Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 90, Issue 2 (2022) 135-159

SEMARAK ILMU PUBLISHING

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage:
https://semarakilmu.com.my/journals/index.php/fluid_mechanics_thermal_sciences/index
ISSN: 2289-7879

Effects of Minimum Quantity Lubrication Technique in Different Machining Processes - A Comprehensive Review

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ARTICLE INFO

Article history:
Received 7 August 2021
Received in revised form 5 December 2021
Accepted 20 December 2021
Available online 7 January 2022

Keywords:
Minimum quantity lubrication; machining; cutting force; tool life; surface roughness

ABSTRACT

The cooling condition has a significant effect in the metal cutting industry, which has a crucial role in cooling and lubricating the workpiece-tool interface, reducing friction, and removing chips from the cutting area. Almost 15-20% of the overall machining cost was incurred from cooling and lubrication. So, the considerable cost can be occurred due to the supply, preparation, and disposal of cooling lubricants. Moreover, exposure to these substances can pollute the environment and hamper operators' health. Therefore, of late, researchers have been giving priority to investigate the effects of the Minimum Quantity Lubrication (MQL) techniques in machining as it alleviates the coolant usage by splashing fluid and compressed air mixtures. In this lubrication technique, the maximum fluid flow is less than 50ml/h, whereas flooded cooling technology uses up to 12,000 litres per hour. Most researchers found that a lower coefficient of friction, better surface finish, reduced cutting forces, and torques can be obtained using the MQL method in an optimized manner compared to dry and wet machining. Moreover, besides improving machinability characteristics, the MQL technique also complies with green and sustainable machining. Thus, a prospective solution to dry and wet processing. This paper represents the brief discussion and mechanism of the MQL technique and the effects of the MQL technique on the performance parameters of different machining processes.

1. Introduction

Machining is one of the leading manufacturing processes that substantially affect production costs. Machining efficiency is retarded by repeated tool change owing to wear [1]. The consequences of tool wear are low surface integrity, dimensional imprecision resulting in reduced product quality [2]. Besides environmental aspects in machining, the insistence for improved quality directs to

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https://doi.org/10.37934/arfmts.90.2.135159

superior machined surface integrity, which is directly linked to the product's function, reliability, and appearance. Maintaining a proper lubrication system in machining can enhance the machined surface properties. Moreover, friction is experienced with the elevated temperature at the contact zone of the tool and workpiece in the machining process. Among various cooling techniques, the conventional flooded cooling system is complex in maintenance, expensive to run, and hazardous to workers and work due to leakage and troublesome odor. Besides, the dry cutting condition cannot be applied everywhere for the cutting tool's limited capability. On the contrary, from different reviewed literature, it is found that the performance of MQL in various machining is sometimes mostly similar to and even in some cases superior to flooded cooling. Minimum Quantity Lubrication has already been established as a substitute to conventional lubrication systems for its increasing application in metal-cutting machining [3].

In a minimum quantity lubrication system, less lubrication and space are required, and there is no complexity in the treatment and disposal of the fluid, which can only be removed by a tissue [4]. Hence, it is also referred to as 'Near Dry Machining', where very little fluid is splashed at the tool-workpiece contact region [4-6]. Enhanced surface integrity and tool life, less cutting forces, and better process capability exert minimum quantity lubrication [7]. In the MQL system, the lubricant is applied directly at the contact surfaces tool, workpiece, and chip; a minimal amount of liquid is needed to reduce friction between workpiece and tool. The dosage of MQL quantity depends on the materials, tools, and machining process. The typical quantity supplied by MQL per process hour is 5 ml to 50 ml [7]. Besides, the German DIN specification specifies the lubricant range up to 50 ml/h (1.7 oz/h), but 150 ml /h (5 oz/h) in notable instances, whereas some references put the range up to 500 ml/h (17 oz/h). Generally, tools with less than 40mm diameter need 5 to 80 ml/h of lubricant to give better results and keep chips dry whereas flood coolant typically uses 30,000- 60,000 ml/h (8 to 16 gallon/hour) [8]. Moreover, the MQL can be regarded as an environmentally friendly process, and further focus on selection and characteristic of fluids in MQL can make it more sustainable for example if the fluid can be more potential, biodegradable etc.

Cost encountered in flood machining conditions (inventory, maintenance, preparation, disposal of chips and fluids) is much more than MQL costing. Literature found that almost 15-20 % of the overall machining cost is incurred for coolants and lubricants in industries [9-12]. According to DeVries *et al.,* [13] among total operation costs, 8-16% of costing is related to metalworking fluids, and MQL significantly reduces these costs as in MQL, there is no cost for drying the chips and cleaning the workpiece and chips. MQL reduces cost and ensures a better workplace for employees by reducing health hazards from exposure to harmful and toxic fluids and air, leading to adverse health and safety conditions causing respiratory distress syndrome, eczema, and even cancer [7]. MQL has been reported by Banerjee and Sharma [14] as an improved technique than traditional flooded machining at higher speeds and feed rates, as it decreases the friction of the tool-workpiece interface considerably. Ismail *et al.,* [15] stated that MQL shows better machining performance, and cutting oil film average thickness was not noticeably fluctuated with rising speed during milling machining under MQL conditions. The MQL machining with SiO_2-Al_2O_3-ZrO_2 nanofluid revealed lower cutting force during milling of Aluminum Alloy 6061-T6 due to the formation of the thin film of nanofluid on the tool-chip-workpiece interface [16]. Weinert *et al.,* [17] reported that it adversely affects the workplace and worker health during the use and disposal of liquid. Still, complete elimination of coolants is difficult as dry machining drastically eliminates tool life [18,19]. Sreejith and Ngoi [19] also suggested avoiding excessive use of cutting fluids. Lawal *et al.,* [5] investigated and compared different cooling techniques and found superior performance for MQL conditions. German Federal Ministry of Education and Research accomplished a three years project named "Forschung für die Produktion von Morgen" or "Research for Tomorrow's Production" where numerous companies' involvement ensured the completion of fifty-eight studies using many different materials under MQL condition [8]. Table 1 presents the effects of MQL in specific conditions. Many researchers investigated focusing effects of various parameters on available cooling and lubricating techniques using conventional fluids. In this study, different parameters on the MQL system are reviewed, including the mechanism of MQL, challenges, and opportunities of this method.

Table 1
Effects of MQL in different businesses [6]

Business	Product	Material	Process	Results
Automotive Supplier	Throttle Housings	GD-$AlSi1_2Cu_4$	Milling, Drilling, Reaming	8 % component cost reduced.
Automotive Manufacturer	Gears, Car Gearboxes	Case-hardened steel ($20MoCr_4$)	Shaping	5 % component costs reduced and environmental protection.
Power Plant Manufacturers	Turbine Blades	X22CrMoV 12.1, CrNi Steels	Milling	Three folds enhance tool life.
Pneumatic Cylinders Manufacturer	Connector	A1 Die-Cast GD-ZnA14Cul	Tapping, Grooving	Less usage of metalworking fluids, easy maintenance and job cleaning, cleaner machine environment.
Die and Tool Shop	Tools	Tool Steels	Milling, Turning	Maintenance and cleaning work reduced by 80%, more efficient processing time and better surface finish.
Commercial Printing Press Manufacturer	Drilled And Tapped Strips	Ck45	Milling, Drilling, Threading, Reaming	Shortened the processing time from 10.49 min to 7.32 min.
Aviation	Aircraft Components	AL Forged Alloy	Milling	Cleaner machine environment, environmental protection.

2. Mechanism of MQL System

In the MQL technique, the aerosol is formed by mixing a minimal amount of lubricant, and a nozzle is used to splash in the cutting zone at high pressure [20]. MQL system consists of four main components, e.g., machine, tooling, applicator, and output [8]. The applicator defines the quantity of air and fluid to be supplied; output presents the fluid chambers, hoses, and nozzles where the fluid comes across the atmosphere, and the tooling includes tool and tool holder. In a word, an automizer, fluid reservoir, and nozzles consist of the MQL system. The principal purpose of the MQL system is to supply the cutting area with a suitable lubricant [7]. MQL can be classified into two types depending on the cutting fluid supply mode, such as internal and external supply systems. These techniques are also called internal and external delivery or feed system [21]. The aerosol is synthesized in the atomizer in the external system, an ejector for atomizing the coolant at high-pressure air, and sprayed to the tool's outer surface with an external nozzle. This system applies to open machines, intermittent cutting operations, and machines with no internal coolant system [8]. Although external nozzles are associated with low cost and simple installation, manual adjustment and positioning are needed for nozzles. Moreover, the internal system is deployed where the cutting interfaces are not easily accessible in some situations.

On the contrary, the internal system allows the lubricant to be directly supplied to the cutting area using the tool's internal cooling channels with no feed nozzles adjustment [7]. Internal feed systems can be of two types, e.g., single-channel devices and dual-channel devices. Under this system, lubrication and cooling purpose are served by cutting fluid and pressurized air, respectively. Using the internal feed system, optimum lubrication for the cutting zone is possible with no spray losses, but special tools, machines, and high investment are needed. In the MQL system, single and dual channels are usually used for feeding input, e.g., air and oil. The main difference between these two is single-channel system allows the preparation of aerosol in the applicator before the spindle, but in a dual channel system separate channel is used to feed air and oil and come across together while exiting the spindle or in the tool holder so to generate aerosol directly in front of the tool [8].

Several experiments have been accomplished to investigate the performance of MQL in machining. Better surface integrity, prolonged tool life can be achieved near micro-milling using MQL conditions [22]. Also, for micro grinding Li and Lin [22] observed better surface integrity and improved tool life using MQL. Hadad and Sadeghi [23] found enhanced turning performance by using the MQL condition. MQL significantly increased tool life, reduce torque and thrust force while using nano-diamond-based nanofluid (NF) [24]. Shen *et al.,* [25] found that the MQL method with MoS_2 nanoparticles reduces force and friction because the inclusion of nanoparticles shows significant improvement of thermal conductivity, which plays a role in better heat transfer into the cutting zone during machining [26-28]. MQL with Al_2O_3 and diamond nanofluids reduce the machined surface forces and roughness and prevent burning the workpiece using water as a base liquid [29]. Improved tool life and workpiece surface are achieved during Inconel-718 using the MQL technique compared to dry and flooded machining [30]. Moreover, a new method was also investigated, termed a combined cooling technique. In this method, the pre-cooled workpiece is incorporated with a cutting fluid under the MQL technique, and it showed substantial improvement to machining performance, ensuring ecological and health issues [31].

3. MQL in Different Machining

In machining, MQL has become an efficient solution to reduce the excessive use of cutting liquids and maintaining environmental and health issues. This section will present the application of MQL and its effect on machining performance for different machining operations, such as turning, milling, and drilling.

3.1 MQL in Turning

Das *et al.,* [32] carried out a study exploring surface roughness, tool wear, chip tectonic using carbide inserts coated with physical vapor deposition multilayer (MT PVD) Al2O3 external layer has a significance of CNMG120408. This study conducted the turning process of heat-treated AISI4340 (50±1 HRC). In tool wear, flank shows the maximum value of 0.3 mm wear even at higher speed for both dry and MQL machining while using multi-layered coated carbide insert; abrasion and diffusion predominate tool wear cutting edge, there is no chipping and catastrophic failure. Flank wear predominates with the increasing speed, and MQL exhibits a lesser amount of tool wear than dry machining. The color of the chip remains metallic even at higher speed and feed while lubricant is used, but the blue, burnt color chip is generated while machining without lubricant. The maximum surface roughness value does not surpass 1.6 microns even at a higher feed rate while using a multi-layered carbide insert. Surface roughness enhances with the growing feed rate, and MQL shows a reduced amount of surface roughness.

Patole and Kulkarni [33] conducted experiments to optimize process parameters during the turning of AISI4340. Here, the operation was done using a tungsten carbide insert (specification CCMT- 090308) under MQL condition, including 0.20 wt% multi-walled carbon nanotube (MWCNT) nanofluid. Experimental results show that the feed rate is the most influential parameter for achieving minimum surface roughness, whereas cutting speed is the least significant, and depth of cut has a moderate effect on surface roughness. So, they concluded that MQL with nanofluid is an alternative to the conventional flood coolant system. Thus, it is sure to obtain better surface integrity, prolonged tool life through controlling temperature and cutting forces at a rational level. During turning of St 52-3 under minimum quantity lubrication system, 17% less cutting force is required while there is no significant influence of nozzle position on cutting forces [34]. This study proved that a substantial amount of energy savings with sustainable manufacturing is possible through MQL machining, while the suitable oil flow rate was 10ml/h [34]. Joshi [35] made an experiment performing turning of Incoloy 800 under dry, MQL (MQL1-150ml/h, MQL2-230 ml/h), flooded condition, and made a comparison for proper cutting parameters. The results show that under MQL2 condition, tool wear and surface roughness have occurred less than dry, flooded, and even with MQL1. They found that with the enhancement of speed, wear at flank face shows positive growth, so they concluded speed as the most dominant factor followed by feed, depth of cut and also found highest surface roughness at dry turning condition for highest feed and speed, lowest surface roughness at MQL2 machining condition.

During turning of steel alloy (EN 353) using uncoated CNMG carbide tools, chemical vapor deposition (CVD) and PVD coated inserts under dry, MQL, flooded condition Vishnu *et al.,* [36] found optimum condition for minimizing cutting temperature. In this investigation, the optimum machining condition demonstrates with 1100 rpm cutting speed, 0.5mm and 0.2mm/rev depth of cut and feed rate, respectively, along with PVD coated tool. Flooded machining shows better performance than MQL condition, but little difference between them, whereas MQL reduces lubricants' flow considerably compared with the flooded condition. So, they concluded that MQL machining is more suitable than the dry and flooded state in terms of cost, sustainability, and health issues. From their experiment, significant intercommunication between lubrication type with tool type, cutting speed, depth of cut, and feed rate are explored. Under dry machining condition, stable machining condition was achieved with no catastrophic failure, plastic deformation on the cutting edge; and maximum flank wear is 0.3 mm, whereas MQL shows lesser flank wear than dry condition and flank wear encountered for abrasion [37]. Cutting speed predominates flank surface, and surface roughness is influenced by feed derived from this experiment. They also suggested that in comparison with MQL, chipping failure is more dominant in dry machining.

Coolant system influences over the material adhesion eminently and highest adhesion encountered on the flank and rake clearance faces of the tool during dry machining whereas cooling condition has a less substantial impact on tool flank wear. It is reported by Sreejith [38] in turning aluminum 6061 alloys using diamond layered carbide tool under dry, MQL, and flooded conditions. Cutting forces also showed the highest value under dry conditions because of workpiece adhesion on the tool, and for flooded condition, cutting force showed the lowest value for minimum adhesion on the tool, and surface roughness value shows enhancement while increasing cutting speed (400 m/min). Finally, better surface integrity is achieved from MQL machining than dry and wet machining [38]. Sivaiah and Chakradhar [39] investigated the performance of cryogenic coolant on stainless steel (17-4 PH) machining. From this experiment, flank and rake surface wear, surface roughness, cutting temperature is observed for the rising depth of cut under dry, wet, cryogenic and MQL machining condition. The results reveal that cryogenic machining displays improved efficiency for surface finishing, wear of the tool, chip morphology relative to other machining circumstances, and produces less thick chips. This machining also enhances productivity as this condition is health and environment-friendly.

Marques *et al.,* [40] experimented with assessing solid lubricant performance into the vegetable-based oil applied by MQL during the turning process of Inconel 718 with ceramic tools (Al_2O_3 + SiCw) is whisker reinforced. The results showed that LB 2000 with graphite and without solid lubricants led to a shorter lifetime of the tool than dry machining. Besides, the use of MoS_2 as a solid lubricant with the inclusion of base oil into the cutting zone exhibited 12 % and 46 % enhancement of tool life than dry and MQL techniques, respectively. Machining with the MQL technique presented lower cutting forces than dry machining, while cutting forces show a slight increment with rising cutting speed. For a solid lubricant, the cutting force is reduced for both (graphite, $MoS_{2)}$; sometimes, graphite shows better performance depending on the cutting speed. Moreover, for increasing speed, surface integrity also shows better performance. The notch, flank, and small crater were observed as dominant tool wear and adhesion and abrasion as significant wear mechanisms. However, Abd Rahim and Dorairaju [41] explored the MQL technique's performance under various spray and machining conditions. In their experiment, lubricant spray's characterization is done through Phase Doppler Anemometry for two different diameters nozzles (2.5 mm and 3.0 mm) at various input pressure. The investigation revealed the largest spray cone angle as the most effective splash pattern under 0.4 MPa air pressure as they found that with the enhancement of air pressure, the splash angle becomes wider for both diameters nozzles. They also recommended 6-9mm nozzle space for 3.0 mm diameter nozzle at 0.4 MPa while cutting force and temperature reduced remarkably.

The chip-tool interface temperature is enhanced consistently with growing cutting speed. However, other cutting conditions, such as depth of cut, have comparatively less effect on the chip-tool interaction temperature during the investigation of the chip-tool interaction parameters and cutting condition while turning AISI1060 using TiCN coated cemented carbide SNMG 120, 408 insert [42]. In this investigation, important parameters were cutting speed, depth of cut, feed, temperature, shear angle, chip compression ratio, and friction coefficient. The study reveals that though the MQL system reduces the chip tool interface temperature significantly but has a low impact on friction and chip formation issues. The study is significant for exploring the suitable MQL condition, including optimized shear angle, coefficient of friction, chip compression ratio for 90 m/min cutting speed, 0.1mm feed, and 1.5 mm depth of cut simultaneously. Behera *et al.,* [43] performed turning operations for Nimonic 90 and TiAl4V to assess the wear behavior of PVD TiN layered carbide inserts under MQL and dry machining. In the case of machining of Nimonic 90, severe wear of nose over cutting inserts was encountered due to chip tool high contact, and at the same time, eminent strength of Nimonic 90 is responsible for high notch wear. On the contrary for turning of TiAl4V under MQL conditions, better results were derived from the experiment. In this case, a reduction of flank wear and rake wear occurred for good wettability and high penetration characteristics, and this controlled wear, stable, and comparatively low cutting force is required for machining of TiAl4V. Table 2 and Table 3 summarize detailed information of machining parameters, lubrication mode, cutting fluid for turning operation. However, Table 4 presents the experimental results of different lubrication systems for turning various workpieces.

Table 2
Summary of various machining parameters for turning operation

References	Workpiece material and geometry (mm)	Cutting tool material	Tool geometry	Cutting speed	Feed	Depth of cut
Patole and Kulkarni [33]	AISI4340 (Dia 24 and L 100)	tungsten coated CCMT-090308)	Nose radius 0.4, 0.8m	75,90	0.04-0.12	0.5, 1, 1.5
Ekinovic *et al.,* [34]	St52-3; tensile strength 500 MPa, hardness 160 HB	cemented carbide (ISO 1 R 3232 K10)		95	0.142	1.0
Joshi [35]	Incoloy 800 (Dia 32 and L 200)	Uncoated tungsten carbide	CNMG120408	40, 50 and 60	0.033, 0.066, 0.132	0.5, 0.75 and 1.0
Vishnu *et al.,* [36]	EN 353 Steel Alloys	Uncoated, CVD, PVD coated CNMG carbide tools		700, 1100, 1500 rpm	0.2, 0.5, 0.8	0.5, 1.5, 2.5
Das *et al.,* [32]	AISI4340; 50±1 HRC; (Dia 40 and L 18)	MT PVD coated carbide insert with Al_2O_3 external layer	CNMG120408	50, 100, 150, 200	0.04, 0.08, 0.12, 0.16	0.2
Das *et al.,* [37]	AISI4340; 50±1 HRC; Dia 40 and L 180)	MT CVD multilayer coated carbide tool with an external TiN layer	CNMG120408	50, 100, 150, 200	0.04, 0.08, 0.12, 0.16	
Sreejith [38]	6061 aluminum alloy	diamond-coated inserts CNGA 120408 T01020 WG	rake and clearance angle 15°, 7°; nose radius 0.8 mm	50 up to 400	0.15	1.0
Marques *et al.,* [40]	Nickel base super alloys; 40 HRC; Ø 127 x 250mm length	SNGN 120712 T01020, grade CC670	nose radius 1.2mm, tool holder- CSRNR 2525M 12-4	100, 150, 200, 250, 300	0.1	0.5
Abd Rahim and Dorairaju [41]	AISI1045 medium carbon steel; Dia 100 and L 200)	Cemented carbide TNGG220408R insert		100, 160, 220	0.15, 0.30	0.2
Mia *et al.,* [42]	AISI1060; dia. 47.5 mm, L 200 mm	SNMG 120,408 insert; TiCN coated cemented carbide	Rake & cutting angle 0°, 90°; nose radius 0.8mm	45,60,75,90	0.10 0.20	1.0, 1.5
Behera *et al.,* [43]	Nimonic 90 (Dia 60 and L 300), Ti6Al4V (Dia 50 and L 300)	KC730-Kennameta		60, 120	0.15, 0.25	0.5
Sivaiah and Chakradhar [39]	17-4 PH SS bar (Dia 50 and L 300)	AlTiN PVD coated KC5010 WC inserts; SNMG120408 MP	cutting edge angle 75°. nose radius: 0.8 mm	78.5	0.143	0.2, 0.4, 0.6, 0.8 and 1

Table 3
Summary of lubrication mode, cutting fluids, other specifications of various coolant systems for turning

References	Mode of Lubrication	Cutting fluid	MQL flow rate (ml/h)	MQL Air and Fluid Pressure	Nanoparticles, wt%, Spray angle	Other coolant Specifications
Patole and Kulkarni [33]	MQL, Flood	Ethylene glycol	140	5 bar (air)	MWCNT, 0.20%, 30°	distance between nozzle & insert tip 11 mm
Ekinovic *et al.,* [34]	MQL	Biodegradable rapeseed oil	10 to 50 (oil), 0.3 to 1700 ml/h (water)			
Joshi *et al.,* [35]	Dry, MQL, Flood		MQL1 (150), MQL2 (230); Flood- 600			
Vishnu *et al.,* [36]	MQL, Flooded, Dry	Water	85	1bar(air)	Al_2O_3	
Das *et al.,* [32]	Dry, MQL		50	Oil-air mix. 5 bar		
Das *et al.,* [37]	Dry, MQL		50	5 bar		
Sreejith [38]	Gravity-fed MQL system, Dry, Flood	BP Microtrend 231L	50 and 100			
Marques *et al.,* [40]	Dry, MQL	Accu-Lube LB 2000	40	0.5 MPa	Graphite and MoS_2	Nozzle distance from cutting zone 30 mm
Abd Rahim and Dorairaju [41]	MQL			Air pressure 0.2, 0.3, 0.4 MPa		Nozzle dia. 2.5, 3.0 mm; Nozzle space 3, 6, 7, 9 mm
Mia *et al.,* [42]	Dry, MQL	Olive Oil	150(oil)	4 bar		1.0 mm diameter nozzle
Behera *et al.,* [43]	Dry, MQL	Sunflower oil in water (emulsion)	250 ml/h	Air pressure 3 bar		Spray velocity 10-11 m/s
Sivaiah and Chakradhar [39]	Dry, wet, MQL, Cryogenic (LN2)		MQL- 70; (Cryogenic-0.45 kg/min; Flood- 6000 ml/min	Compressed air pressure 4 bar		Nozzle diameters: 1 mm (Cryogenic, MQL), 10 mm (wet)

Table 4
Summary of experimental results of different lubrication systems for turning of various workpieces

Authors	Workpiece Material	Mode of Lubricant	Findings
Patole and Kulkarni [33]	AISI4340	MQL, Flood	MQL with NF is a substitute for the traditional wet cooling condition for improved surface integrity and prolonged tool life.
Ekinovic *et al.,* [34]	St52-3	MQL (oil-in-water droplet system)	17 % less cutting force is required for MQL machining.
Joshi [35]	Incoloy 800	Dry, MQL, Flood	MQL2 (230 ml/h) condition, tool wear, and surface roughness intensity are less than dry, flooded, and even MQL1 (150 ml/h). The dry turning condition gives the highest surface roughness for the highest speed and feed combination, and MQL2 gives the lowest surface roughness.
Vishnu *et al.,* [36]	EN 353 Steel Alloys	MQL, Flooded, Dry	MQL machining is better than dry and flood conditions in cost, ecology, and human health issues.
Das *et al.,* [32]	AISI 4340	Dry, MQL	Flank wear increases with the rising speed. MQL shows a lesser amount of wear of the tool than dry condition machining.
Das *et al.,* [37]	AISI 4340	Dry, MQL	MQL shows a lesser amount of flank wear. Cutting speed predominates flank face wear, whereas surface integrity is influenced mainly by feed rate.
Sreejith [38]	6061 aluminum alloy	Gravity-fed MQL system, Dry, Flood	Dry machining shows the highest cutting forces, and flood shows the least. MQL displays a reduction of surface roughness than dry and flooded conditions.
Marques *et al.,* [40]	Nickel-based superalloys	Dry, MQL	12 % and 46 % tool life enhancement are possible using MoS_2 with base oil into the cutting zone compared to dry and MQL machining.
Abd Rahim and Dorairaju [41]	AISI1045 medium carbon steel	MQL	Cutting temperatures and forces are reduced remarkably for 6-9mm nozzle space at 0.4 MPa.
Mia *et al.,* [42]	AISI1060 steel	Dry, MQL	MQL condition reduces the temperature of the chip-tool contact region significantly, but this system has very few impacts on friction and chip formation issues.
Behera *et al.,* [43]	Nimonic 90; TiAl4V	Dry, MQL	Minimum flank wear is derived from the MQL machining of TiAl4V for good wettability.
Sivaiah and Chakradhar [39]	17-4 PH SS	Dry, wet, MQL, Cryogenic (LN2)	Cryogenic machining shows better performance for surface finishing, wear of the tool, chip morphology, and thinner chips than dry and MQL machining.

3.2 MQL in Drilling

Biermann and Iovkov [44] experimented to explore workpiece temperature directs to deformation and possible straightness accuracy of the borehole. In their experiment, they used MQL and high feed process guiding strategies for enhancing deep hole drilling. The high feed process shows better productivity and less heat in the workpiece during drilling. High-speed steel (HSS) drill bit was used to drill magnesium alloy UNS M11917 under dry and MQL machining conditions to identify the best tool and surface integrity for the aeronautical sector [45]. The results revealed that the minimum and maximum surface roughness value was in the range of established value (0.8 to 0.16 µm) for the aeronautical sector, which improved the rising cutting speed. Moreover, 0.13 µm and 0.87 µm were the lowest and highest surface roughness values, respectively. They found that point angles of 118° and 135° are responsible for achieving the minimum surface roughness for higher and lower speed tools, respectively. They also suggested the feed rate's significance on the surface roughness for various cutting speeds and concluded that a higher feed rate exerts minimum surface roughness for lower cutting speed. On the contrary, enhanced surface roughness was obtained at higher feed rates for higher cutting speed due to evacuation difficulties of generated long chips.

Kuzu *et al.,* [46] reported that dry machining is more feasible and economical in terms of cost and energy than MQL and even dry with compressed air condition as the critical factor- chip evacuation that influences the drill life for specific cutting parameters. Drilling throughput was investigated for compacted graphite iron (CGI) under dry (EXP-I), dry with compressed air (EXP-II), MQL (EXP-III) conditions. EXP-II (3150 and 2969 holes) provides better tool life for better cooling and chip evacuation capability in tool life. In this experiment, spiral chip (SC- long; difficult to evacuate), triangular chip (TC- less significant; easy to evacuate), and rectangular chip (RC) were found in the SEM micrographs. The maximum TC (66 %) ratio found in EXP-II, which results in better drill life, whereas 52 % in EXP-I and 60% in EXP- III. However, for all the experiments, almost the same cutting force and torque were identified. They concluded that the MQL provides better lubrication while producing long chips, which are difficult to evacuate and reduces tool life.

On the contrary, under dry conditions, drilling of magnesium alloy AM60 was associated with concise drill life due to the formation of build-up-edge (BUE) and magnesium adhesion [47]. On the other hand, they found stable drilling performance for fatty acid (FA) and mineral oil (MO) based MQL providing small chips, soothing hole surface, increased tool life, comparatively less, and uniform torque and force. Moreover, under MQL conditions, the workpiece's maximum temperature is comparable to flooded and much less than dry condition. In this experiment, for their selected higher temperature and feed rates, they suggested the MQL flow rates. The results revealed that there were not any notable differences for 10, 20, 30 ml/h flow rates while five ml/h flow rate directs to higher torques. MQL lubricants with high viscosity and cooling capacity extend tool life; dry drilling accelerates tool wear significantly during an investigation of the effect of MQL and its supplying behavior on various HSS twist drills during drilling of 0.45 % carbon-containing plain carbon steel [48]. Three types of MQL were under consideration, such as MQL using synthetic ester (SE) and additives (add), Synthetic ester, additives, and 20 % alcohol, Oil-free synthetic lubricant (SL) with 40% water. In addition, four types of twist drills were used in this study, such as uncoated HSS (type A), Uncoated Co-HSS (type B), TiN-coated Co-HSS (type C), TiAlN coated Co-HSS (type D). The TiAlN multi-layered coated drills performed better for dry drilling due to their high hot hardness than uncoated HSS, Co-HSS, and even TiN coated drills. In the case of MQL supplying manner from continuous supply to discontinuous supply, they reported 98% (536 to 13 boreholes), 42% (709 to 411), 27% (966 to 709) tool life drop for type B, C, D tools respectively. Le Coz *et al.,* [49] experimented with establishing a temperature measurement system for rotating cutting tools. An integrated thermocouple position is very close to the cutting edge during the drilling and milling of titanium aluminum alloy under MQL and dry conditions, respectively. They found that the maximum temperatures for drilling (MQL) and milling (Dry) are 160° and 620 °C for a hole depth of 20mm and cutting length of 500mm and concluded that cutting condition, tool geometry, and tool coating affects tool mechanism. However, Tasdelen *et al.,* [50] compared cutting torques and forces, surface roughness, tool wear under air, emulsion, and MQL (flow rates- 5, 15, 23 ml/h) condition during short hole drilling using 880-D1900L25-03 Coro drill with GM 1040 inserts. MQL and air-assisted drilling showed reduced tool wear at the periphery and midst of the edge, whereas emulsion exerted maximum tool wear. The highest value of flank and crater wear, the lowest value of cutting force were derived from the emulsion technique. They also found maximum cutting force from air-assisted drilling and five ml/h flow of MQL but the comparatively lower force from 15 ml/h and 23 ml/h flow of MQL. In addition, this study also revealed air-assisted drilling is responsible for the highest surface roughness.

Minimizing friction at the contact region during hole drilling is hindered by the chips' upward motion along the flute surface. Micro-textured drill tool surfaces may address this obstacle. Niketh and Samuel [51] experimented with understanding the effect of non-textured, margin, and flute textured drill tools using dry, wet, and MQL systems. They found the margin textured tool the most efficient, which reduces thrust force 10-12 %, 15-20 %, 15-19 % in dry, wet, and MQL conditions, respectively. Again, Girinon *et al.,* [52] explored 316L austenitic stainless steel drilling under dry, internal and external coolant systems. The results showed that the dry condition is severe for temperature, forces, and chip tectonics. In this condition, generated high heat of final workpiece directs to tensile residual stresses whereas heat generation is lower for external condition and tensile stress is originated from only circumferential residual stresses and for internal condition, heat is carried away by coolant and residual stresses are compressive.

In the case of surface integrity, internal coolant gives the best results, and dry condition gives the worst condition showing the highest roughness, which leads to crack propagation and part breakage [53]. Amini *et al.,* [53] investigated the optimization of surface roughness and thrust force in drilling AISI1045 steel under dry, MQL, ultrasonic vibration (UV), and combined UV-MQL system. From single objective optimization findings, it is evident that a 14 % reduction of thrust force and 11 % reduction of surface roughness is possible under UV drilling.

The experiment also found that 931 rpm speed and 90 mm/min feed is the optimum point for lowest thrust force and 954 rpm speed and 110 mm/min feed for lowest surface roughness regarding multi-objective optimization. The findings also showed that broken chips produced under UV and UV-MQL conditions leading to a reduction in friction and consequently force, and under UV-MQL drilling, better surface quality is generated for lower BUE on the drill bit. Bhowmick and Alpas [54] performed drilling of 319 grade Al-Si alloys under H_2O- MQL conditions. Hydrogenated (H) and non-hydrogenated (NH) diamond-like carbon (DLC) layered drills were used for this study. The results showed the best performance in both types of DLC layered drills by reducing drilling torque which is most comparable to flooded drilling performance. They also specified that under NH-DLC coating is preferable for drilling Al-Si than H-DLC coated drills because this coating showed lower thrust force, torque, and BUE. Besides, the H_2O-MQL condition exerts a minimum area of aluminum adhesion of for both tools.

Immediate tool failure found for HSS dry drilling and tapping, but considerable improvement exhibited for DLC coated HSS dry tapping due to low friction coefficient, which prevents high heat generation and BUE formation [47]. The authors found a similar type of average torque of flooded tapping in the 80ml/h flow rate of the MQL condition. The results showed 55 °C temperature reduction for MQL condition, and sulfur and phosphorus-based additives significantly prevent aluminum adhesion. Bhowmick and Alpas [55] experimented with cast AZ91, a magnesium alloy, using NH-DLC HSS drills under dry, MQL, and flooded conditions. Initially, they experimented with 1000, 1500, 2000, 2500 rpm and 0.10, 0.15, 0.20, and 0.25 mm/rev but noticed higher average torque for higher speed and feed rate combinations. Finally, they conducted experiments at 2500 rpm and 0.25 mm/rev. Under the dry condition, this study revealed the flank type wear with NH-DLC due to high-temperature generation accompanying coating degradation. Recrystallization of AZ91 surfaces was also experienced under dry conditions using both uncoated and NH-DLC HSS drills. On the other hand, enhanced life of NH-DLC drills with reduced temperature, torque, and friction, comparable to flooded drilling conditions at 30,000 ml/h flow rate of mineral oil, was observed for H_2O- MQL drilling conditions 30 ml/h.

Giasin and Ayvar-Soberanis [56] experimented with investigating the impact of dry, liquid nitrogen coolant, MQL condition, and other cutting parameters on drilling-related damage fiber metal laminates. They found that under LN2 condition, the depth of erosion in glass fiber holes is higher than MQL and dry drilling and borehole surface damage intensity is lower than MQL and dry drilling. This experiment proved that the generation of waste reduced by using MQL and cryogenic cooling. Though increased spindle speed gives a better surface finish, it demonstrates more waste and chip adhesion under MQL and LN2. Moreover, increased speed and feed worsen the borehole surface, such as erosion, interlayer burr, and surface delamination. Under MQL condition heat balance of the drilling process and the workpiece's temperature outline are represented by Biermann and Iovkov [57]. Besides providing good machinability, they also mentioned that the production cost reduced through an environmentally friendly MQL system. Table 5 and Table 6 summarize detailed information of various machining parameters for the drilling operation, lubrication mode, cutting fluids, other specifications of various coolant systems. However, Table 7 presents the experimental results of different lubrication systems for drilling of various workpieces.

Table 5
Summary of various machining parameters for the drilling operation

References	Workpiece material and geometry	Cutting tool material	Tool geometry	Cutting speed	Feed	Drilling depth
Kuzu *et al.,* [58]	CGI (Dia 20 and L 200) mm	Uncoated two-flute carbide drill	10 mm dia; helix, point, chisel angle 30°, 118°, 120°	EXP. I- 25, EXP II-50, EXP III- 75	EXP I 0.15, EXP II- 0.15, EXP III- 0.1	
Chatha *et al.,* [59]	Aluminium 6063	HSS Drill Tool	Drill bit 6 mm	30 and 53.7	60	20
Berzosa *et al.,* [45]	Magnesium alloy UNS M11917; 110 × 62 × 50 mm	HSS Steel Twist Drill;	dia. 6 mm, flute L 28 mm, point angles 118°, 135°	40, 60	0.05, 0.2	
Kuzu *et al.,* [46]	CGI-Compacted Graphite Iron	5 µm multi-coating (AlCrN, TiAlN/AlCrTiN)	Dia. 4 mm, 135°-point angle	7961 rpm (spindle); 100 (drill)	26.5 mm/s	
Bhowmick *et al.,* [60]	Magnesium alloy AM60; 60 × 10.16 × 7.62 cm^3	HSS twist drills;	Dia 6.35 ± 0.01 mm dia; HRC: 64± 2.50	1000,1500,2000, 2500 rpm	0.10,0.15,0.20, 0.25 mm/rev	
Heinemann *et al.,* [48]	Plain carbon steel (0.45% carbon);	Uncoated HSS, Co-HSS, TiN coated Co-HSS-TiN, TiAlN coated Co-HSS.	Straight shank, dia. 1.5 mm, helix, point angle 40°, 130°	26 m/min	0.26 mm/rev	
Le Coz *et al.,* [49]	Titanium alloy Ti6Al4V	Uncoated Twist Drill	Dia. and length 10 mm & 43mm; point, helix angle: 130°, 15°	30 and 35 m /min	0.1; 0.12; 0.14; 0.16 mm/rev	20
Tasdelen *et al.,* [50]		Coro drill 880-D1900L25-03; Inserts GM 1044- centrum	Drill dia. 19mm	155m/min	0.11 mm/rev	33
Niketh and Samuel [51]	Ti-6Al-4V			60 m/min	0.07 mm/rev	

Girinon *et al.,* [52]	stainless steel 316L; (Dia 60 and thickness 36) mm	TiAlN-TiN Coated carbide drill bit	Dia. 12 mm			
Amini *et al.,* [53]	AISI1045 carbon steel; 150 × 75 × 10 mm^3	HSS drill bit	Dia. 5 mm	828, 891, 955 rpm	83, 124, 165	
Bhowmick and Alpas [54]	Al–6%Si (319 Al); 30 × 15 × 2.54 cm^3	Uncoated HSS, H and NH DLC HSS drills	Dia. 6.35+-01mm	50 m/min	0.25 mm/rev	
Bhowmick *et al.,* [47]	Al–6.5%Si alloys; 30 × 15 × 2.5cm	Uncoated and DLC HSS taps	Dia. 8, L 95; pitch L 1.25; flute angle 90°	50 m/min	0.25 (drill) & 1.25 (tap) mm/rev	25
Bhowmick and Alpas [55]	AZ91; (60 × 10.16 × 7.62- cm^3)	NH-DLC HSS drills (PTD JL 010616)	Dia. 6.35±0.01; helix, point angle 37°, 118°	1000,1500, 2000, 2500 rpm	0.10, 0.15, 0.20 and0.25 mm/rev	19
Giasin and Ayvar-Soberanis [56]	GLARE panel sheets of Al2024-T3 alloy	OSG HYP-HP-3DTiAlN layered carbide twist drills	Dia. 6; flute L 28, helix angles 30°	3000, 6000, 9000 rpm	300,600, 900	

Table 6
Summary of lubrication mode, cutting fluids, other specifications of various coolant systems for drilling

Authors	Mode of lubrication	Cutting fluid	MQL & flood flow rate	MQL air, fluid pressure	Nanoparticle, WT%, Spray angle	Other coolant specification
Kuzu *et al.,* [58]	MQL		100ml/h(MQL)	6 Bar(air)		
Chatha *et al.,* [59]	Dry, Flood, MQL, NF- MQL	Soya Bea Oil	200 ml/h(oil), 30,000 ml/h (flood)	70 Psi(air)	Al_2O_3 of 20 nm, 1.5%	
Biermann and Iovkov [44]	Internal three-channel MQL			15 bar		
Berzosa *et al.,* [45]	MQL		0, 50 ml/h (MQL)			
Kuzu *et al.,* [46]	EXP-I-dry, EXP-II- compressed air, EXP- III-MQL		5 ml/h(MQL)	690 kPa (compressed air)		
Bhowmick *et al.,* [60]	Dry, MQL, Flooded	i. H20-MWQL ii. FA_MQL iii. Mineral oil-Flooded	10 ml/h [i, ii]; 30.0 l/h (Flood)			
Heinemann *et al.,* [48]	MQL_SE+add; MQL_SE +add +20% alcohol; MQL_oil free SL +40% water		18 ml/h (MQL)			
Le Coz *et al.,* [49]	Internal MQL					
Tasdelen *et al.,* [50]	Air, emulsion, MQL		5, 15, 23 ml/h (MQL)			
Niketh and Samuel [51]	Dry, Wet, MQL		200 ml/h (MQL)	6 bar		

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
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Girinon *et al.,* [52]	Dry, internal, and external coolant (8.3% emulsion)					
Amini *et al.,* [53]	Ordinary, MQL, UV, UV-MQL	Accu-lube FG-2000	100 ml/h (MQL)	4 bar		Injection frequency 10 cycle/min
Bhowmick and Alpas [54]	MQL	Distilled Water	30 ml/h (MQL)			
Bhowmick *et al.,* [47]	Dry, FA-MQL; MO-MQL; Flood	Mineral-based tap Oil, Fatty acid Based MQL	80 ml/h(FA-MQL), 10,000 ml/hr (flood)			
Bhowmick and Alpas [55]	MQL	Distilled water (MQL); Mineral oil (flood)	30 ml/h (MQL), 30,000 ml/h (Flood)	0.6 MPa(air)		
Giasin and Ayvar-Soberanis [56]	Cryogenic Liquid Nitrogen cooling, MQL		20, 40, 60 ml/h (MQL)	1, 2, 3 bar (air)		

Table 7
Summary of experimental results of different lubrication systems for drilling of various workpieces

Authors	Workpiece Material	Mode of Lubrication	Findings
Kuzu *et al.,* [58]	CGI	MQL	Heat energy increased by twice for increasing cutting speed from 25 to 50m/min, whereas thrust and torque values are equal.
Chatha *et al.,* [59]	Aluminum 6063	Dry, Flood, Pure MQL, NF-MQL	NF- MQL technique shows an increased number of drilled holes, less cutting and friction forces, torques and surface roughness, and improved tool life, compared with the dry and flooded conditions.
Biermann and Iovkov [44]	EN AC-46000	Internal MQL supply	The high feed process shows better productivity and less heat in the workpiece during drilling.
Berzosa *et al.,* [45]	UNS M11917	MQL	Smallest and largest surface roughness values are 0.13 µm and 0.87 µm, respectively. At less cutting speed with higher feed rates exerts lower surface roughness.
Kuzu *et al.,* [46]	CGI-Compacted Graphite Iron	EXP-I dry, EXP-II dry with compressed air, EXP- III-MQL	Almost the same cutting force and torque required for all three conditions. MQL provides better lubrication but generates long chips which are difficult to evacuate, leading to low tool life.
Bhowmick *et al.,* [60]	AM60	Dry, MQL, Flooded	The drilling performance was stable for both H_2O-MQL and FA-MQL conditions. At MQL, the workpiece's maximum temperature is comparable to flooded conditions and much less than dry.
Heinemann *et al.,* [48]	Plain carbon steel (0.45% carbon);	MQL_SE+add; MQL_SE +add +20% alcohol; MQL_oil free SL +40% water	Dry drilling accelerates tool wear significantly. Excellent cooling capability with lower viscosity type lubricant gives prolonged tool life. Tool life degradation seen for discontinuous MQL supply.

Le Coz *et al.,* [49]	Ti6Al4V titanium alloy	Internal MQL	Maximum temperatures for drilling (MQL) and milling (Dry) are 160° and 620 °C for a hole depth of 20mm and cutting length of 500 mm.
Tasdelen *et al.,* [50]		Air, Emulsion, MQL	Air-assisted drilling and MQL show maximum cutting force.
Niketh and Samuel [51]	Ti-6Al-4V	Dry, Wet, MQL	Margin textured tool reduces thrust force 10-12 %, 15-20 %, 15-19 % in dry, wet, and MQL conditions, respectively.
Girinon *et al.,* [52]	austenitic stainless steel 316L	Dry, internal coolant (8.3%), external coolant (8.3%)	Dry condition is severe in terms of chip morphology, forces, and temperature. For the internal state, heat is carried away by coolant, and residual stresses are compressive.
Amini *et al.,* [53]	AISI1045 carbon steel	Ordinary, UV, MQL, and UV-MQL	14% and 11% reduction of thrust force and surface roughness occurred by UV drilling. UV-MQL drilling produces better surface quality for lower BUE generation.
Bhowmick and Alpas [54]	Al–6%Si (319 Al)	MQL	NH-DLC coating is preferable for drilling Al-Si than H-DLC coated drills because this coating showed minimum torque, BUE, thrust force, and less aluminum adhesion on the flute.
Bhowmick *et al.,* [47]	Al–6.5%Si (319 Al) alloys	Dry, FA-MQL; MO-MQL; Flood	MQL drilling shows 55°C temperature reduction and lower average torque, which is similar to flooded condition.
Bhowmick and Alpas [55]	AZ91; Mg–Al–Zn	MQL	30ml/h flow rate of H_2O- MQL drilling reduces friction, torque, temperature, and enhancement of NH-DLC drills.
Giasin and Ayvar-Soberanis [56]	Fiber metal laminates (FMLs)	LN2 cooling, MQL	MQL and cryogenic cooling reduce waste generation. Increased spindle speed and feed rate deteriorate borehole surface.

3.3 MQL in Milling

In a milling machine, end milling is a slot cutting technique, making flat surfaces and even complex profiles by end mills. End Milling is associated with a better material removal rate, a simple setup with minimum cost, and most importantly, creating various products with different shapes for many applications through this machining. Optimization of end milling machining parameters is essential due to this operation's significant role in the recent manufacturing world. Khatri and Jahan [4] performed end milling on TI-6Al-4V alloy for comparatively higher cutting speed and various feed depth of cut while both coated and uncoated tools used. They suggested that abrasion is the most preeminent type of tool wear for all machining conditions, e.g., flood, MQL, dry. Abrasion wear is comparatively low in MQL than dry machining and least in flood machining, and it found to be dominant in flank and rake faces which faces contributing most to tool life and surface integrity. Chipping and adhesion are the second most prevalent wear that occurs most in dry and least in MQL condition. Some plastic failures of flutes and edges observed in flood and dry machining than MQL machining. Moreover, delamination was less significant in dry drilling than MQL and flood machining due to the efficacy of coated tools. Finally, they concluded that MQL is the sustainable machining condition over dry and flood machining, which is liable for the least tool wears. Again, wear analysis of uncoated and PVD coated TiAlN and AlTiN tools was accomplished by Bandapalli *et al.,* [61] while performing micro end milling of 12 grade Ti alloy (Ti-0.3Mo-0.8Ni) under dry condition. In this study, speed and feed found to be the most prevalent variables affecting the tool wear. Moreover, wear of the tool can be attenuated for AlTiN coated and uncoated WC tool while increasing cutting speed (at 70,000 and 1,10,000 rpm) and without changing feed and depth of cut. In addition, it is recommended from the investigation that the uncoated WC tool is superior to AlTiN and TiAlN tools for high-speed milling of 12-grade Titanium alloy. During conventional milling of Al6061-T6 using WC tool

(AE302100) at 5000 rpm/min speed, 100 mm/min feed, 5 mm depth of cut for 0.0, 0.2, 0.5, and 1.0 wt% nanolubricant, 3.87 % improvement of surface roughness is reported with 0.5wt% MoS_2 nanolubricants MQL system compared with pure oil [62]. Similarly, in the case of end milling of stainless steel, the performance of MQL excelled over dry and flood machining conditions in terms of tool life and surface roughness [63]. In this experiment, vegetable oil used as the base fluid and TiAlN multilayers coated carbide tools. Uysal *et al.,* [64] also performed the milling process on AISI420 under MQL and even with one wt% MoS_2 nanoparticle into the MQL system. This investigation was conducted at 995 rpm speed, 5 bar pressure, 20 ml/h, and 40 ml/h flow rates of MQL. However, the 40 ml/h flow rate of MQL shows the best results both for tool wear and surface roughness. They revealed that 9.8 % and 15.5 % tool wear reduction is possible at 20 ml/h and 40 ml/h flow rates, respectively, for an ordinary MQL system.

On the contrary, for the NF- MQL system, 16.8 % and 19.9 % tool wear reduction reported at 20 ml/h and 40 ml/h flow rates compared to dry milling. Moreover, the minimum value (0.8644 µm) of surface roughness derived from the NF- MQL system at a 40ml/h flow rate. Finally, they concluded that increment of fluid flow rate with nanoparticles' inclusion gives lower tool wear and higher surface integrity because the nanoparticles dispersion into the traditional fluid improves thermophysical properties showing good stability [65]. Hence, the NF-MQL system functions as a better cooling and lubrication system. Wang *et al.,* [66] suggested the optimal cutting parameters of up and down milling of Inconel 182. The investigation was performed under MQL and dry conditions while using the S/N ratio. It is evident from the study that surface roughness is not prone to lubrication mode at 160mm/min speed, 0.2mm/tooth feed rate, 1mm depth of cut, and for down milling, surface roughness remarkably increases when MQL is applied. In up milling, tool wear is significant, and MQL works significantly. In reverse, MQL shows ineffectiveness for down milling operation due to unstable milling processes or significant self-excited vibration. In terms of energy consumption, up milling needs less energy compared with down milling. So, they concluded that tool waste and manufacturing costs significantly reduced by using up milling with MQL during machining Inconel 182 [66]. In the investigation of spray cooling with MQL for milling machining of Ti-6Al-4V alloy, spray angle of 90° is not appropriate from the lubrication prospect using WC tool as MQL droplets rarely enter into the cutting zone despite showing a lower temperature for 0° and 90° of spray angle in comparison of 45° spray angle [67]. Again, for end milling of AISI4140 steel using carbide end mill cutter under MQL system, it is found that cutting energy is most significantly affected by speed, feed, and last but not least MQL flow rate, whereas surface roughness notably impacted by the flow rate of MQL and also cutting speed [68]. Comparison among dry, wet, CO_2 stand-alone, MQL system was made by Pereira *et al.,* [69], and the proposed hybrid CO_2+ MQL lubrication system while investigated the cooling process of Inconel 718 during milling machining. From their experiment, surface integrity not demonstrated clearly, and it found that better lubrication cannot be derived from a higher speed. They concluded that the tool life shows the best results being over 90% more eco-friendly at a 100 ml/h flow rate of oil than wet machining [69].

Table 8
Summary of various machining parameters for milling operation

References	Machining	Workpiece material and geometry	Cutting Tool Material	Tool Geometry	Cutting Speed	Feed	Depth of cut
Khatri and Jahan [4]	End milling	Ti-6Al-4V	Uncoated and TiAlN tools		50m/min	0.1, 0.3, 0.5mm/ rev	0.2, 0.3, 0.4, 0.5
Rahmati *et al.,* [62]	End milling	Al6061-T6 (40 ×40 ×100 mm^3)	WC tool (AE302100)	2 flutes with 10mm dia.	5000/min	100mm/min	5
Bandapalli *et al.,* [61]	Micro end milling	Ti Alloy-Ti-0.30Mo-0.8Ni (60 ×40 ×4 mm)	Uncoated, PVD coated AlTiN, TiAlN WC	Dia. 500 Microns; rake angle +5°	47, 110 and 173 m/min	2, 5 & 8 µm/tooth	0.02, 0.06; 0.1
Uysal *et al.,* [64]	Milling	AISI420 martensitic stainless Steel	SPHN120404 uncoated WC	Dia. 32 mm end mill	995 rpm	180 mm/min	0.5
Wang *et al.,* [66]	Face Milling (Up & Down)	Inconel 182 (80 × 40 ×40 mm)	Sandvik milling cutter R390-050Q22-17M	Dia. 50 mm; insert-Sandvik R390-17 04 08M	V=80, 120, 160m/min	0.1, 0.2, 0.3mm/tooth	Width 40 depth 0.5, 1, 1.5
Kim *et al.,* [67]	Milling	Ti-6Al -4V (40×20mm)	WC	Radius 8 mm	10 0 0 rev/min	0.48 mm/rev	Radial depth of cut 4
Pereira *et al.,* [69]	Milling	Inconel 718(45HRC)			120 m/min		
Kumar [74]	Micro end milling	Copper alloy C360	WC flat end mill	size 700µm & 800µm			Depth & length of cut 70µm 10
Tunc *et al.,* [70]	Robotic Milling	AISI316L; (50 mm x 110 mm)	Three flutes inserted cutter	Dia. 25 mm	1800 rpm (140m/min)	0.1mm/rev	1.5
Kedare *et al.,* [71]	End Milling	Bright Mild Steel (100 x 110 x 25)	Four flutes, HSS end mill (uncoated)	Dia. 5mm; axial rake angle 5°	160,225,300 rpm	constant	0.1, 0.2, and 0.3
Iskandar *et al.,* [72]	Milling	Carbon fibre reinforced plastics (CFRP)	Uncoated WC end mills (SGS-30131).	Helical 4-flutes 1/400	15,000 rpm	1500mm/min	cutting length 90
Liao *et al.,* [73]	End Milling	NAK80 mold steel (41 HRc)	TiAlN and TiN layered carbide tool		300 to 500 m/min	0.1, 0.2 mm/rev	axial 0.3;5

Tunc *et al.,* [70] reported surface roughness, and residual stress of austenitic stainless steel during MQL assisted robotic milling. They found that MQL settings, having a hardly prominent effect on surface roughness and tensile residual stress, increases with decreasing oil flow rate. So, they finally suggested a well-controlled flow rate and duty cycle for reducing residual stress in the milling process. However, 27% improvement of surface roughness is possible during end milling of mild steel under 900ml/h flow rate of MQL while uncoated end mill cutter of HSS used, and it is also evident that MQL works efficiently at less speed and depth of cut [71]. Iskandar *et al.,* [72] conducted experiments to establish optimum MQL conditions by considering various parameters such as flow rate of oil and air, spray angle, nozzle distance, and flow characteristics of the milling process of carbon fiber reinforced plastics (CFRP). The study uncovers that if the nozzle placed near the cutting zone, optimum MQL spray achieved from low oil and high airflow rate, verified from Phase Doppler Anemometry and Particle image velocimetry. It found that for MQL condition, flank wear is reduced by 30% compared to pressurized air and 22% compared to dry and wet conditions. Cutting temperature reduced by using a cutting fluid of low viscosity at lower cutting speed; on the contrary, cutting fluid of greater viscosity contributes to improving cooling capability at higher cutting speeds, and the combination of superior heat resistant, coated carbide tool with MQL gives better tool life compared with other methods [73]. Machining with MQL concluded as a replacement and economical alternative to dry and flood cooling as it dramatically reduces lubricant consumption, especially when ecology and operators' physiology is an important issue [71]. Finally, Table 8 and Table 9 represent the summary of details information of machining parameters, lubrication mode, cutting fluid for milling operation, and Table 10 summarizes the investigations' findings.

Table 9
Summary of lubrication mode, cutting fluids, other specifications of various coolant systems for milling

Authors	Mode of Lubrication	Cutting fluid	MQL & Flood Flow Rate	MQL Air and Fluid Pressure	Nanoparticles, wt% & Spray angle	Other coolant Specification
Rahmati *et al.,* [62]	MQL	ECOCUT HSG 905S FUCHS	30 ml/min	20 Mpa. (Oil); 4 bars (Air)	0.0, 0.2, 0.5 & 1.0wt%, 60°	nozzle's orifice dia. 1 mm
Uysal *et al.,* [64]	MQL	Eraoil KT/2000 vegetable oil	Oil-20 ml/h; Nanolfuid-40 ml/h	5 bar	1wt% MoS_2	Nozzle dia., distance and angle 1 mm, 50 mm and 10°
Wang *et al.,* [66]	Dry, MQL		125 L/min(air)	0.7 MPa (air)		Elevation angle 30°, spray angle 45°
Kim *et al.,* [67]	MQL	Vegetable oil	Oil- 3.32 ml/min; air- 1362 ml/min		0°, 90°, 45°	Nozzle dia & distance 1.7 mm 7 23 mm; MQL droplet avg. dia. 11.2 µm
Pereira *et al.,* [69]	Dry, wet, CO_2, MQL, CO_2+MQL	Vegetable oil	100ml/h	Wet- 6 bar; Cryogenic- 14 bar		MQL- 100 ml/h + CO2- 14 bar & -80°C
Tunc *et al.,* [70]	MQL		75, 140, 280, 600 ml/h; 0.04, 0.08 ml/ stroke;	Air- 6, 7 bar		Duty Cycle 75, 140, 280, 600 strokes/min; nozzle to tooltip distance 30 mm
Kedare *et al.,* [71]	MQL + Flood		900 ml/hr (MQL); 2 litre/h (Flood)	5 bar		Nozzle dia 3 mm; spot distance 20mm
Iskandar *et al.,* [72]	Dry, MQL, Pressurized air, flood		Air- 20, 25, 28 l/min; oil- 10, 17.5, 24 l/min			Nozzle distance to the cutting zone 40, 60, 80 mm
Liao *et al.,* [73]	Dry, MQL, Flood	ES3, ES1	Oil Mist-10 ml/	0.45 MPa		

4. Recommendation for Future Work

Numerous researchers have studied the MQL technique in different kinds of machining, mostly with conventional fluids and some with nanofluids. There are some discrepancies in the research findings. For example, a few researchers found no significant difference in tool life during drilling of AISI4140 steel (24-26 RC) using oxide coated HSS drills and found minor differences in tool life using grade SM-30 uncoated carbide tool between flood and MQL cooling [75]. Some reported dry drilling as more efficient in terms of sustainability, cost, and energy savings than dry with compressed air and MQL conditions as they found chip evacuation comparatively difficult in the MQL technique [56]. Some researchers revealed MQL as a more prominent cooling method in grinding hardened steel rather than soft steel for grinding forces and surface integrity [76,77]. In contrast, others found that MQL is appropriate for softer materials but not harder [78,79]. Further research can be done to resolve contradictory findings. Higher cutting speeds and higher viscous cutting fluids play a significant role in improving the cooling capability for cutting, but its correlation with MQL has not yet been explored [73]. Some researchers found the lowest axial force from the emulsion, the maximum cutting force from MQL and air-assisted drilling, and the highest surface roughness from air-assisted drilling [50]. Though most of the researchers found that surface roughness is noticeably affected by the MQL technique. Still, a few findings revealed that MQL settings show a hardly significant effect on surface roughness [70].

Table 10
Summary of experimental results of different lubrication systems for milling of various workpieces

Authors	Workpiece Material	Mode of Lubrication	Findings
Khatri and Jahan [4]	Ti-6Al-4V	Dry, MQL, Flood	MQL is responsible for least tool wear leading to sustainable and effective machining.
Rahmati *et al.,* [62]	Al6061-T6 (Al-Mg-Si)	MQL	Surface roughness improved by 3.87%.
Bandapalli *et al.,* [61]	Ti Alloy (Ti-0.30Mo-0.8Ni)	MQL	Uncoated carbide tool shows a smaller amount of wear of the tool than PVD coated TiAlN & AlTiN WC tools. AlTiN tools perform superior to TiAlN tools while machining.
Uysal *et al.,* [64]	AISI420	MQL	Under the MQL system, tool wear reduced by 9.8% and 15.5% at 20 ml/h and 40 ml/h flow rates, respectively. Similarly, 16.8%, 19.9% tool wear reduction is noticed for the NF- MQL flow (20ml/h & 40ml/h) compared to dry milling.
Wang *et al.,* [66]	Inconel 182 overlays	Dry, MQL	Under the MQL system, surface roughness increases abnormally in the case of down milling.
Kim *et al.,* [67]	Ti –6Al –4 V	MQL	The spray angle of 90° unsuitable for the lubing purpose as the MQL droplet hardly reaches the cutting zone.
Pereira *et al.,* [69]	Inconel 718	Dry, wet, CO_2, MQL, CO_2+MQL	At 100ml/h oil flow rate of MQL, the tool life shows the best results being more sustainable than wet machining.
Tunc *et al.,* [70]	AISI316L	MQL, Flood	MQL settings show a hardly significant effect on surface roughness.
Kedare *et al.,* [71]	Bright Mild Steel 15 HRc	Dry, MQL, Pressurized air, flood	27% improvement in surface roughness achieved by MQL (900 ml/h).
Iskandar *et al.,* [72]	Carbon fiber reinforced plastics (CFRP)	Dry, MQL, Flood	MQL shows 30% less wear at the flank face than pressurized air condition and 22% less wear than flood and dry conditions.
Liao *et al.,* [73]	NAK80 mold steel (41 HRc)	Dry, Flood, MQL	Combining superior heat-resistant, coated carbide tool with MQL gives better tool life than other methods.

Some researchers added some other new techniques and different types of tools with the MQL system, such as. UV- MQL, CO_2+MQL, Cryogenic cooling. For example, under UV- MQL conditions, better surface quality is generated due to lower BUE, generation of broken chips, secure chip evacuation method, and lower friction and force [53]. Using cryogenic cooling severity of borehole surface damage is found less compared to MQL and dry drilling, whereas waste generation is found less in the MQL and cryogenic coolant system [56]. However, some MQL condition parameters, such as spray angle and distance, air pressure, flow rates, and the effects, including optimizing these parameters, have not been appropriately explored until now. Also, the impact of nanofluid and especially the hybrid nanofluids with MQL has not been unfolded yet broadly. So further attention can be paid to the implication of NF- MQL system during machining of various materials, including alloys in the practical field.

5. Conclusion

This paper systematically represents a comparative discussion of the MQL technique its application in various machining operations. Several studies concluded that MQL is an efficient substitute for flooded machining conditions, safe for operators' health and the environment. Moreover, the production cost decreased by using the MQL technique as it reduces the coolant cost. From this review article, the following remarks can be drawn

i. The application of the MQL system can reduce the temperature of the tool-chip interface significantly.
ii. UV and UV-MQL conditions produce lower BUE on the drill bit by reducing friction and cutting forces through broken chip formation.
iii. The NF- MQL technique can prolong tool life and improve surface integrity by reducing friction, cutting forces, and torques.
iv. Compared to dry and LB 2000 fluid by MQL technique, 12%, and 46% tool life enhancement are possible, including MoS_2 in the base oil and cutting zone.
v. Under MQL condition, the use of lubricant with low viscosity and high cooling capability can upgrade tool life.
vi. Due to the use of MQL, a noticeable reduction of cutting temperature and forces is possible for nozzle distances of 6-9 mm at 0.4MPa while turning medium carbon steel (AISI1045).
vii. H_2O- The MQL drilling technique can also increase the NH-DLC drill's life by reducing the contact zone, cutting force, torque, and temperature.
viii. Under CO_2+ MQL condition, the tool life exerts excellent results over 90% more eco-friendly than wet machining.

So, it concluded that adapting MQL condition over general condition can bring potential improvement in machining, reduction in cost, and, most importantly, environmental-friendly working conditions.

Acknowledgements
The authors would like to thank University Malaysia Pahang for providing the laboratory facilities and the financial support under the University LEAP-3 FLAGSHIP Research Grants (Project number RDU172203), University Research Grants No. RDU190367 and Post-graduate Research Scheme PGRS1903167.

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