nanoparticle concentrations affected the decrease of cutting forces and the improvement of surface quality. According to the study's findings, the introduction of carbon onion nano lubricant resulted in lower cutting forces and higher surface roughness values, hence improving overall machining performance. In another study conducted by Mohd et al. [132], it was discovered that introducing SiO_2 nanolubricant into the machining process could lead to a reduction in thermal deformation and friction, hence improving surface quality.

The study focused on the machining of AL6061-T6, and it was discovered that when the nanolubricant concentration was higher, namely at 0.2%, a thin protective layer formed on the machined surfaces. This behavior was linked to the breaking process assisted by numerous nanoparticles rolling between the tool and chip surfaces. The invention of this thin layer was critical in enhancing machining performance. Ooi et al. [133] study utilized fuzzy logic to analyze the impact of air pressure, nozzle angle, and nanoparticle concentration on optimal machining conditions, aiming to achieve the lowest cutting temperature, cutting force, and surface roughness, using these variables as predictors. Pham et al. [134] study on nanoparticle-enhanced cutting fluids in micro milling revealed that using ionic liquids as lubricants with higher viscosity improved machined surface properties compared to conventional lubrication conditions. In a study led by Rahmati et al. [135], research was conducted to identify the most favorable variables for MoS_2 nanolubrication in Al6061-T6 milling. The objective was to minimize cutting force, reduce surface roughness, and lower cutting temperature. The study took into account factors such as air carrier pressure, nozzle orientation, and the concentration of the nano lubricant. To evaluate the impact of these variables, the signal-to-noise ratio of cutting force and surface roughness was analyzed, and variance analysis was employed to identify key process parameters.

4.3 Drilling

A study on deep-hole drilling in plain carbon steel found that using dry machining as an alternative to MQL significantly reduced tool life, especially for heat-sensitive drills. A discontinuous supply of MQL resulted in accelerated tool wear for most twist drills, leading to a significant reduction in tool life. The research highlights the need for continuous supply of minimum quantity lubricant in drilling processes [99]. The study compared two coolant methods: cryogenic LN2 coolant and a traditional wet coolant, examining their effects on cutting temperature, thrust force, torque, and surface roughness. The results showed that cryogenic coolant, used in the cutting zone, provided excellent lubrication properties, enhancing machining performance, and the study also assessed changes in the cryogenic LN2 coolant to assess chip morphology and tool wear [136]. A study using curve fitting methods found that Gaussian Process (GP) models outperformed other modeling techniques. Both 3-D and 2-D surface analyses were conducted to validate these models. The study found that nanofluid concentration significantly impacts power consumption, with reduced drill diameter leading to higher torque and spindle speeds, lower material removal rate (MRV), and reduced thrust forces [137]. The study evaluated various lubrication conditions, including dry machining, MQL, conventional flooded lubrication, and MQL with nanofluid. It examined drilling process response characteristics, tool wear, cutting forces, and surface roughness. The authors used MQL with nanoparticles, a nanolubricant containing 20 nm Al_2O_3 particles mixed with soya bean oil. The MQL nanofluid approach reduced drilling torques and thrust forces, effectively managing burrs and chips, and enhancing hole surface quality compared to other coolant-lubrication conditions [138].

4.4 Grinding

The study examined the surface properties of AISI D2 tool steel materials subjected to nano-machining using Atomic Force Microscopy (AFM). It found that the inclusion of carbon nanotubes (CNTs) in the lubricating fluid improved thermal conductivity and heat-carrying capacity, potentially improving machining performance and thermal management during the process. This research provides insights into the surface properties and quality of machined materials [139]. A study developed a novel Al 7075 metal matrix nanocomposite reinforced with nanoparticles. The material was machined using a copper electrode through electrical discharge machining. The study employed the Response Surface Methodology to investigate how various process parameters affect the machining process. Analysis of Variance (ANOVA) and a mathematical model were used to predict machining characteristics. The results of the study showed that pulse current had the most significant impact on material removal rate, surface roughness, and electrode wear rate [140]. In another study, it was discovered that incorporating nanofluid in MQL grinding led to improved performance by reducing surface roughness and grinding force. The researchers also conducted wear and friction studies on nanoparticles and found that adding nanoparticles to the base fluid reduced friction and exhibited anti-wear properties, thus enhancing the overall grinding performance [141]. A study found that the introduction of solid nanoparticles into a grinding process's cooling system improved energy efficiency by 64.3%. This was compared to 36.8% for flood lubrication, 52.1% for nanoparticle jet lubrication, and 41.4% for a combination of these processes. The study concluded that CNT nanoparticles effectively improved the grinding process's cooling effectiveness [142]. A study used nanofluids like hydroxyapatite, SiO_2, Fe_2O_3, and carbon nanotube nanofluids in a cooling grinding experiment. The nanoparticles' mass fraction was set at 2%, 4%, 6%, 8%, and 10%. The temperature of the grinding process was monitored and measured. The study found that the temperature peak during bone micro-grinding was consistently inversely correlated with the nanofluids' mass fraction. This suggests that higher mass fractions result in lower temperature peaks during the grinding process [143].

5. CONCLUSIONS

This work provides a review of various published research on the use of cutting fluids, the MQL uses fluids like mineral oils, vegetable oils, and nanofluid-based solutions, offers several advantages in various machining operations like drilling, turning, milling, and grinding. These include extended tool life, improved surface quality, lower cutting temperatures, improved chip formation, and reduced cutting forces. MQL machining is a viable and environmentally friendly alternative to conventional wet machining techniques. The literature evaluation supports the conclusion that MQL is a valuable method for improving machining performance, managing cutting temperatures, producing favorable chip shapes, decreasing cutting forces, and aligning with environmentally friendly practices due to reduced coolant usage. The current literature evaluation allows for the following inferences:

(i) MQL led to significant improvements, albeit to varying degrees, in chip formation modes, tool wear, and surface finish across the range of cutting speeds and feed rates. This improvement was primarily attributed to the reduction in the average temperature at the chip-tool interface. In comparison, wet cooling with soluble oil showed limited effectiveness in controlling cutting temperature, which further diminished with higher cutting velocities and feed rates.

(ii) The MQL systems employed in this study reduced the average chip-tool interface temperature by up to 10% compared to wet machining, depending on the cutting conditions. Despite the apparently small temperature reduction, it resulted in notable enhancements in major machinability indicators contrary to common belief.

(iii) The use of MQL decreases the temperature in the cutting zone, minimizes workpiece material adhesion to tools, and mitigates built-up edges.

(iv) Surface roughness and tool wear both decreased when the MQL flow rate increased. Also, the MQL technique decreased cutting forces significantly.

(v) MQL, through its effective delivery of oil mist into the contact zone, succeeded in significantly reducing the friction coefficient. This, in turn, led to a substantial reduction in tangential forces when compared to traditional grinding methods.

(vi) The study found that the optimal volume fraction of castor palm oil in Inconel 690 machining yielded superior results in milling operations, reducing surface roughness, cutting forces, and tool wear.

High-speed MQL milling demonstrated excellent cutting performance when contrasted with MQL, flood cooling, and dry conditions. It exhibited minimal flank wear. However, its performance in milling medium carbon steel fell short in terms of MRV and machined length, with the MQL technique registering the lowest MRV value.

While the review comprehensively covers the current state-of-the-art MQL assisted machining, there are several intriguing avenues for future research that could further enrich our understanding and application of this technology:

(a) *Advanced MQL Formulations*: Investigating novel lubricant formulations tailored for specific machining processes and materials could significantly enhance the effectiveness of MQL. Future research could focus on developing eco-friendly and bio-based lubricants with superior lubricating properties and minimal environmental impact.

(b) *Optimization Algorithms*: Implementing advanced optimization algorithms, such as artificial intelligence and machine learning techniques, to optimize MQL parameters (e.g., flow rate, nozzle geometry) for improved machining performance and sustainability. These algorithms could adapt in real-time to changing machining conditions, leading to enhanced efficiency and productivity.

(c) *Multi-Scale Modeling*: Integrating multi-scale modeling approaches to better understand the complex interactions between MQL parameters, tool geometry, material properties, and machining performance. Coupling computational fluid dynamics simulations with finite element analysis could provide valuable insights into the thermal and mechanical aspects of MQL-assisted machining processes.

(d) *Surface Engineering*: Exploring surface engineering techniques, such as laser surface texturing and coatings, in conjunction with MQL to further enhance surface quality, reduce friction, and improve wear resistance. These hybrid approaches could unlock new possibilities for achieving ultra-smooth surfaces and extending tool life in high-speed machining applications.

(e) *Environmental Impact Assessment*: Conducting comprehensive life cycle assessments to evaluate the environmental footprint of MQL-assisted machining compared to traditional coolant-based methods. Future research could quantify resource consumption, energy use, and emissions throughout the entire lifecycle of MQL systems, from production to disposal, to provide valuable insights for sustainable manufacturing practices.

(f) *Application in Additive Manufacturing*: Exploring the potential of MQL-assisted machining techniques in post-processing operations for additive manufacturing components. Investigating how MQL can improve surface finish, dimensional accuracy, and overall part quality in various additive manufacturing processes, such as selective laser melting and fused deposition modeling.

By addressing these future research directions, we can further unlock the potential of MQL-assisted machining as a sustainable and efficient manufacturing solution, paving the way for advancements in precision engineering and industrial production.

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CONFLICT OF INTEREST

The authors whose names are listed in this manuscript certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial in the subject matter or materials discussed in this manuscript.

AUTHORS CONTRIBUTION

M. A. Parray (Project administration, Writing - original draft; Writing - review & editing, Data curation)
M. J. Khan (Supervision, investigation)
A. Gulzar (Software, Formal Analysis)
A. Fayaz (Resources, Visualisation)

AVAILABILITY OF DATA AND MATERIALS

The data supporting this study's findings are available on request from the corresponding author.

ETHICS STATEMENT

Not applicable

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