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CRITICAL REVIEW

Recent progress and evolution of coolant usages in conventional machining methods: a comprehensive review

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Abstract

This paper reviews recent progress and applications of usage of cutting fluids in conventional machining processes. In addition to reviewing the various conventional and advanced cooling techniques during machining, the paper also discusses the use of minimum quantity lubrication (MQL) in several types on metals such as steel, aluminum, alloy, and titanium alloys. Due to the toxicity of conventional cutting fluid resulting in ecological problems, the demand for environmentally friendly cutting fluid is rising. Therefore, natural vegetable oil is chosen as potential replacement as an environmentally friendly cutting fluid which fulfills the important aspects of biodegradability and sustainability. Application of vegetable oil-based cutting fluids under MQL techniques are also discussed. Moreover, the potential of palm oil as biodegradable and environmentally friendly natural vegetable oil-based metal-working fluids in MQL are reviewed.

Keywords: Machining · MQL · Conventional cutting fluid · Vegetable oil

1 Introduction

Machining operations play an important role in the manufacturing industries nowadays. Through machining operations, desired dimensions, shapes, and surface finishes can be achieved via removal of workpiece materials in form of metal chips from the direct contact of cutting tools and workpiece. The process of excess material removal is known as plastic deformation of the workpiece surface, where almost 99% of energy fed to the cutting tool and these energies are converted into heat and frictions. When ferrous metals and other high-strength metals or alloys are machined, the temperature rises with the cutting speed and depth of cut and the tool strength decreases, leading to increase in tool wear and tool failure [1]. Machining at higher speed is more desirable for better product quality; however, higher temperature is produced. Therefore, cutting fluids are used during machining operations not only to cool down the cutting zone, so that the cutting tool and workpiece not only can be kept at a controlled temperature, but also provide significant lubrication between the cutting tool and workpiece to reduce friction which improves overall machining performances in any machining processes [2–4].

To improve machinability of hard-to-machine metals like titanium and alloy metals, cutting fluids are introduced into conventional machining processes [6]. Cutting fluids or metal-working fluids (MWFs) allow removal of excess heat and improve the machinability and cutting tool's effective life through cooling of workpiece interface during machining processes [7–9]. Cutting tool wear can be reduced when overheating is prevented to maintain cutting tool sharpness which results in better surface finish in machining operations [10, 11]. It also improves chip removal process from the tool–workpiece interface and prohibits built-up edge formation on the surface of the cutting tool. Before the introduction of cutting fluids, dry machining is the most common type of material removal process which allows cost-saving in terms of the eliminations of metal-working fluids. Conventional applications of cutting fluids such as flooded cooling, solid coolants, cryogenic cooling, and high-pressure coolant as shown in Fig. 1 are commonly used as cutting fluid delivery methods where large amounts of coolant are sprayed onto the cutting zone. However, excessive use of cutting fluids leads to several environmental hazards and health and safety issues which also subsequently increase the

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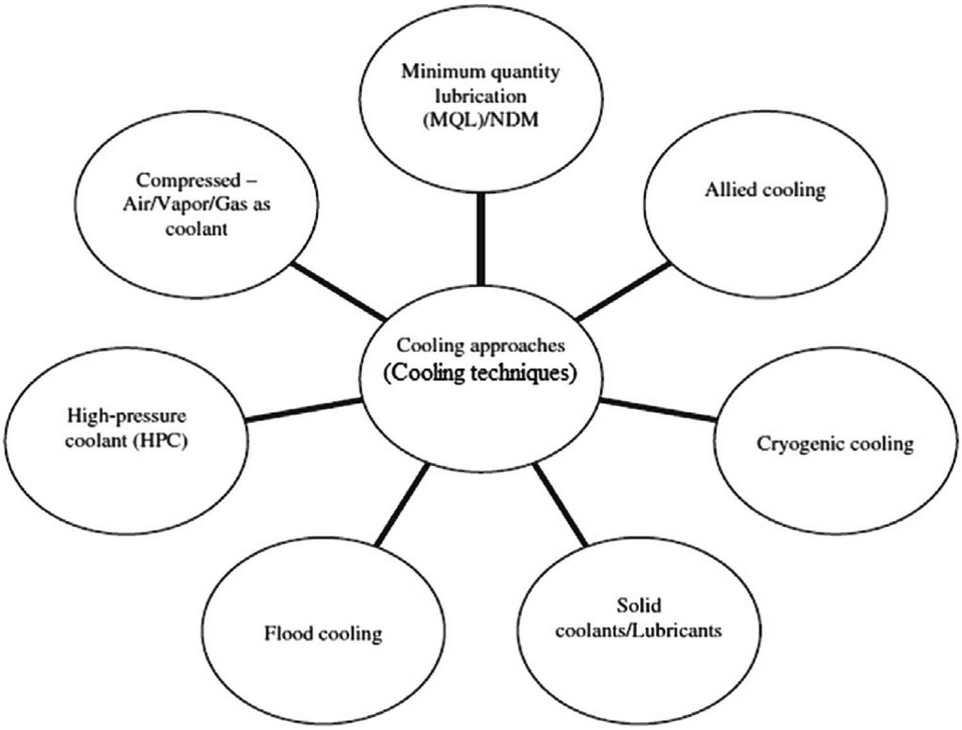


Fig. 1 Different types of cooling techniques [5]

total costs of manufacturing industries [7]. Hence, minimum quantity lubrication (MQL) are introduced as an alternative cutting fluid delivery method during machining processes to minimize the amount of cutting fluid used to achieve "green" machining [12].

In the past several years, an effort has been made to perform more research on to study and improve machining with major focuses on the applications of MQL, and usage of vegetable oil-based cutting fluids in machining of difficult-to-machine materials such as titanium alloys. Based on the graphical representation of research published by year as shown in Fig. 2, pioneering period can be seen in the first years between year 1998 and year 2008 where the published papers are very low, followed by a steady increase in published research papers from year 2009 all the way up to year 2020. There is a slight reduction of publication numbers between 2020 and 2021 which might be due to the COVID-19 pandemic that limited the experimental research across the world. Based on the geographic distribution of the published research papers, researchers from India respond with the most publications at more than 264, followed by China at 81, Brazil at 71, and Malaysia at 60 as seen in Fig. 3.

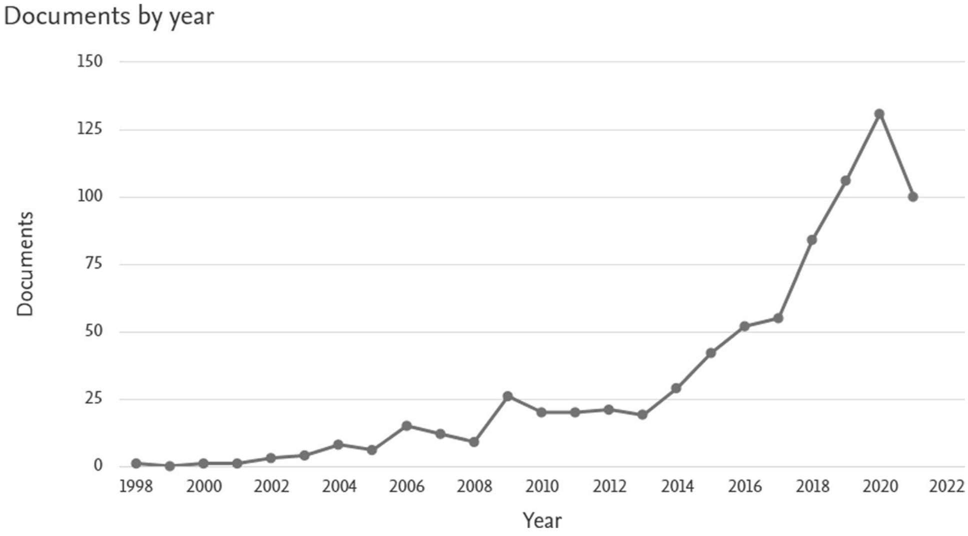


Fig. 2 Numbers of paper publications per year [13]

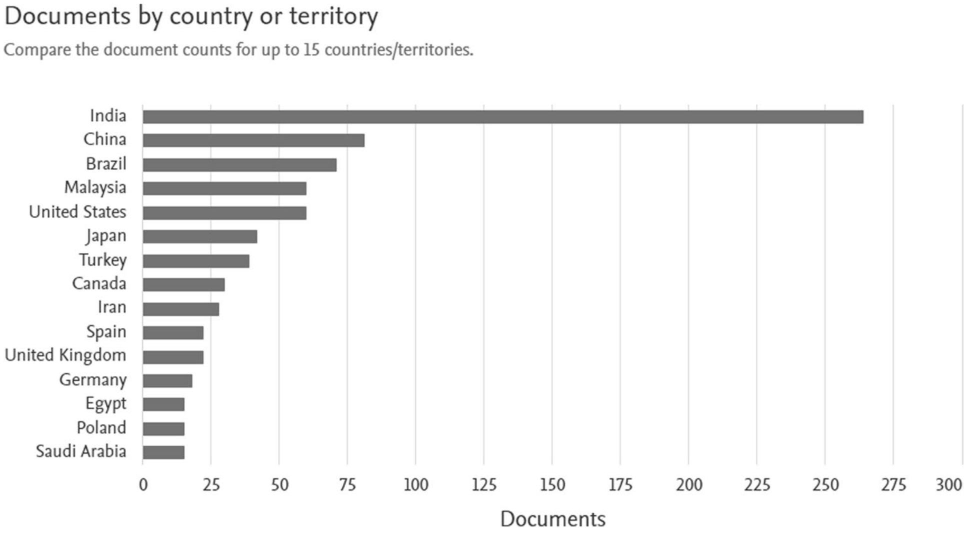


Fig. 3 Numbers of paper publications by country [13]

2 Types of coolant delivery

2.1 Machining under dry condition

Dry machining involves metal removal process with the absence of any metal-working fluids [14–17]. In dry machining, formation of built-up edge occurs when machining is carried out at lower cutting speed, high tool feed rate, and low rake angle. The development of higher cutting temperature at high machining speed often leads to poor surface finish and tool life due to thermal shock. Moreover, high cutting temperature leads to reduce the strength of the workpiece material, causing lower cutting forces at the cutting zone [18–20]. However, in some cases, dry machining is preferred for cost-saving and sustainability of the environment. An experimental setup for dry machining of stainless steel by Galanis et al. [21] is shown in Fig. 4.

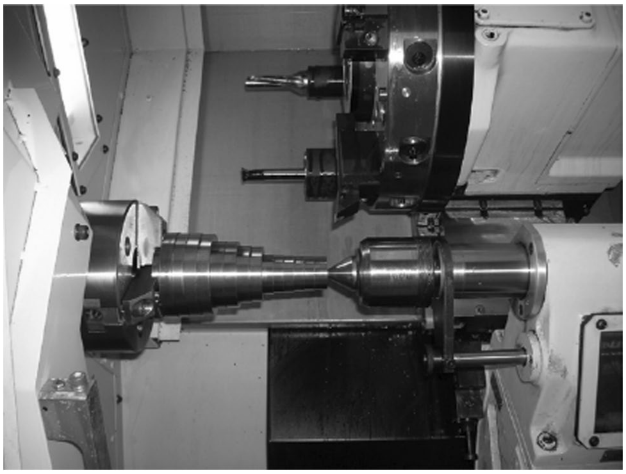


Fig. 4 View of dry machining for stainless steel turning [21]

In this study, cutting parameters such as cutting speed, feed rate, and depth of cut were varied to investigate the machining performances such as surface roughness and cutting temperature. They found that dry machining performed significantly better in terms of surface finish and tool life in comparison to wet machining. In more recent study, the influence of cutting fluid on tool performance of wet and dry drilling of carbon fiber-reinforced polymer (CFRP) was investigated and they found that dry drilling produced lower thrust force and longer tool life compared to wet cutting conditions as shown in Fig. 5. Dry drilling managed to produce mean circularity of 30 µm across the tool life, in contrary of using cutting fluids produced the least effective circularity of 42 µm.

Moreover, another study was performed by Songmene et al. [23] on the effect of lubrication and machining condition on tool wear and tool life to find the machinability of tool steels. It is found that dry milling of the alloy improved tool wear and tool life over wet machining as shown in Fig. 6. They also concluded that dry milling of low hardness material can produce better tool life compared to harder materials, showing the sensitivity of dry machining conditions on material compositions over wet machining.

Revuru et al. [24] performed comparative studies on the performance of dry, flooded, and MQL machining with soybean vegetable oil-based cutting fluid using TiC/TiCN/TiN-coated carbide inserts in turning of 4140 steel. The authors found that feed rate is the most significant cutting parameters to influence the surface roughness while the cutting speed did not have any significant impact on the tool wear. Dry machining is involved to produce the best results in comparison to flooded or MQL machining which implement that the removal of cutting fluids can be achieved by selecting the suitable machining parameters and cutting tool materials.

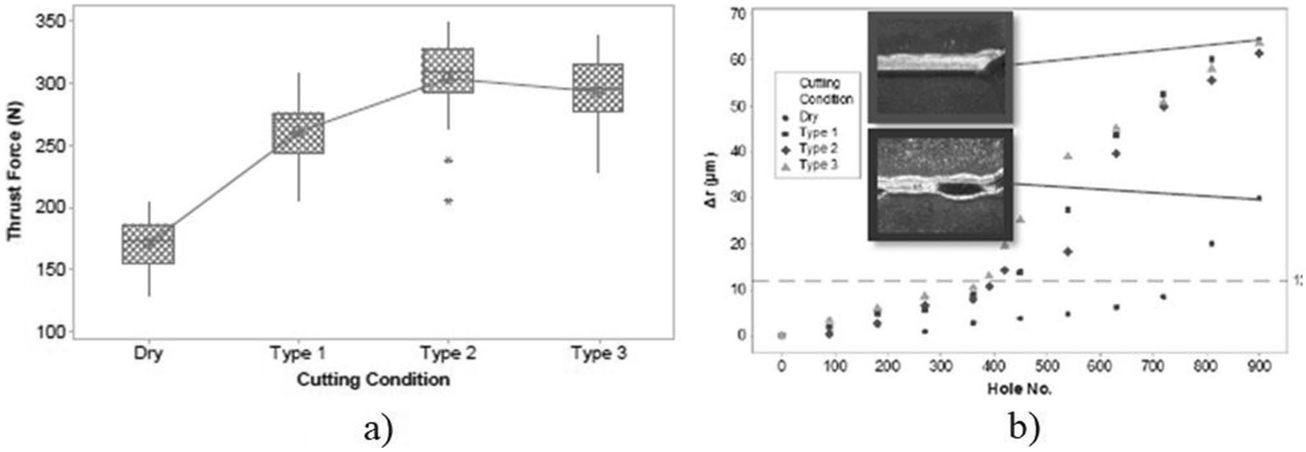


Fig. 5 Machining performance comparison of **a** thrust force and **b** tool life between dry and wet machining of CFRP [22]

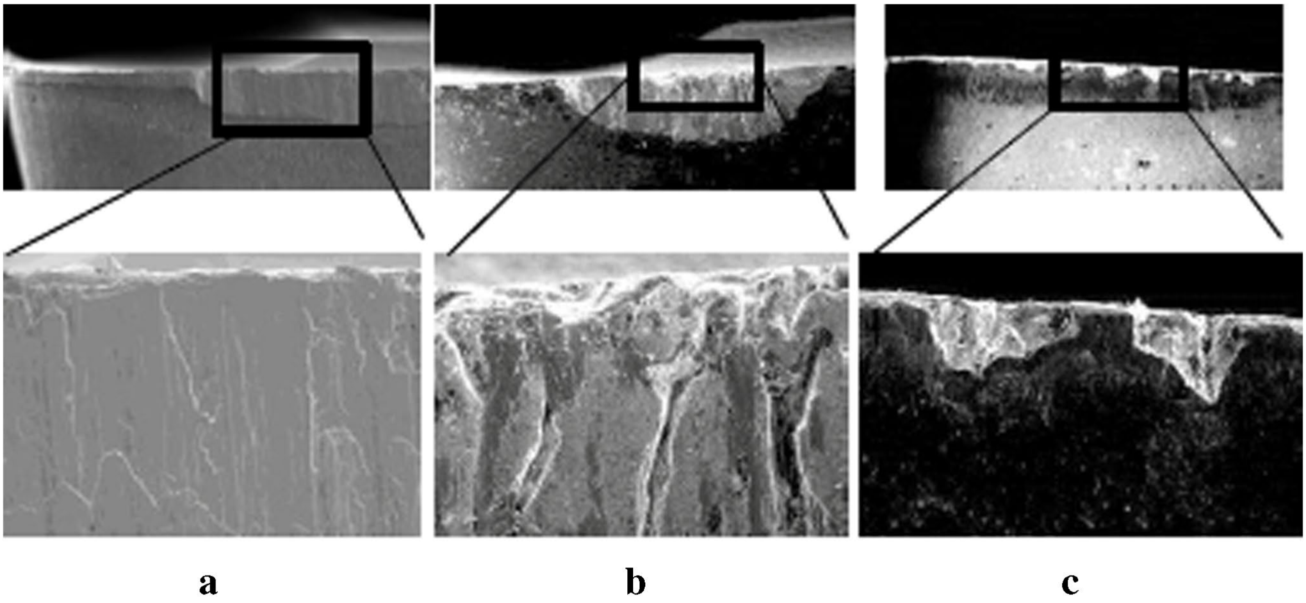


Fig. 6 Tool wear analysis on flank face of cutting inserts under **a** dry milling compared to wet milling in **b** and **c** [23]

2.2 Machining under flooded cooling

Flood cooling and MQL are two prominent fluid delivery techniques that can be applied to most machining processes. In flood cooling delivery, metal-working fluids are delivered out of a nozzle in the form of liquid jet to immerse the entire cutting zone which can be seen in Fig. 7.

Large volume of cutting fluids is dispersed at high flow rate at the cutting zone which completely covers the tool–workpiece interface [26–28]. Generally, in flooded cooling, the flow rates range from 10 to 225 L/min based on the type of machining operations[29]. The large quantity of cutting fluids applied to the machining zone are able to remove the excess heat and provide lubrication. Flooded cooling machining has the advantage over dry machining of producing better surface finish and maintain better tool life [25]. Though there are some advantages of using flooded coolant, it has also various disadvantages. One of the disadvantages is to find sustainable ways of disposing contaminated cutting fluids with metal chips. The overall cost for this and its exposure to the machine operators need to be addressed to improve the sustainability of flood cooling methods in machining.

An experimental study and modeling is carried out by Sankar and Choudhury [30] on machining of microalloyed steel under dry, flooded, and MQL cutting fluid delivery methods. The authors found that the machining performance of flooded cooling in terms of surface roughness, tool wear,

Fig. 7 View of wet machining [25]

and chip thickness were improved over dry machining. Senevirathne and Punchihewa [31] performed a comparison between the effect of dry cutting, flooded cooling, and MQL on tool life and surface roughness during the machining of P20 and D2 steel using coated carbide tools with emulsion cutting oil as cutting fluid. In their study, they concluded that MQL does not necessary always produce the best machining performance as shown in Fig. 8. The flooded cooling method improved the surface roughness and tool wear significantly in comparison to dry cutting and MQL.

Peng et al. [32] performed a study on the design and performance of internal cooling turning tool with microchannel structures on the machining of Inconel 718. They found that flood cooling was able to improve drilling force, cutting temperature, and surface roughness compared to dry drilling. Chen et al. [33] investigated the effect of cooling methods such as dry, flooded, MQL, cryogenic, and cryogenic MQL methods on the machining performances of beta-type titanium–zirconium–niobium alloy (Ti-Zr-Nb alloy). Their research showed that flooded cooling had significant improvement in terms of drilling force, surface roughness, microhardness, and tool flank wear in comparison to dry drilling process as shown in Fig. 9.

2.3 Machining under high-pressure coolant

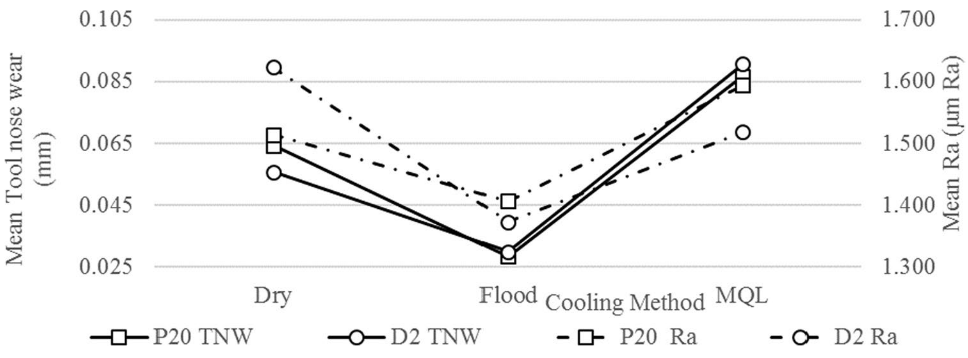
High-pressure coolant delivery (HPC) system pumps coolant at high pressure ranging from 300 to 1000 PSI which allows improvements in penetration of cutting fluids at the tool–workpiece interface and provide better cooling and lubrication effects [34]. A photographic view of high-pressure coolant delivery system is shown in Fig. 10.

HPC can provide an alternative cooling during machining, especially during the process of turning operation where coolants are delivered through specialized cutting tool insert with built in nozzles as shown in Fig. 11. During the machining process, a layer of steam forms on the surface of the cutting tool and workpiece known as "vapor barrier" which acts as a heat insulator to provide cooling on the tool–workpiece interface [37]. High-pressure coolant supply also tends to lift the chips from the workpiece quickly. Therefore, it reduces contact length and area between the tool and metal chips resulting into improved tool life.

Moreover, HPC can penetrate the vapor barrier, causing the formation of a "hydraulic wedge" which results in cooling and quenching of the metal chips. Plastic deformation would occur, forcing the metal chips to slide over the tool rake face and removed from the workpiece as visualized in Fig. 12.

Yusuf Kaynak et al. [35] performed a study on comparison of flood cooling, MQL, and high-pressure coolant on the machining and surface integrity of titanium alloy. They found that high-pressure coolant was able to provide significant improvement on machining performance such as surface roughness of titanium alloy compared to flooded cooling and MQL. Tamil Alagan et al. [37] investigated the effects of high-pressure cooling in flank and rake faces of WC tools in turning of 718 alloy and showed that at higher pressure coolant delivery improved the tool life and overall machining performances. The study of influence of cutting fluid flow under high-pressure coolant turning using internally cooled cutting insert was performed by Fang and Obikawa [39]. They concluded that the increase of coolant pressure enhanced the resistance against flank wear of the cutting inserts as shown in Fig. 13. Similar results are also

Fig. 8 Mean tool wear and surface roughness with dry, flooded, and MQL methods [31]



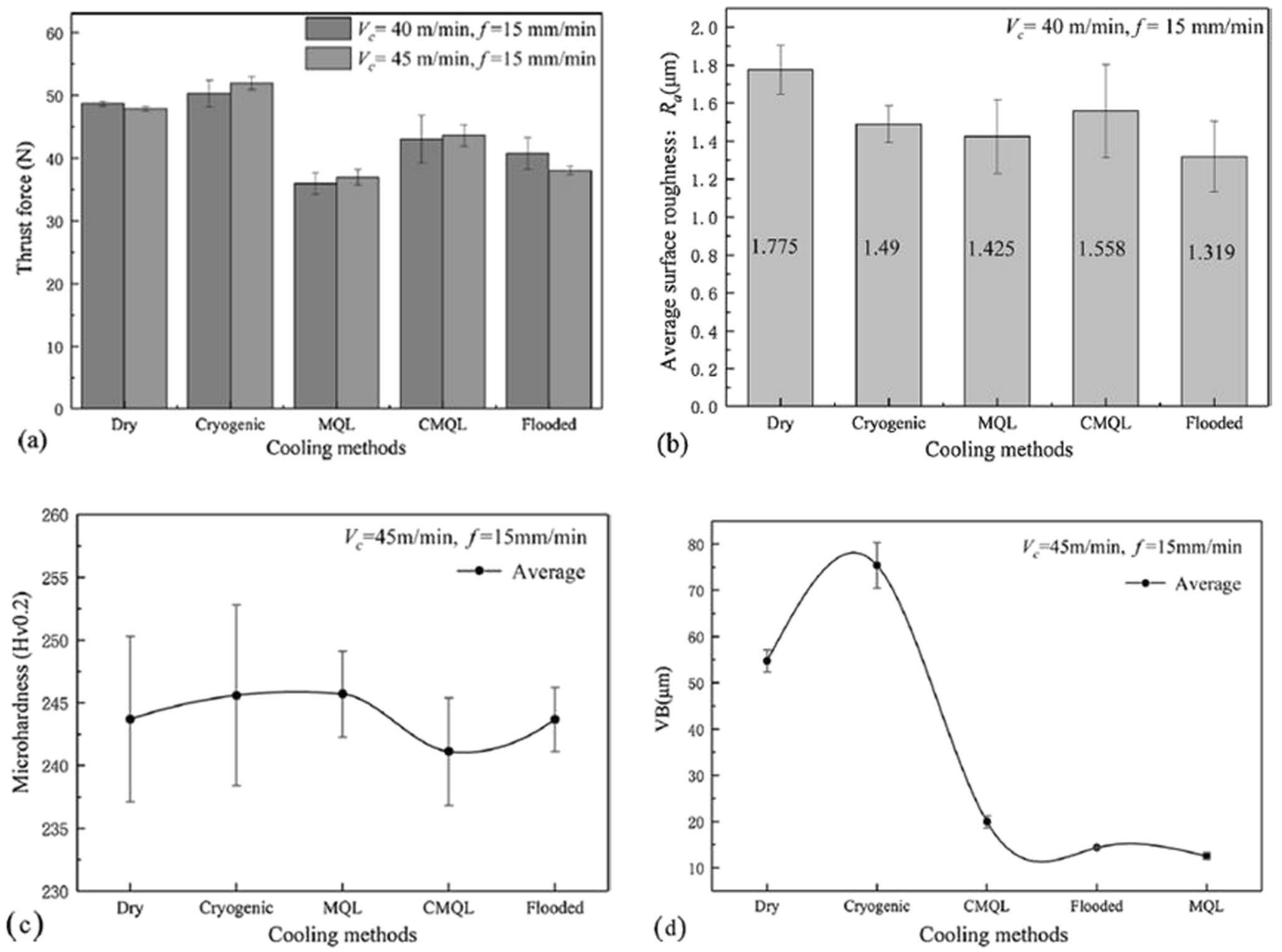


Fig. 9 Machining performance comparison between dry, cryogenic, cryogenic MQL, flooded, and MQL methods for ***a*** thrust force, ***b*** surface roughness, ***c*** microhardness, and ***d*** tool flank wear [33]

observed in terms of surface roughness and tool life even at critical pressure as shown in Fig. 14.

Nasr et al. [40] used high-pressure jet cooling in nickel-based superalloy turning at different level of cutting speeds and feed rates and found that 70 bar of coolant delivery pressure was the optimum pressure to produce best tool life, tool wear, and material removal rates along with selected cutting parameters.

2.4 Machining under solid coolant/lubricant

Solid lubricant is an attempt of lubrication and cooling using solid materials in machining which consisted of organic and inorganic compounds or metal flakes. There are variety of materials with the inherent lubricating capability which can be used as solid lubricant such as molybdenum disulfide (MoS_2), graphite, and polytetrafluoroethylene [41]. Solid lubricant is usually delivered in dry powder form which contains lubricant additives due to the nature of their crystal lattice structures arranged in layers for improvement in terms of friction and minimizing tool wear under extreme machining operations [42–44]. Solid lubricants were able to withstand extreme temperature due to their high chemical inertness and low volatility. Moreover, as shown in Fig. 15, solid lubricant consisting of dry powder contains lamellar structures which are parallel to the direction of the motion causing the lamella layers to shear resulting in lower friction [45].

In related study, machining performance of molybdenum disulfide (MoS_2) nanolubricant during CNC milling operation of aerospace grade aluminum was investigated by Rahmati et al. [46]. They found that using 1 wt% of MoS_2 nanolubricant at a pressure of 4 bar and 30° nozzle orientation resulted in the best machining force, while at 0.5 wt% of MoS_2 nanolubricant at 4 bar of pressure and 60° nozzle orientation yields best surface quality. Zalaznik et al. [47] performed an investigation on the effect of type, size, and concentration of solid lubricants using MoS_2 and tungsten

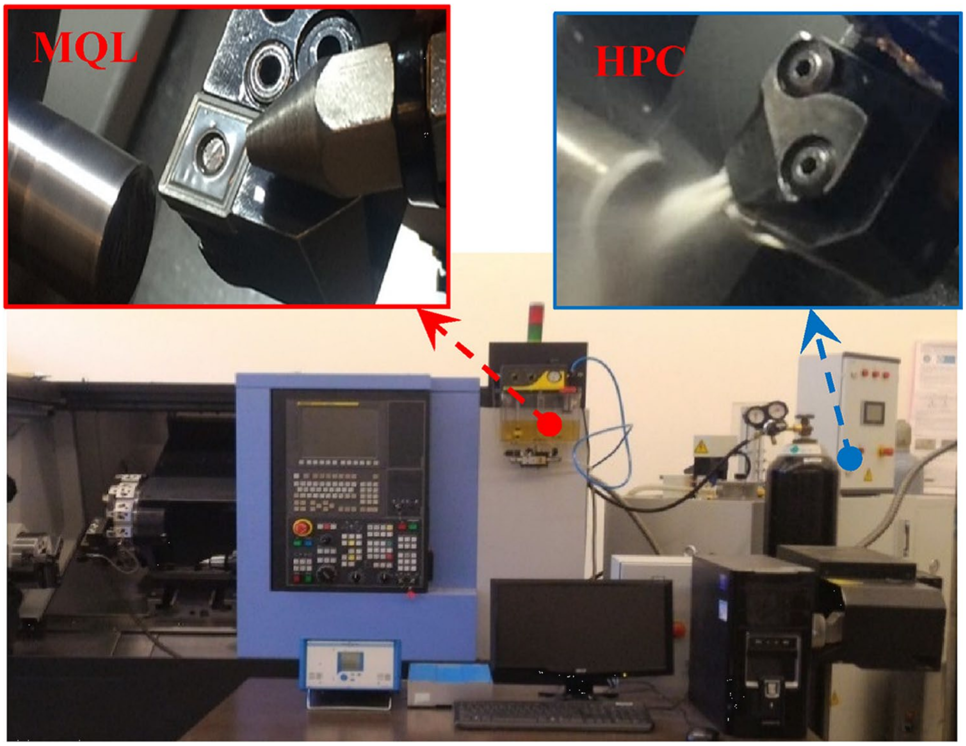


Fig. 10 View of minimum quantity lubrication (MQL) and high-pressure coolant (HPC) coolant supply [35]

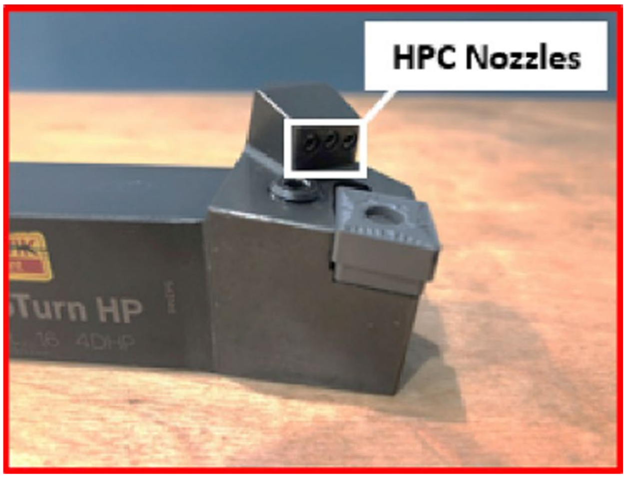


Fig. 11 View of coolant-through cutting tool holder [36]

disulfide (WS_2) on the tribological properties of polymer polyether ether ketone (PEEK). They showed that solid lubricant's microsize was able to reduce the generated friction by up to 30%. However, they also mentioned that higher concentration of nanoscale particles is required to form a low friction tribo-film effectively to reduce the wear of the composites. A comparative performance study of different lubricants conducted by Sterle et al. [48] concluded that MoS_2 outperformed other conventional lubricants. Sartori et al. [49] investigated solid lubricant-assisted MQL and minimum quantity cooling (MQC) strategies to improve the machinability of titanium alloy in turning operation as shown in Fig. 16. They concluded that solid lubricant-assisted MQC was able to provide optimum lubrication and cooling capacities that resulted into reduction in tool wear in terms of flank and crater wears. Moreover, it reduced the overall surface roughness in comparison to dry and flooded machining.

2.5 Machining under cryogenic cooling

Cryogenic coolants as cutting fluids are also gaining interest from machining industries and researchers alike due to eco-friendliness while being recyclable and with no side effects on the machining operators. In cryogenic machining, liquid nitrogen (LN_2), carbon dioxide (CO_2), and compressed air were used for the delivery of the coolants onto tool–chip interface at low temperature of − 196 °C [50]. An example of cryogenic cooling delivery setup is shown in Fig. 17. The utilizations of liquid nitrogen effectively decreased the heat generation between the tool–workpiece interface rapidly while also providing lubrications at the cutting zone [51]. During the cryogenic cooling process, nitrogen evaporates at a rapid rate, therefore leaving no residue of cutting fluids to be disposed. Metal chips produced from the machining process under cryogenic cooling do not contain contaminations of metal-working fluids which allow easy recycling of the scrap metals [5]. Cryogenic cooling improved machinability by reduction of diffusion related tool wear mechanism at low operating temperature. Therefore, proper deployment

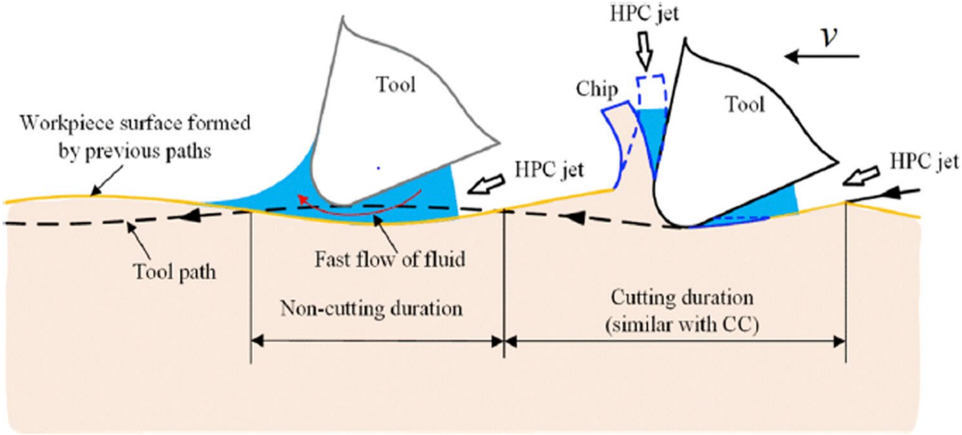


Fig. 12 Visual representation of HPC cooling condition [38]

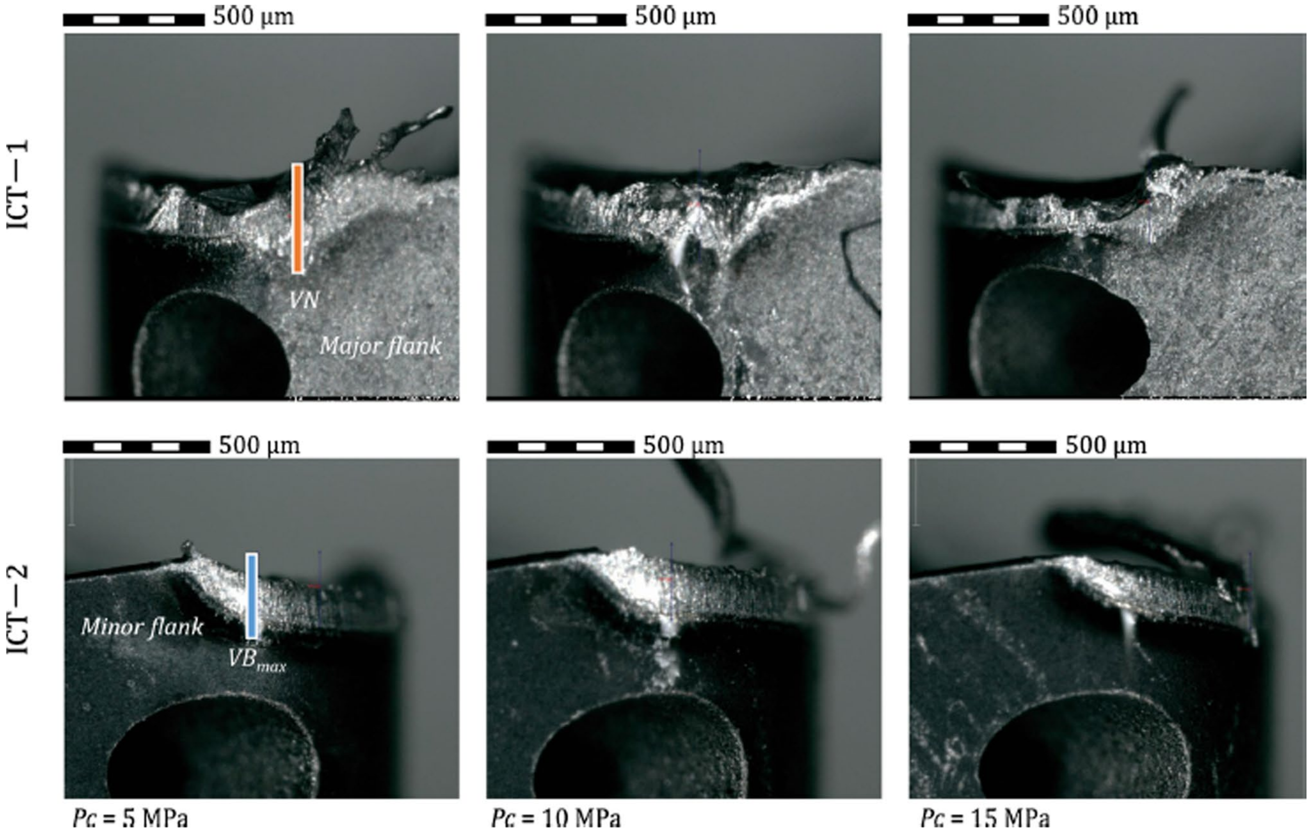


Fig. 13 Tool wear performance of internal cooled tools at various coolant pressure [39]

of cryogenic cooling during any machining process is able to significantly improve machining quality and reduces manufacturing costs.

Many researchers investigated the effectiveness of cryogenic cooling in machining [53–59]. Sivaiah and Chakradhar [60] investigated the effect of cryogenic coolant on turning of 17–4 PH stainless steel and compared the performance of cryogenic coolant to that of MQL, flooded, and dry machining. They found that under cryogenic coolant-assisted machining, the overall machining performance was significantly improved in terms of surface roughness, tool wear, and chip thickness with better health and environmental benefits as shown in Fig. 18.

The characterization of machinability and environmental impact of cryogenic turning of titanium alloy conducted by Damir et al. [61] found that cryogenic coolant performed better than flooded coolant by decreasing 15% cutting forces, and better surface finish and tool life were also obtained.

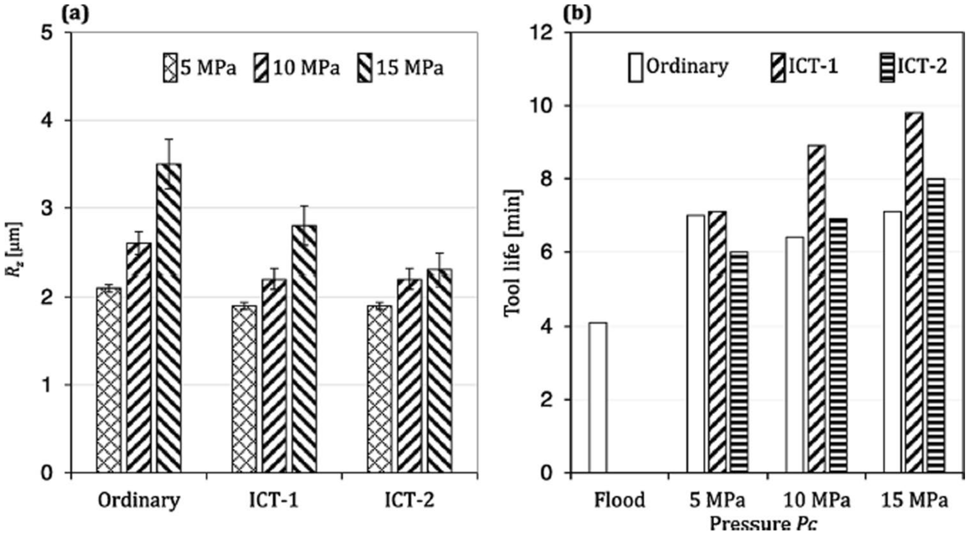


Fig. 14 **a**, **b** Surface roughness and tool life graph of high-pressure coolant-assisted machining [39]

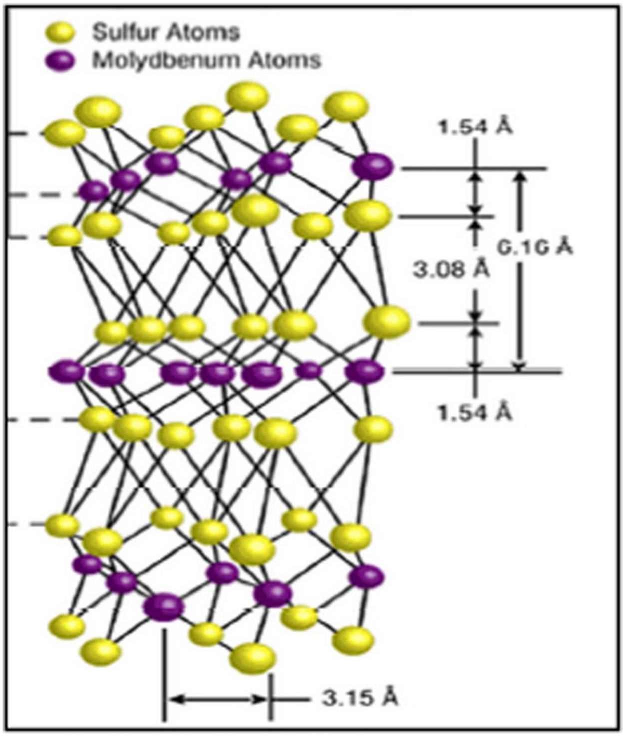


Fig. 15 Structure of molybdenum disulfide (MoS_2) [41]

In recent study, Danish et al. [62] investigated the effect of cryogenic and dry machining on the surface integrity of AZ31C magnesium alloy. The authors concluded that cryogenic-assisted machining was able to produce improved surface finish in comparison to dry machining by margin close to 50% as shown in Fig. 19. Moreover, microhardness of the magnesium alloy was increased drastically to 98.61 HV for cryogenic machining as compared to 76.10 HV produced from dry machining observed in Fig. 20.

Kumar et al. [63] investigated the machinability and surface integrity of Ti/CFRP/Ti hybrid composite laminates under dry and cryogenic conditions. They found from the study that cryogenic condition not only reduced drilling torque by 7–25% but also surface integrity of drilled hole was improved from reduced built-up edge formations. Fernandes et al. [64] investigated the economics of turning operations on AISI D6 steel under dry, wet, and cryogenic conditions using LN_2 at three different flow rates. They found that cryogenic turning of steel effectively enhanced tool life compared to dry and flooded machining under high liquid nitrogen flow rates. However, the machining costs were found to increase as the flow rate increased. Moreover, Stampfer et al. [65] concluded that machining forces and cutting tool temperatures were reduced by using high-pressure cryogenic coolant (nitrogen) supply on orthogonal turning of titanium alloy. Also, the tool wears on internal rake face of the cutting tool were reduced under cryogenic cooling compared to dry cutting. Wang et al. (2020) [66] performed research on hole milling on aramid fiber-reinforced composite (AFRP) under liquid nitrogen-based cryogenic cooling technique. They found that under cryogenic cooling, the cutting force and machining defects during the cutting process on AFRP were significantly improved in comparison to dry milling. Cutting temperature were significantly reduced under cryogenic cooling due to instantaneous heat removal at the cutting zone. The efficiency of chip removal under cryogenic cooling were also enhanced due to high outlet pressure, effectively suppressing erosion milling hole defect.

3 Machining under the MQL technique

Due to high volume of heat and stresses generated during machining process at tool–workpiece interface, cutting fluids are essential not only to remove heat but also to

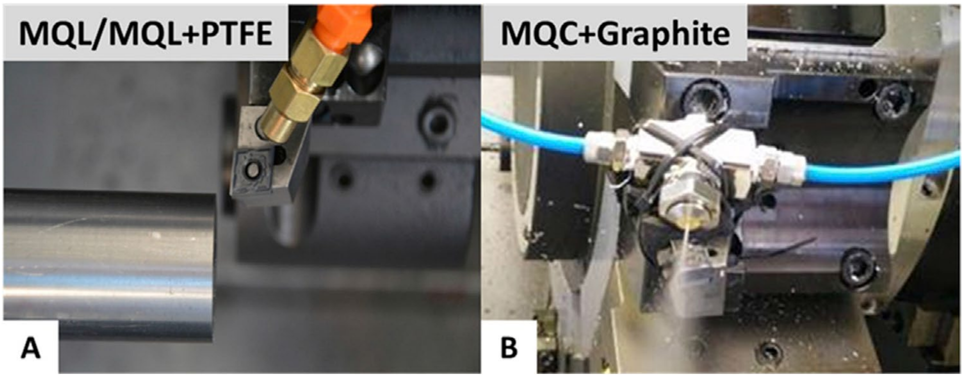


Fig. 16 Solid lubricant delivery setup in **a** MQL + PTFE and **b** MQC + graphite for titanium alloy machining [49]

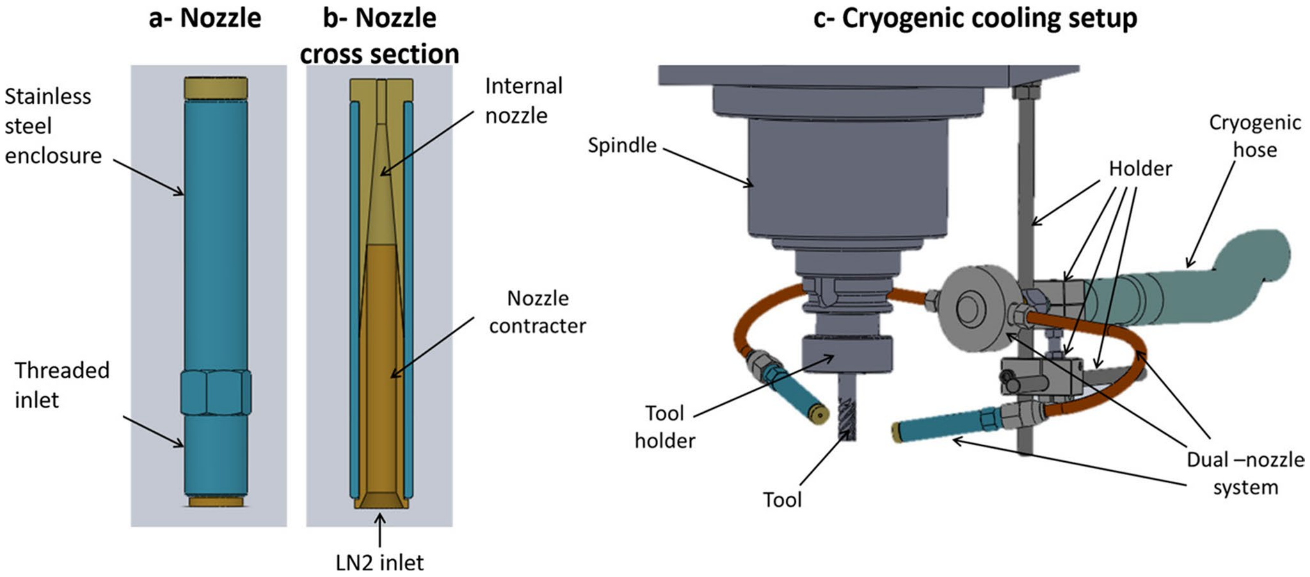
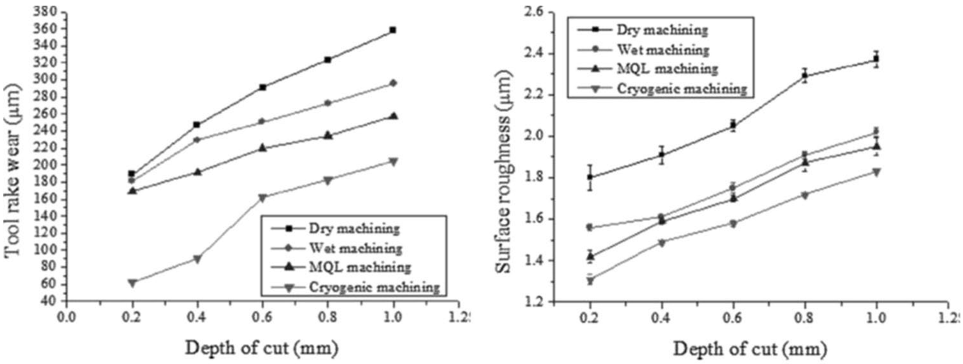


Fig. 17 Cryogenic nozzle layout and cryogenic machining cooling setup [52]



a) b)

Fig. 18 Performance comparison of ***a*** tool rake wear and ***b*** surface roughness under dry, wet, MQL, and cryogenic machining [60]

allow the surface to be lubricated, reducing temperature at tool surface, thus improving tool life and surface finish of the final product [67–73]. Dry machining was the first alternative method in manufacturing which eliminates cutting fluids during machining process. However, due to the lack of coolant or lubrication on the surface of machining tool and workpiece, more friction, heat, and adhesion were generated which results in high level of abrasion, diffusion, and lower surface finish and tool life [74, 75]. Thus, many researchers have been conducting studies on using

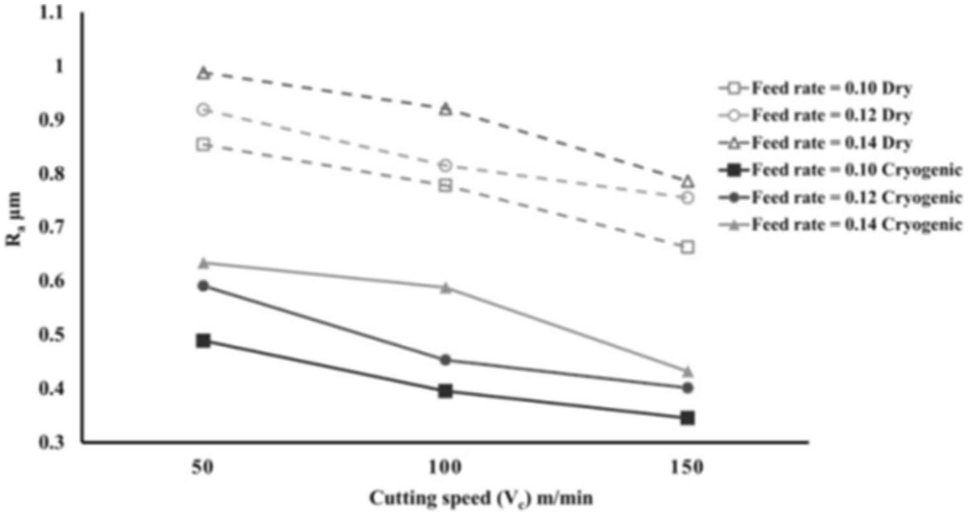


Fig. 19 Cryogenic cooling performance on surface roughness [62]

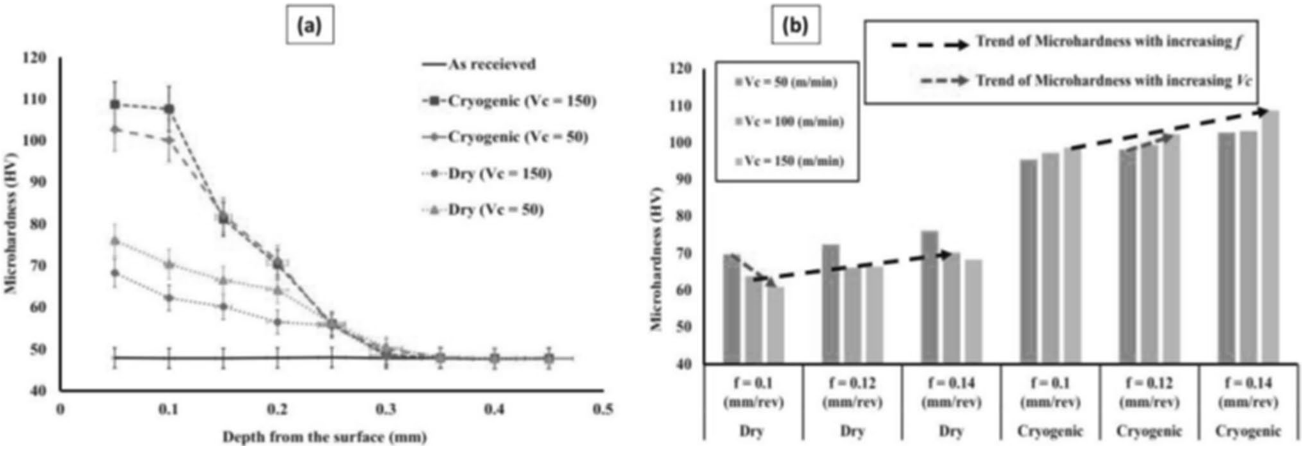


Fig. 20 **a**, **b** Effect of cryogenic and dry machining on microhardness improvement of magnesium alloy [62]

alternative methods of conventional cutting fluids applications such as flooded and minimum quantity lubrication techniques [76,77,78,79,80]. Conventional application of cutting fluids such as flooded machining and dry machining have been questioned for their sustainability in the machining industries which caused numerous environmental issues and health and safety concerns [81–86]. Hence, throughout the years, there are increasing number of studies of MQL fluid delivery method for optimum supply of cutting fluids during machining to effectively reduce manufacturing costs and improve the machinability [87–90]. The MQL cutting fluid delivery technique, which can also be referred as microlubrications or near-dry lubrications, involves significantly reduced lubricant/coolant which are hybrid coolant or water-based coolant delivered from the nozzle of a spray to the cutting zone via compressed air as delivering medium. Cutting fluids are usually sprayed at the cutting zone in mist form which function as both coolant and lubrication at the tool–workpiece interface [7–9]. The reduction of coolant allows for minimizing the total energy consumption and manufacturing costs [91–93].

Machining fluid accounts to about 20% of the total manufacturing cost; therefore, optimum use of cutting fluids became the top priority to maximize the profit in any manufacturing industries [8]. Two types of MQL were identified, namely internal and external mist supply as shown in Fig. 21. External application involves spraying lubricant directed at the tool–workpiece interface which requires manual adjustment of spray nozzle angle and positions. However, internal application requires specialized tool pieces that allows lubricant to be delivered through the cutting tool itself via internal through channels integrated in the tool [91].

Internal MQL application during drilling process can improve the chip removal efficiency for conventional mass production applications [94]. A comparative study between internal spray cooling and conventional external cooling in the drilling of Inconel 718 was conducted by Qin et al. [95]. They found that internal spray cooling

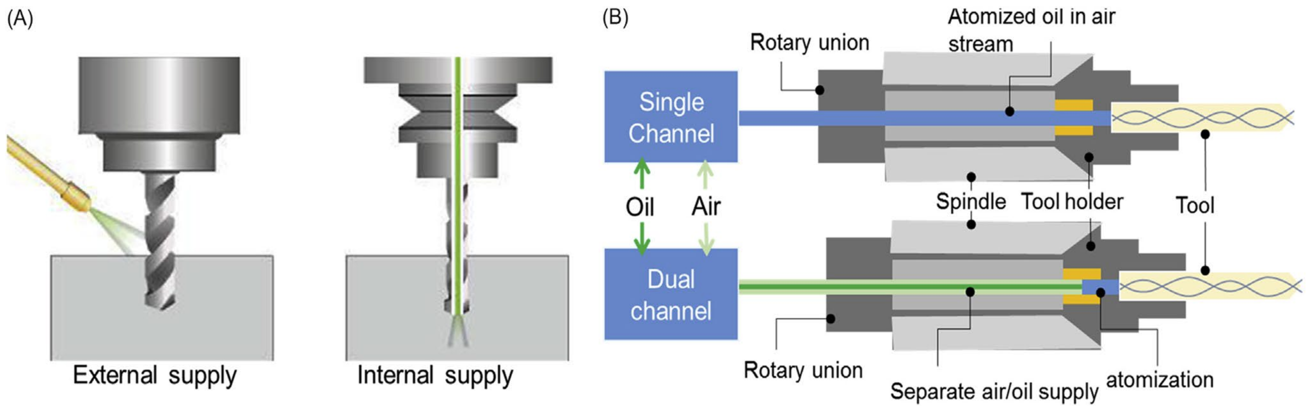


Fig. 21 **a**, **b** External and internal supply of MQL configurations for drilling [91]

is able to significantly reduce thrust force and improve tool life by two times over conventional external cooling. As a result, more stable surface roughness and accuracy of hole diameter were achieved. The MQL technique evolved and improved throughout the years of studies. These includes but not limited to usages of cutting fluids, search of optimum machining parameters suitable for the MQL method in various types of machining, and the suitability of MQL techniques in different types of metals and alloys which are presented in Figs. 22, 23, and 24.

3.1 MQL machining on steel

Steel has been the most popular metal used in industries for decades. Thus, MQL techniques has been widely applied in machining of steel for manufacturing and research. A summary of the MQL machining of steel under different machining operation is presented in Table 1.

Many researchers (Choudhury and Dhar [106], Dhar et al. [96], Saha et al. [107], Uysal et al. [108], Garcia et al. [68], and Gupta et al. [109]) conducted experimental studies and concluded that the application of MQL in machining of steel were able to improve final surface roughness effectively. Dhar et al. [53] investigated the

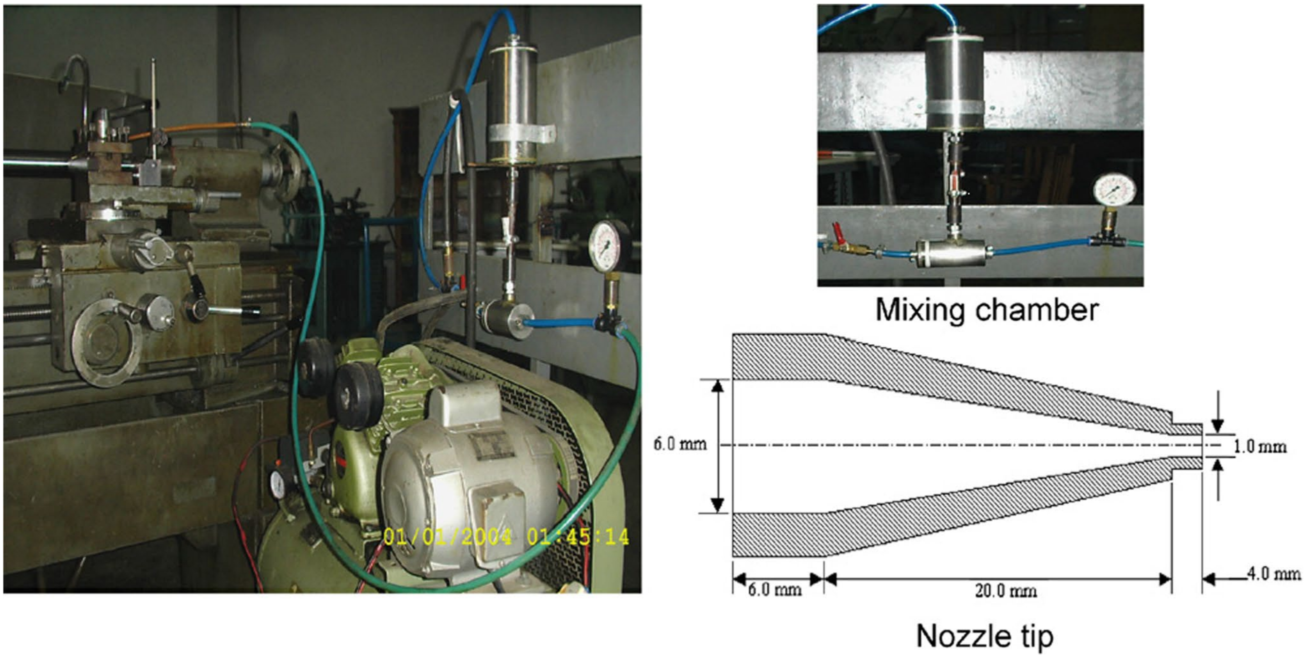


Fig. 22 View of the MQL experimental setup [96]

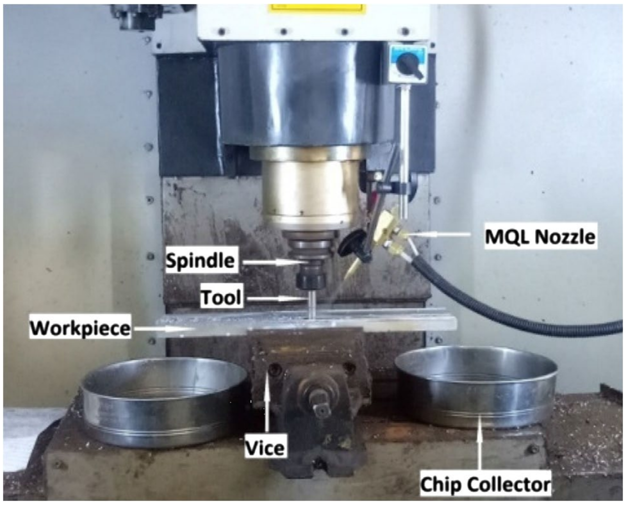


Fig. 23 External MQL delivery setup for milling [97]

influence of MQL on the cutting temperature, chip formation, and dimensional accuracy in turning of AISI-1040 steel. They concluded that the cutting performance of the MQL method surpassed the flooded cutting fluid delivery method. MQL was able to reduce cutting temperature and improve dimensional accuracy significantly due to the reduction of tool wear and improved lubrications at tool–workpiece interface. Kedare et al. [110] concluded that the MQL technique was preferred as an ideal replacement of dry machining to reduce negative aspects of cutting fluids and significantly improve overall cutting performances. Chinchanikar and Choudhury [99] demonstrated that lower cutting temperature improved tool life and better surface roughness were achieved under MQL techniques. Moreover, the study conducted by Vishnu et al. [12] on machining of EN 353 steel alloys using dry, flooded, and MQL conditions showed that there were minor differences in machining performances. They also mentioned that the MQL condition was the best choice of cutting fluid delivery. Tomaz et al. [103] studied the influence of MQL in the surface quality, machining forces, and residual stress of milled maraging 300 steels compared to flooded cooling under various cutting speeds, depth of cuts, and feed rates. MQL methods were found to reduce surface roughness by 10% in comparison to the flooded method while resultant force and residual stress generated by both methods were similar. Thus, the authors concluded that MQL applications were considered more economical and environmentally advantageous in the milling of maraging 300 alloy over flooded machining. Naresh Babu et al. [100] reported that AISI 304 steel end milling using MQL was able to reduce tool wear and surface roughness by 70% and 66% respectively compared to dry and flood lubrication as shown in Fig. 25.

Furthermore, Lai et al. [111] investigated the adaptability of AlTiN-based tool coating in machining of 316L stainless steel and concluded that near-dry cutting technologies like MQL techniques had great potentials to sustainable manufacturing for producing good surface finish and reducing the production cost. Özbek and Saruhan [70] studied the surface roughness and tool wear during eco-friendly MQL turning of AISI D2 steel under the effect of vibration and cutting zone temperature. The authors showed that the eco-friendly MQL system was superior to dry machining by improving 89% of surface roughness and 267% of tool wear. Mishra et al. [104] conducted a case study on the surface quality characteristic of MQL machining of high tensile steel. Experimental results showed that measured surface roughness values were under 1 µm which were lower than the standard surface roughness criteria of 1.6 µm. Praveen et al. [105] experimentally found that MQL cutting fluid delivery was able to reduce surface roughness by 48.35% in comparison to dry machining during the machining of EN 47 chromium–vanadium steel materials at different level of cutting parameters as shown in Fig. 26.

Muaz and Choudhury [102] investigated solid lubricant-assisted cutting fluids applied under MQL for AISI 4340 steel machining using TiCN/Al2O3/TiN chemical vapor deposition-coated tungsten carbide inserts during flat end milling process. They concluded that using recommended low viscosity cutting fluids under MQL led to environmentally and economically sound manufacturing. Bonfa et al. [101] studied the surface roughness of machined AISI D6 hardened steel and tool life of PCBN tools under MQL cooling. Vegetable-based MQL coolant were delivered at different location of cutting tools, namely the main and secondary tool flank faces and overhead of the cutting insert. When compared with dry turning, it was found that the MQL method provided better cooling and lubrications during machining, subsequently reducing surface roughness of AISI D6 steel and improving the tool life.

3.2 Machining aluminum under MQL

The MQL technique is not necessarily only applied on steel machining but also applied in other common metal machining such as aluminum. Table 2 shows the summary of the machining parameters for aluminum machining under the MQL method.

Sreejith [112] investigated machining of 6061 aluminum alloy under dry, flooded, and MQL conditions and concluded that MQL is the preferable choice for a coolant delivery method. Investigation of deep hole drilling on aluminum cast alloy using twist drill under MQL was performed by Biermann et al. [113]. The author concluded that MQL techniques was able to improve overall machining performance of aluminum alloy. Chatha et al. [114] concluded in

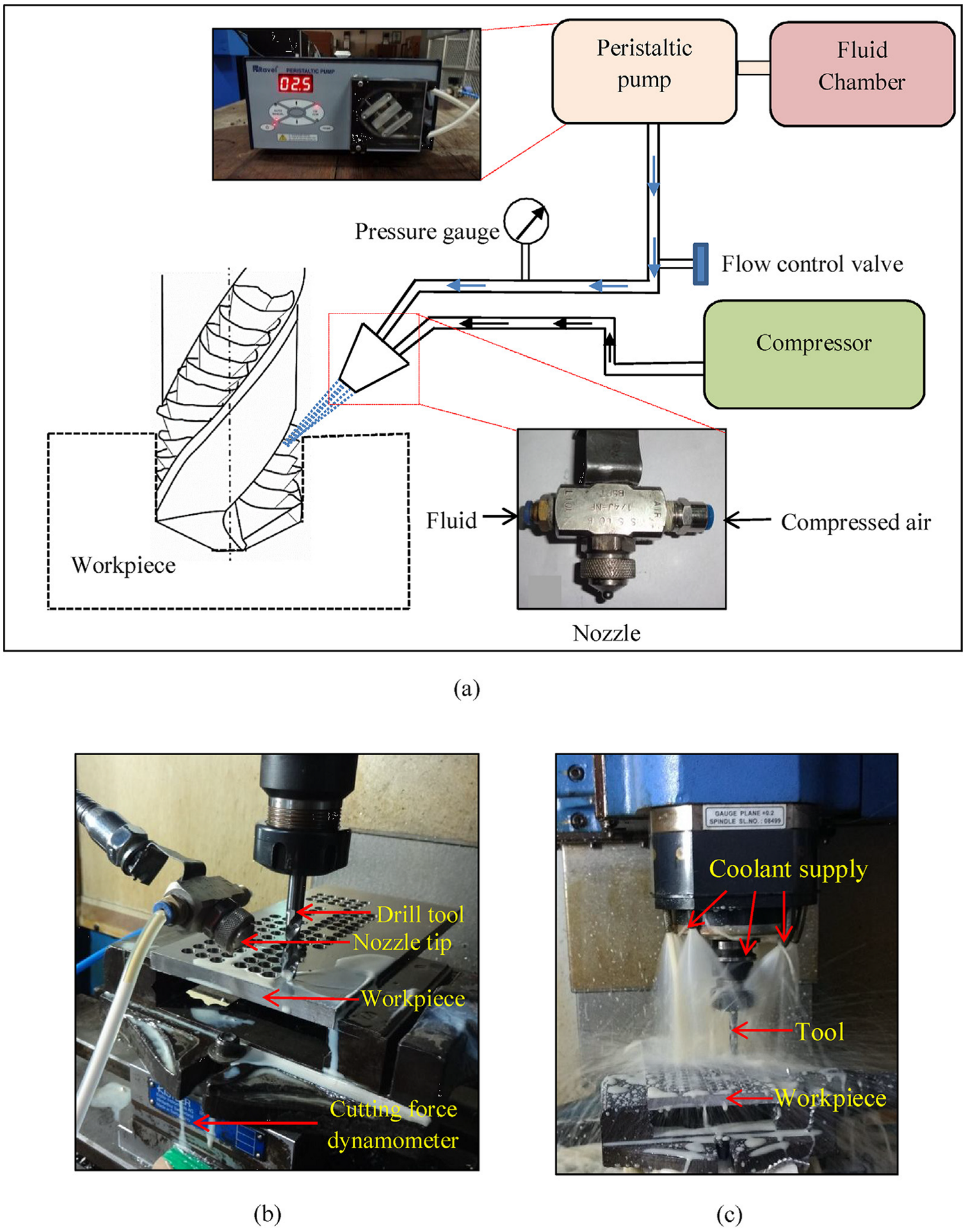
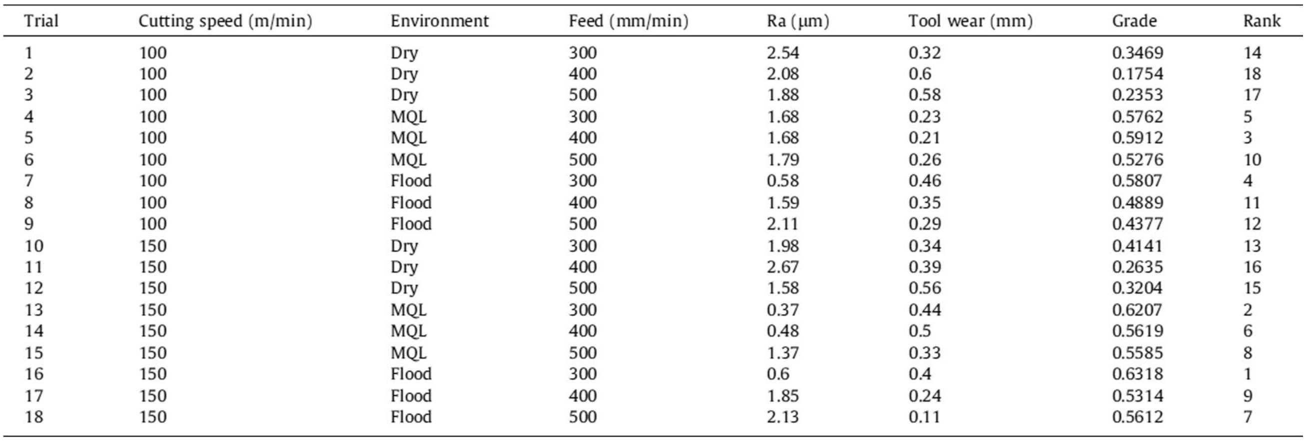


Fig. 24 **a**–**c** The drilling process under MQL and flooded cooling [98]

their performance evaluation on aluminum drilling under the influence of MQL where the nanofluid MQL technique showed best results in terms of surface roughness, cutting forces, and tool wear compared to dry and flooded machining. Sumaiya Islam et al. [115] carried out experimental studies on the development of low-cost MQL setup for the turning operations of aluminum alloy 6061. Different variations of depth of cut and cutting speed along with cutting environments such as dry, flooded, and MQL conditions were used to evaluate the cutting performance of each parameter. The authors concluded that the performance of the MQL technique provided lower surface roughness and tool wear values at lower cutting temperature due to the improvement of lubrication penetration and chip flushing. The MQL technique was also able to reduce the formation of built-up edges (BUE) and decreased chip thickness as compared to wet and dry machining. Shukla et al. [97] conducted experiments to study the characterization of vegetable oil as lubricant on CNC milling of aluminum 6061 under dry, flood, and MQL cutting fluid delivery methods. In the research, they found that surface roughness and tool wear were significantly improved under MQL-assisted cooling techniques on aluminum milling at lower cutting speeds. Another study completed by Zhu et al. [117] investigated the temperature distribution on the tools during MQL-assisted aluminum drilling using different cutting parameters. The study showed that the MQL coolant delivery system was able to better reduce cutting temperature when compared to

Table 1 Process parameters used during steel MQL machining using various machining operations

Ref	Material	Machining process	Lubrication	Cutting speed (m/min)	Feed (mm/min)	Depth of cut (mm)	Responses
[53] (2006)	C60 steel	Turning	MQL	110	0.20	2.0	Surface roughness, tool wear
[99] (2014)	AISI 4340 steel	Turning	MQL	100, 125, 150	0.088	0.3	Tool wear, tool life
[98 (2014)	15 HRC mild steel	Milling	MQL	160, 225, 300	–	0.1, 0.2, 0.3	Surface roughness, machining temperature
[12] (2018)	EN 353 steel	Turning	MQL	73.3, 115.19, 157.08	0.2, 0.5, 0.8	0.5, 1.5, 2.5	Cutting temperature
[100] (2019)	AISI 304 steel	Turning	MQL	100, 150	300, 400, 500	n/a	Surface roughness, tool wear, chip morphology
[101] (2019)	AISI D6 steel	Turning	MQL	160, 190, 250, 310, 340	0.05, 0.10, 0.15, 0.20, 0.25	0.05	Tool life, tool wear mechanisms, surface roughness
[102] (2019)	AISI 4340 steel	Milling	MQL	251.37, 376.99	0.05, 0.066	0.5	Surface roughness, resultant force
[103] (2019)	300 steel	Milling	MQL	100, 200	0.02, 0.1	1.0, 2.0	Machining force, surface roughness
[104] (2020)	EN24 steel	Turning	MQL	80, 160, 240	0.04, 0.08, 0.12	0.2, 0.3, 0.4	Surface roughness
[105] (2021)	EN47 steel	Turning	MQL	256, 399, 625	0.10, 0.15, 0.20,	0.1, 0.15, 0.2	Surface roughness



Trial	Cutting speed (m/min)	Environment	Feed (mm/min)	Ra (µm)	Tool wear (mm)	Grade	Rank
1	100	Dry	300	2.54	0.32	0.3469	14
2	100	Dry	400	2.08	0.6	0.1754	18
3	100	Dry	500	1.88	0.58	0.2353	17
4	100	MQL	300	1.68	0.23	0.5762	5
5	100	MQL	400	1.68	0.21	0.5912	3
6	100	MQL	500	1.79	0.26	0.5276	10
7	100	Flood	300	0.58	0.46	0.5807	4
8	100	Flood	400	1.59	0.35	0.4889	11
9	100	Flood	500	2.11	0.29	0.4377	12
10	150	Dry	300	1.98	0.34	0.4141	13
11	150	Dry	400	2.67	0.39	0.2635	16
12	150	Dry	500	1.58	0.56	0.3204	15
13	150	MQL	300	0.37	0.44	0.6207	2
14	150	MQL	400	0.48	0.5	0.5619	6
15	150	MQL	500	1.37	0.33	0.5585	8
16	150	Flood	300	0.6	0.4	0.6318	1
17	150	Flood	400	1.85	0.24	0.5314	9
18	150	Flood	500	2.13	0.11	0.5612	7

Fig. 25 Taguchi experimental design for L18 array [100]

dry and air-cooling conditions. Kannan et al. [116] reported that the MQL techniques improved cutting forces, surface roughness, and tool wears in comparison to dry and flooded machining in turning of unreinforced aluminum alloy as shown in Figs. 27, 28, and 29.

Abas et al. [118] studied the optimization of machining parameters such as depth of cut, feed rate, cutting speed, and positive rake angle which affect surface roughness, tool life, and material removal rate of aluminum alloy under MQL-assisted turning process. They found that MQL was more efficient in comparison to dry machining in terms of better surface finish and longer tool life. Cagan et al. [119] investigated the surface roughness and chip morphology of aluminum alloy in dry and MQL machining. They found from their experimental results that the surface quality was improved by 15% under MQL conditions in comparison to dry machining as shown in Fig. 30, and MQL techniques were more environmentally friendly and provided better machining quality than dry machining.

In a more recent study, Javidikia et al. [120] reported the effect of turning environments and machining parameters on the surface finish of aluminum alloy at low-speed and

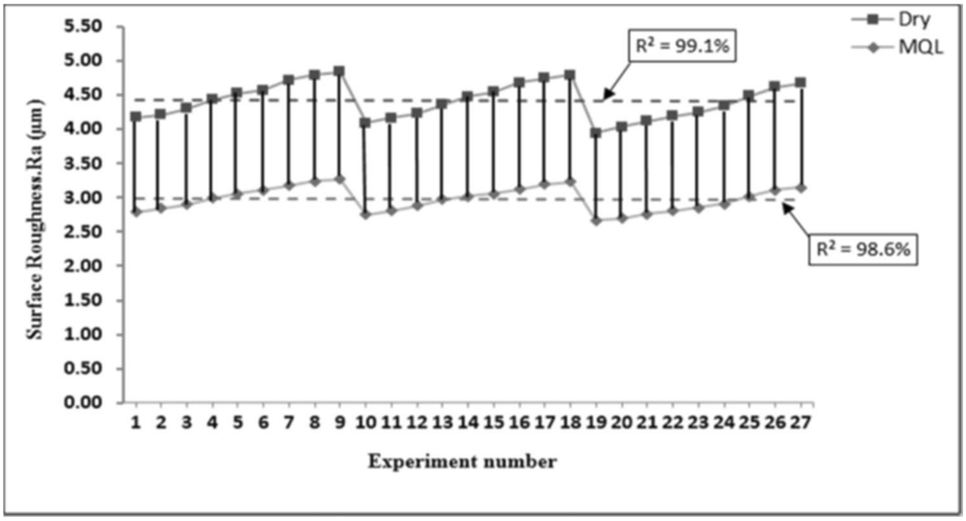


Fig. 26 Improved surface roughness comparison of dry machining and MQL [105]

Table 2 Process parameters used during MQL machining of aluminum

Ref	Material	Machining process	Lubrication	Cutting speed (m/min)	Feed rate (mm/min)	Depth of cut (mm)	Responses
[112] (2008)	6061 aluminum	Turning	MQL	400	0.15	1.0	Surface roughness, tool wear, cutting force
[113] (2012)	EN AC46000 aluminum	Drilling	MQL	140, 170, 200	0.1, 0.2, 0.3	250	Machining temperature
[114] (2016)	6063 aluminum	Drilling	MQL	30, 53.7	60	20	Drilling thrust force, drilling torque, surface roughness, tool wear
[115] (2017)	6061 aluminum	Turning	MQL	300, 420, 700	0.15	1.0, 1.5	Surface roughness, tool wear
[97] (2020)	6061 aluminum	Drilling	MQL	100, 200, 300	0.045, 0.0675, 0.09	0.5, 1.0, 1.5	Surface roughness, tool wear
[116] (2020)	7075 aluminum	Turning	MQL	150, 250	0.1, 0.2, 0.3	n/a	Cutting force, surface roughness, tool wear
[117] (2020)	AA2024 aluminum	Drilling	MQL	60, 80, 100, 120	0.2, 0.3, 0.4, 0.5	n/a	Drilling thrust force, drilling torque, machining temperature, tool wear
[118] (2020)	6026 aluminum	Turning	MQL	400, 500, 600, 700	0.3, 0.4, 0.5, 0.6	1.0, 1.5, 2.0, 2.5	Surface roughness, tool life, material removal rate
[119] (2020)	AL7075-T6 aluminum	Turning	MQL	400, 450, 500	0.1	1	Surface roughness, chip morphology
[120] (2020)	6061-T6 aluminum	Turning	MQL	145, 350, 650, 950, 1155	0.07, 0.12, 0.19, 0.26, 0.31	0.66, 1.0, 1.5, 2.0, 2.34	Surface roughness, residual stress,

high-speed turning. The machining was carried out under dry, wet, and minimum quantity lubrication environments combined with various cutting speed, feed rate, and depth of cut. They found that changing of cutting speeds and feed rates had significant effects in MQL turning environments especially at high cutting speed. The MQL cooling

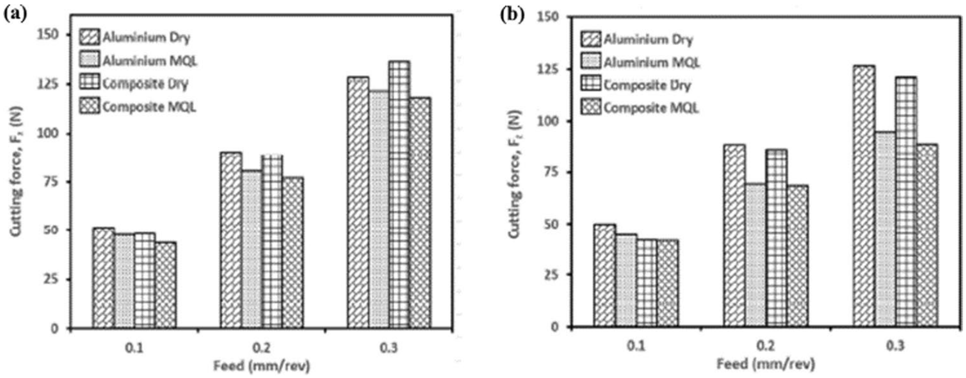


Fig. 27 Cutting force comparison between dry and MQL-assisted aluminum alloy turning at cutting speed of 150 m/min (***a***) and 250 m/min (***b***) [116]

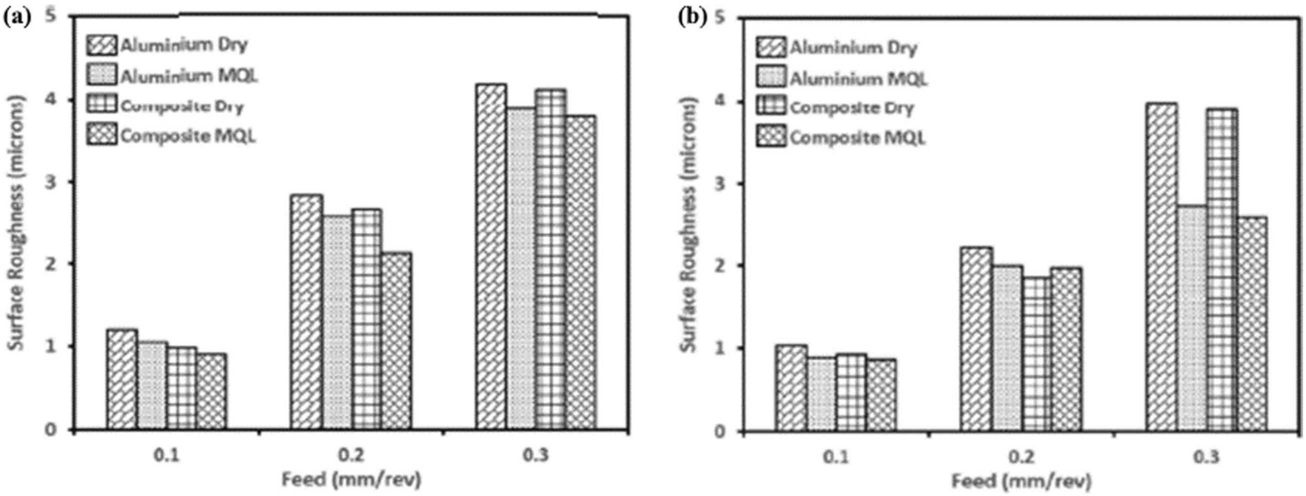


Fig. 28 Surface roughness comparison between dry and MQL-assisted aluminum alloy turning at cutting speed of 150 m/min (***a***) and 250 m/min (***b***) [116]

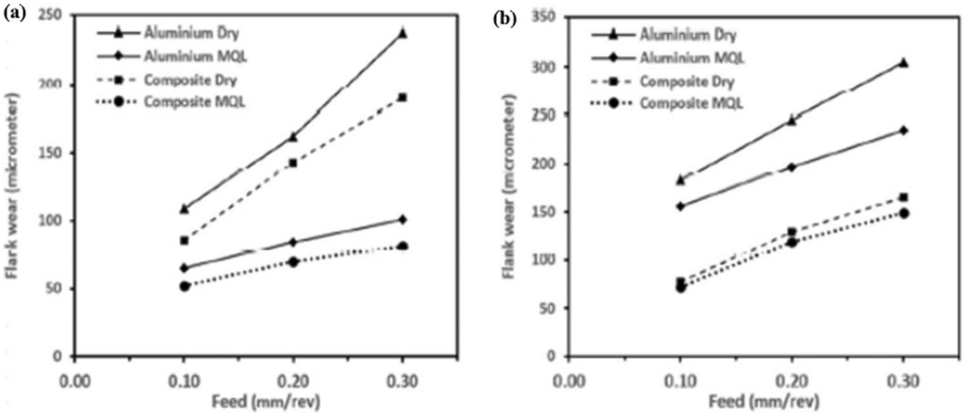
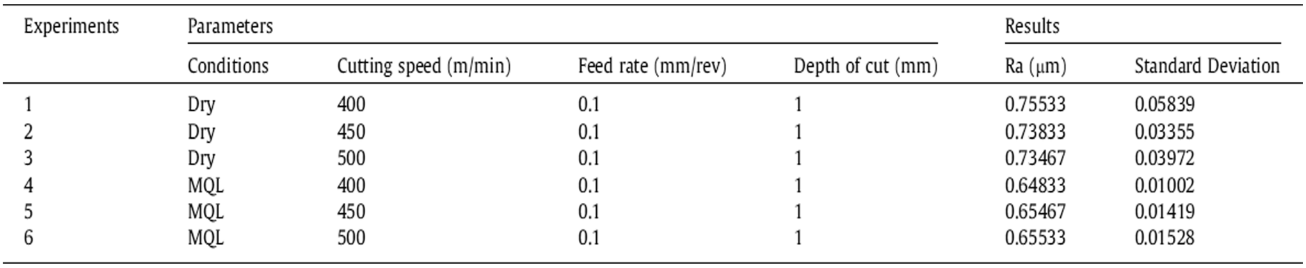


Fig. 29 Tool flank wear comparison between dry and MQL-assisted aluminum alloy turning at cutting speed of 150 m/min (***a***) and 250 m/min (***b***) [116]

method also produced lower surface roughness value on the aluminum workpieces; thus, it is recommended as the most eco-friendly cooling methods in machining.

3.3 MQL machining on alloys and hybrid composites

The MQL technique is also applicable in the case of metal alloys which has prompted several researches summarized in Table 3 over the years by various authors [123, 130–134].



Experiments	Parameters				Results	
	Conditions	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Ra (μm)	Standard Deviation
1	Dry	400	0.1	1	0.75533	0.05839
2	Dry	450	0.1	1	0.73833	0.03355
3	Dry	500	0.1	1	0.73467	0.03972
4	MQL	400	0.1	1	0.64833	0.01002
5	MQL	450	0.1	1	0.65467	0.01419
6	MQL	500	0.1	1	0.65533	0.01528

Fig. 30 Surface roughness performance of dry and MQL-assisted aluminum alloy machining [119]

Table 3 Process parameters used during MQL machining of alloys using various operations

Ref	Material	Machining process	Lubrication	Cutting speed (m/min)	Feed rate (mm/min)	Depth of cut (mm)	Responses
[121] (2002)	A356 alloy	Drilling	MQL	300	0.1, 0.2	–	Tool wear, cutting forces, power consumption, surface roughness
[122] (2009)	AISI 9310 alloy	Turning	MQL	223, 246, 348, 483	0.10, 0.13, 0.16, 0.18	1.0	Chip formation, tool wear, surface roughness
[123] (2018)	Incoloy 800	Turning	MQL	40, 50, 60	0.033, 0.066, 0.132	0.50, 0.75, 1.0	Surface roughness, tool wear
[124] (2018)	Inconel 718 alloy	Turning	MQL	40, 50, 60	0.08, 0.125, 0.16	0.3	Cutting force, tool wear, surface roughness
[125] (2020)	Inconel 718 alloy	Milling	MQL	25.1	0.05	0.4	Surface roughness
[126] (2020)	CFRP	Drilling	MQL	90	0.2-8	1.0, 4.0, 7.0, 12.0	Drilling thrust force, drilling torque, delamination, hole diameter1
[127] (2020)	Inconel 625 alloy	Turning	MQL	50, 75, 100	0.12	0.5	Tool wear, machining temperature, surface roughness, chip morphology
[128] (2020)	TC4 alloy	Milling	MQL	600, 1200, 1800, 2400	n/a	0.2	Cutting force, surface roughness, surface topography
[129] (2020)	Inconel 718 alloy	Milling	MQL	65, 80, 95	0.1, 0.15, 0.20	0.4	Surface roughness, surface topography, microhardness, residual stress

Braga et al. [121] studied the use of diamond-coated tools on drilling of aluminum–silicon alloy (A356) with MQL and flooded cooling techniques. It was concluded that MQL produced better performance in terms of surface roughness and tool life. Khan et al. [122] concluded in their experiment of the MQL lubrication technique on AISI 9310 alloy steel turning where MQL improved overall machinability, decreased cutting temperature, reduced tool flank wear which results in better tool life, and provided better end surface finishes compared to dry and flooded machining. Moreover, Gutnichenko et al. [124] studied the effect of MQL-assisted machining performance on Alloy 718 turning. They noticed effective improvement in tool life, surface finish, and machining stability under MQL machining. Joshi et al. [123]

conducted experiment involving performance comparison of dry, flooded, and MQL turning operations on Incoloy 800. The results showed in Fig. 31 that in MQL cooling condition provided minimal surface roughness value and noticeable gain in tool life of the uncoated tungsten carbide tool.

Moreover, Nagaraj et al. [126] established that the MQL technique was considered as an alternative cooling delivery method for process performance in carbon fiber-reinforced polymer (CFRP) drilling besides dry and cryogenic environments. They concluded in the study that the MQL method was able to reduce the delamination factor at the drilled hole entrance and exit while producing higher accuracy hole diameter compared to dry machining. Yıldırım et al. [127] compared the performance of MQL, cryogenic cooling, and cryoMQL cooling on tool life, surface roughness, and chip morphology of nickel-based 625 alloy machining as shown in Fig. 32. It revealed that the significant reduction of surface roughness, cutting temperature, and tool degradation were recorded in the experiment performed under cryoMQL.

Ni and Zhu [128] investigated the machining characteristic of TC4 alloy under ultrasonic vibration-assisted milling (UVAM) and economical–environmental MQL technology. The results showed that UVAM-MQL produced improved surface roughness by 10 to 30% and reduction of cutting force by 30 to 55% as compared to UVAM. De Oliveira et al. [125] also studied the influence of cutting fluid applications under dry and pulsed MQL delivery on the surface quality of micromilled slots on Inconel 718 alloys. Conclusions were made where surface roughness was significantly improved from MQL coolant delivery compared to dry machining by approximately 60% which is shown in Fig. 33.

Zahoor et al. [129] studied the sustainability assessment of cutting fluids under dry, flooded, and MQL cooling approaches through comparative surface integrity evaluation of Inconel 718 milling. Dry milling, mineral oil-based flooded lubrication, and synthetic vegetable ester biodegradable oil-flooded lubrication were deployed to find their impacts on surface roughness, surface topography, residual stress, microhardness, and microstructures. They concluded that the biodegradable oil-based MQL approach on nickel-based alloys had improvements in surface integrity and microhardness over dry milling and mineral oil-based milling.

3.4 MQL machining of titanium alloys

In recent years, researchers had been investigating the applications of MQL machining in titanium alloys to reduce cost, usage of coolant, and sustainability of the method [135–137]. Table 4 shows the summary of recent journals published regarding the usage of the MQL cooling technique in the machining of titanium alloys.

A study on microdrilling performance with dry, wet, and MQL cutting fluid delivery methods was performed by Davis et al. [138]. They found in their research that ionic liquid-based MQL successfully improved tool life by 60% when compared to dry machining during commercially available grade 2 pure titanium turning. Qin et al. [140] found that MQL was able to improve tool life by up to 88% while obtaining low cutting temperature and good surface finish during turning of TC11 titanium alloy as shown in Fig. 34. MQL was opted for less cutting fluid utilization while still being able to perform similarly to flood cooling.

Venkata Ramana [139] performed a study on the effect of cutting parameters on the surface roughness during titanium alloy turning under dry, flooded, and MQL conditions. It was concluded that MQL showed superior results in terms of cutting performance when compared to dry and flooded machining conditions. In another study, Niketh et al. [98] concluded that the cutting thrust force was reduced effectively by 15–19% in MQL machining as compared to flooded machining. Both MQL and flood machining allowed the reduction in tool–workpiece contact length and chip removal and improved the lubrication effect at the cutting

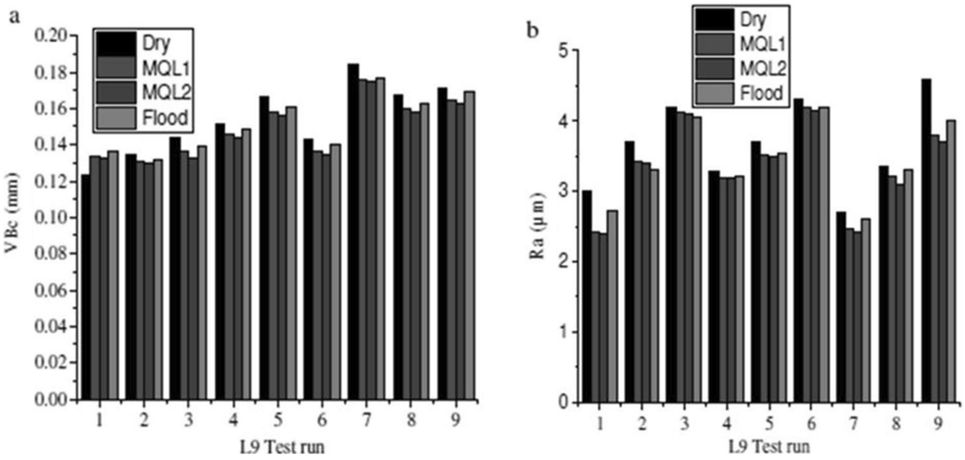


Fig. 31 **a, b** Surface Roughness and Tool Wear Performance of Dry, Flooded and MQL Cooling Turning Operation on Incoloy 800 [123]

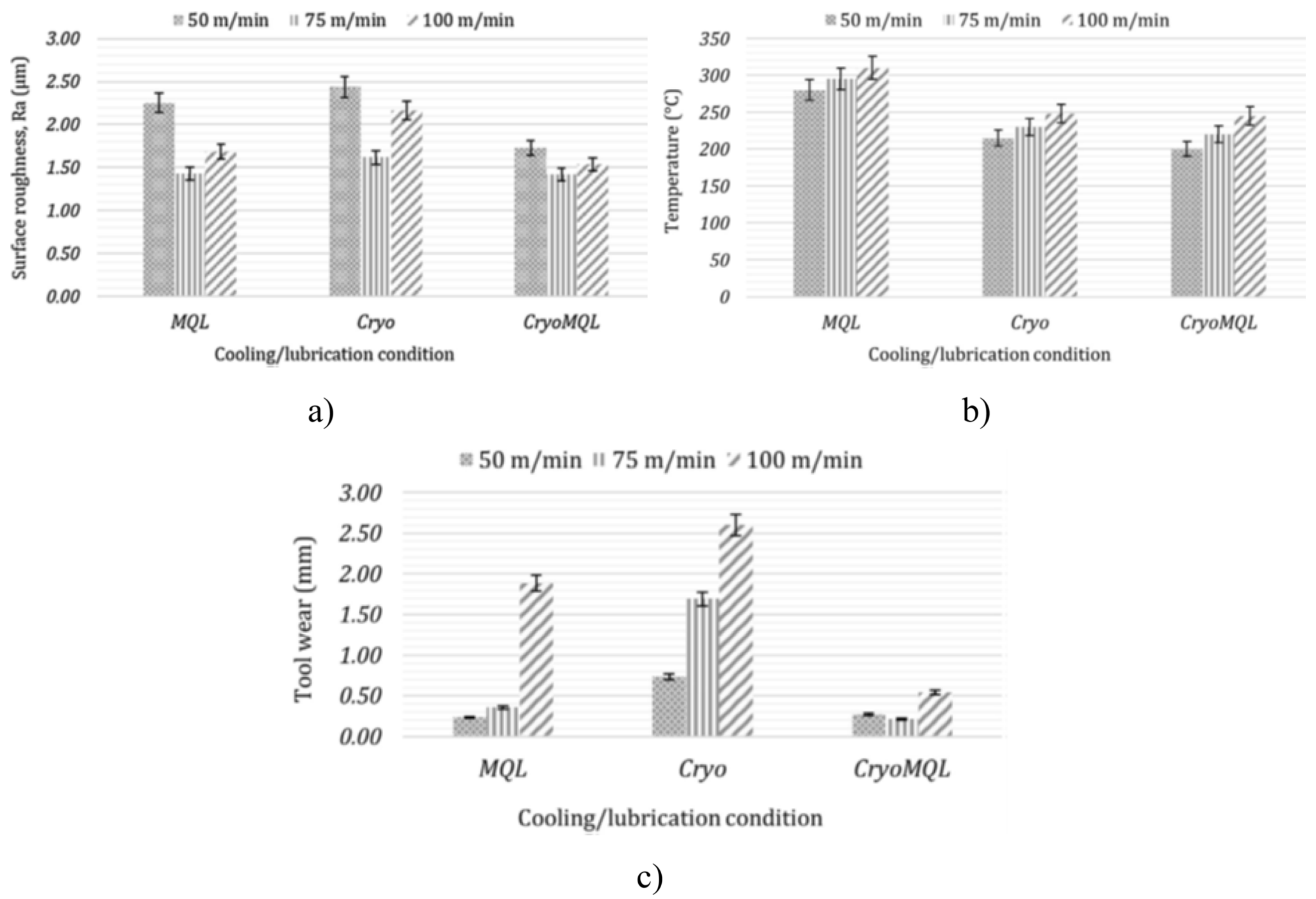


Fig. 32 Machining performance comparison between MQL, cryo, and cryoMQL for ***a*** surface roughness, ***b*** cutting temperature, and ***c*** tool wear [127]

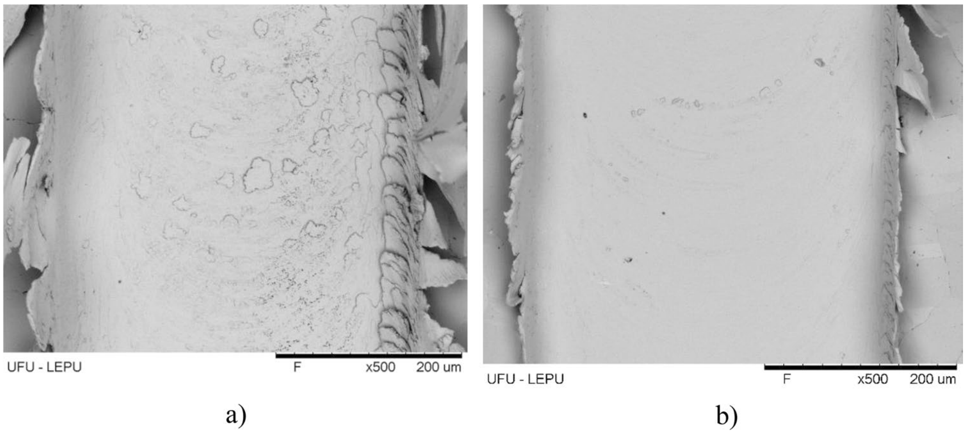


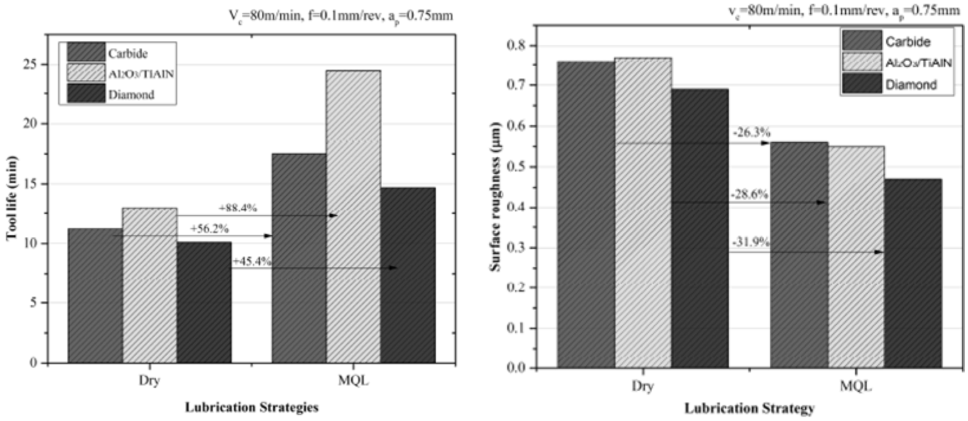
Fig. 33 Surface integrity of micromilled slots on Inconel 718 under ***a*** dry machining and ***b*** MQL coolant [125]

area. However, MQL was opted where energy consumption in terms of cutting fluids was minimized and sustainable machining is achieved. Moreover, Sartori et al. [49] concluded that solid lubricant-assisted MQL machining were able to effectively reduce crater wear and nose wear of cutting inserts and best surface roughness were achieved as shown in Fig. 35.

Khatri and Jahan [141] investigated the effect of dry, flood, and MQL conditions on tool wear in machining of titanium alloy and stated that MQL performed the best in terms of tool wear. A study by Shokrani et al. [52] on end milling machining of grade 5 titanium alloy using flooded, MQL, and hybrid cryogenic MQL conditions with coated solid carbide tools showed promising results in tool life improvement and surface finish due

Table 4 Process parameters used during MQL machining of titanium alloys using various operations

Ref	Material	Machining process	Lubrication	Cutting speed (m/min)	Feed rate (mm/min)	Depth of cut (mm)	Responses
[138] (2015)	Grade 2 titanium alloy	Turning	MQL	120	0.05	0.1	Cutting force, tool wear, surface roughness
[139] (2016)	Ti6Al4V alloy	Turning	MQL	63, 79, 99	0.206, 0.274, 0.343	0.6, 1.0, 1.6	Surface roughness,
[140] (2016)	TC11 alloy	Turning	MQL	80	0.1	0.75	Cutting force, machining temperature, surface roughness
[49] (2018)	Ti6Al4V ELI alloy	Turning	MQL	80	0.2	0.25	Tool wear, surface roughness
[98] (2018)	Ti6Al4V alloy	Drilling	MQL	60	0.07	n/a	Coefficient of friction, tool wear, drilling thrust force, drilling torque
[141] (2018)	Ti6Al4V alloy	Milling	MQL	50	0.1, 0.3, 0.5	0.2, 0.3, 0.4, 0.5	Tool wear
[142] (2019)	Ti6Al4V ELI alloy	Turning	MQL	55, 80, 105	0.1	1.0	Surface roughness, machining temperature, chip morphology, tool wear
[143] (2019)	Ti6Al4V alloy	Turning	MQL	60, 120, 180, 240	0.05, 0.10	0.25	Tool wear
[144] (2020)	CFRP/Ti6Al4V alloy	Drilling	MQL	15, 30, 45, 60	0.025, 0.050, 0.075, 0.100	1.5	Drilling force, drilling torque, surface roughness
[145] (2020)	Ti6Al4V alloy	Milling	MQL	23.6, 31.4, 39.3, 47.1, 55.0	30, 60, 90	0.075	Tool wear, surface roughness, residual stress

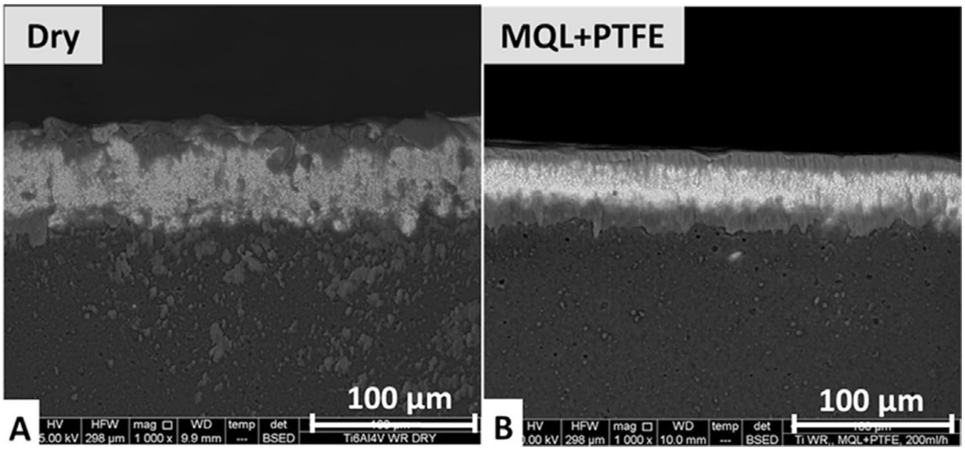


a) b)

Fig. 34 **a**, **b** Tool life and surface roughness improvement of MQL over dry machining [140]

to sufficient lubrication which reduced friction wear and adhesion. Rahman et al. [142] reported that a nanofluid-aided MQL technique reduced overall tool wear of the cutting inserts during biomedical grade titanium alloy turning. An et al. [6] performed a surface roughness and tool life analysis of titanium alloy side milling under dry, flooded, and MQL techniques and they concluded that MQL lubrication significantly improved tool wear and machinability. Flank wear, rake wear, formation of built-up edges, and chip adhesion on the cutting tool were reduced under the MQL lubrication method as shown in Fig. 36.

Fig. 35 **a**, **b** Tool flank wear comparison between dry machining and MQL-assisted machining [49]



On the other hand, Khaliq et al. [145] performed a tool wear, surface quality, and residual stress analysis on micromachined additive manufactured titanium alloy under dry and MQL conditions. They concluded that MQL lubrications were able to reduce the cutting tool radius increment rate and improve flank wear by 26.2% compared to dry machining with the increase in cutting speeds and constant feed rate. Improvement on surface roughness and tool

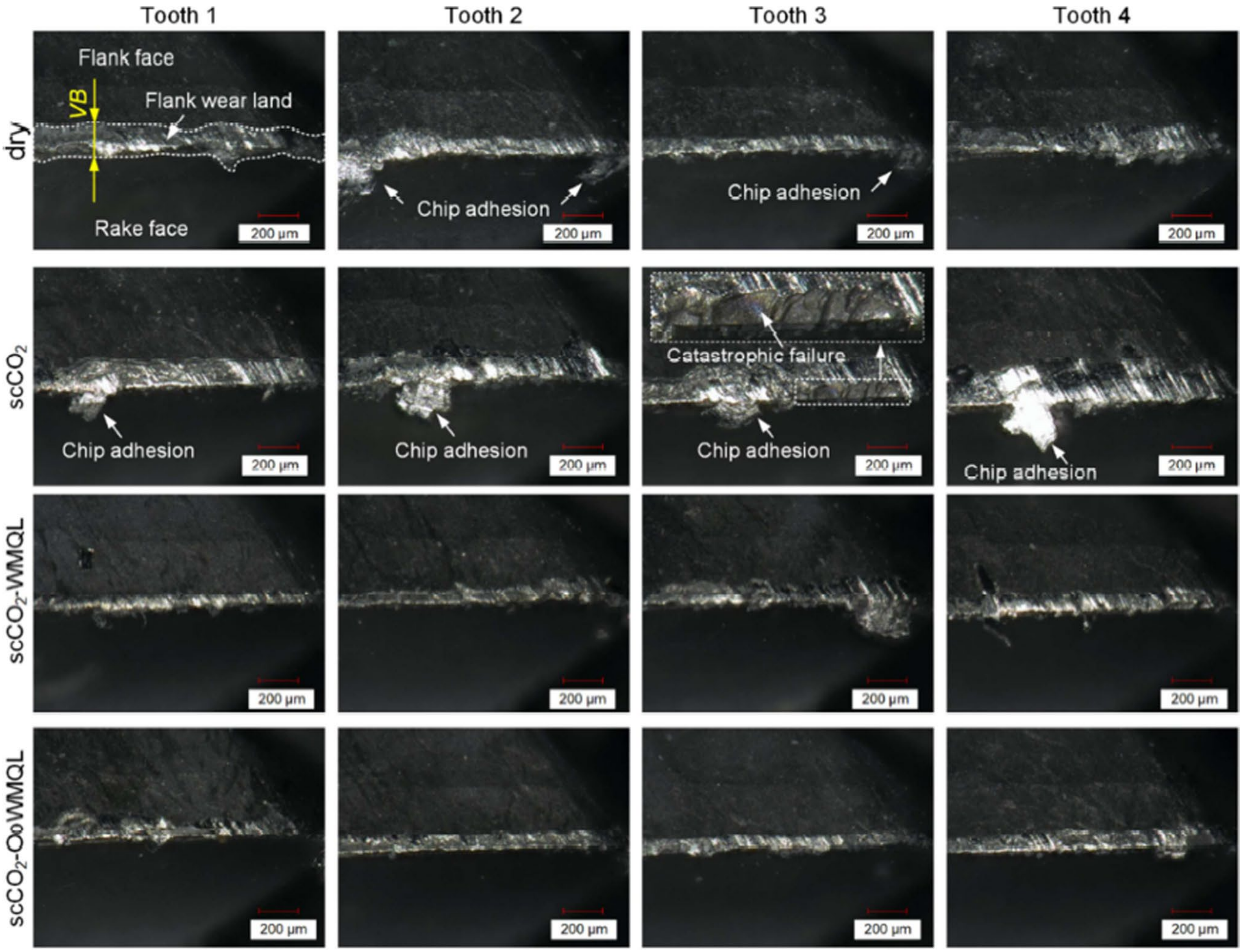


Fig. 36 Microscope view on tool wear comparison between dry and mql milling of Ti6Al4V [6]

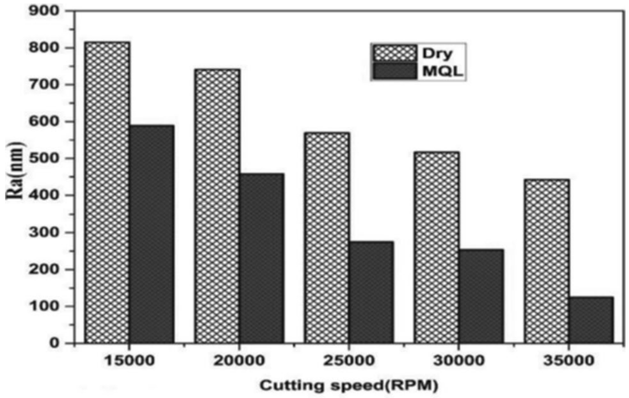


Fig. 37 Surface roughness performance between dry and MQL machining [145]

diameter reduction were also achieved under MQL lubrication environment which is shown in Fig. 37. In a nutshell, most researchers agreed that applications of MQL lubricant delivery during the machining of titanium alloys is beneficial and compatible for improved machinability and tool life while achieving desired surface roughness.

Da Silva et al. [143] studied the turning of titanium alloy under dry, jet, and MQL cooling methods using synthetic polycrystalline diamond (PCD) and cement carbide (H13A) tools to investigate the wear mechanisms. The authors found that the MQL cooling technique produced better machining performance and improved cutting tool life at different cutting speeds and feed rates in comparison to dry turning which is shown in Fig. 38.

Xu et al. [144] investigated the drilling performance of carbon fiber-reinforced polymer (CFRP) laminated titanium alloy plates under dry and MQL conditions. MQL coolant was delivered at 15 mL/h flow rate via compressed air pressure of 0.6 MPa through the spindle system of the drilling bits. The authors concluded that MQL condition was able to significantly reduce drilling torque and energy consumption due to reduction of frictional force at the tool–workpiece interface. MQL condition also improved surface finish of the composite holes and suppressed burr formation on the workpiece.

4 Types of cutting fluids

4.1 Synthetic/commercial oil as cutting fluid/lubricant during machining

Most manufacturing industries demand both high productivity and profit. High productivity can be achieved by using better machining techniques and optimum machining

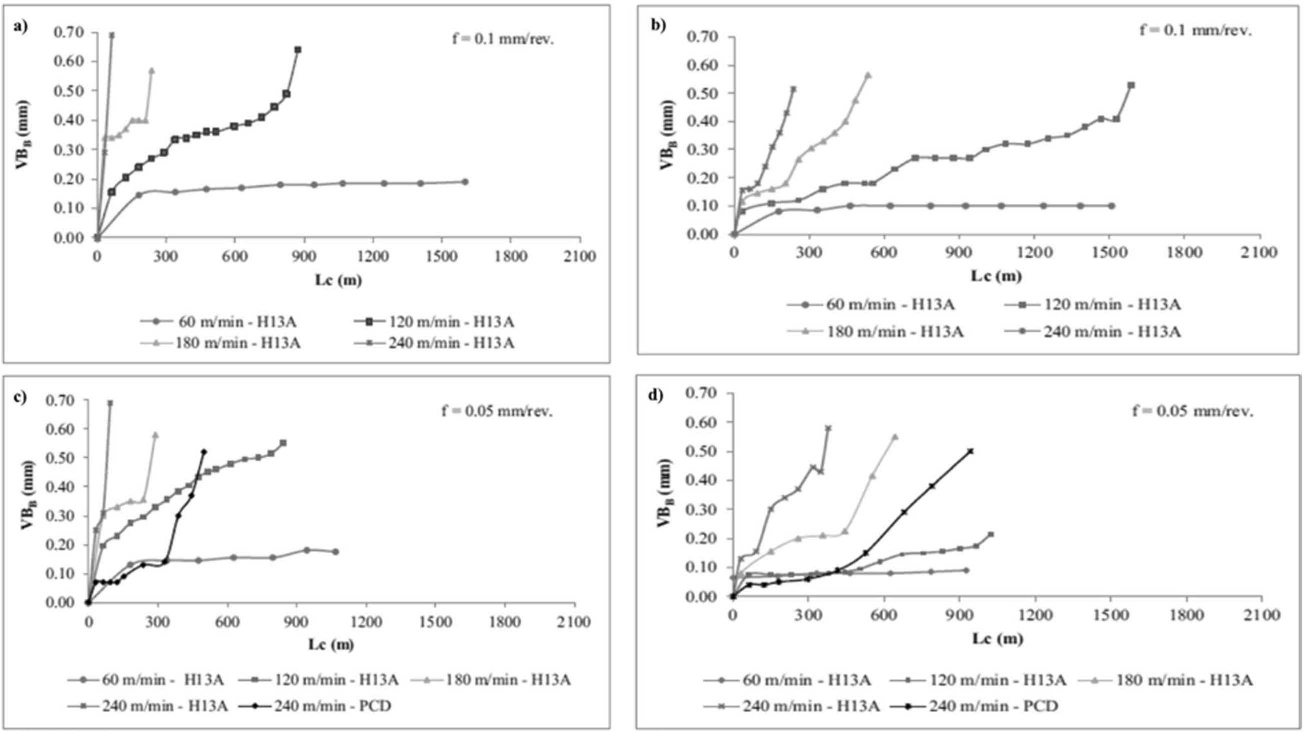


Fig. 38 Flank wear (VBB) of cemented carbide (H13A) and PCD tools in function to the length of cut in dry condition (**a**, **b**)) and MQL condition (**c**, **d**)) with feed rates of 0.1 and 0.05 mm/rev [143]

parameters. On the other hand, high profitability can only be achieved by ideal use of resources and maintaining low cost of production. Machining coolant accounts for around 10–17% of the total manufacturing cost which is shown in pie chart of Fig. 39. Therefore, the optimum use of cutting fluids becomes priority to minimize the total cost in manufacturing industries [91]. Generally, a water-soluble-based oil or chemically synthesized oil is used as a coolant to cool and lubricate at the material–tool interface[146]. These advantages make it widely usable in various industrial applications. Therefore, many researchers are continuously investigating the use of coolants and lubricants to enhance the machining performances under different coolant delivery methods.

Lubrication performance of diamond nanoparticles mixed with synthetic oil on steel machining were investigated by Raina and Anand [147] with different concentration of nanoparticles in addition to PAO oil. The study revealed that the addition of 0.2 wt% of diamond nanoparticles to PAO synthetic oil was able to substantially reduce coefficient of friction and adhesion wear on machining tools due to the reduction of sliding contacts between tool–workpiece interface and smoothening of sharp asperities. In another study by Lopes et al. [148] on the application of wheel cleaning system during alumina grinding under semi-synthetic oil MQL delivered through air jet showed that flooded machining provided the optimal experimental results. However, the delivery of the semi-synthetic oil under MQL at air jet angle of 30° showed similar results to flooded cooling, with the increase of grinding wheel diameter by 83% and improvement of surface roughness and power consumption by 53% and 22% respectively. De Oliveira et al. [149] studied the influence of graphene platelet concentration in semi-synthetic oil on the grinding performance of Inconel 718 alloy using dry, flooded, and MQL techniques. The addition of graphene of 0.05% in the semi-synthetic emulsifiable Vasco 7000 oil performed the best in terms of surface roughness under MQL condition compared to dry and flooded machining as shown in Fig. 40.

Rajeshkumar and Ramesh [150] performed an investigation on design and optimization of machining parameters of MQL titanium alloy milling under dry, water-based MQL (MQL-W), vegetable-castor oil-based MQL (MQL-V), and synthetic ester oil-based MQL (MQL-S). The effect of feed rate and cutting speed on surface roughness, tool wear, and coefficient of frictions were also investigated with the combinations of the lubrication techniques. They found that the combinations of MQL-S, 0.4 mm/rev feed rate, and cutting speed of 25 mm/min were able to generate the optimum machining performance in terms of cutting force, surface

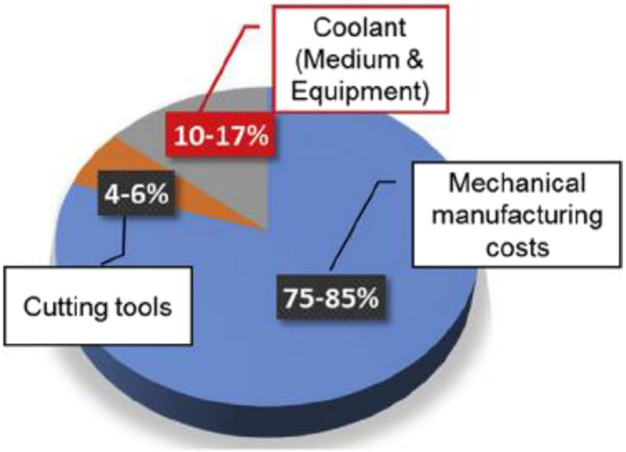
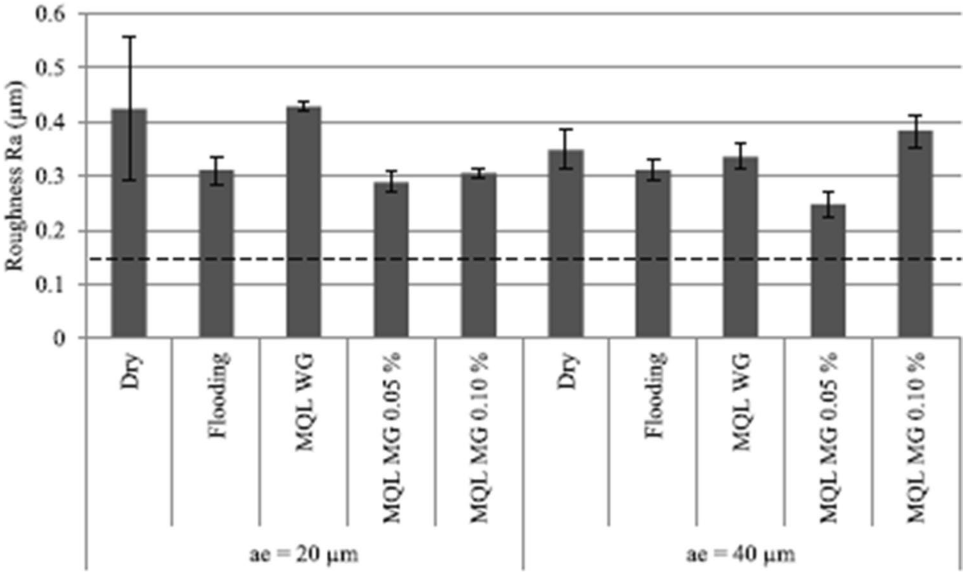


Fig. 39 Numerical proportions of manufacturing costs [91]

Fig. 40 Surface roughness of Inconel 718 after grinding under different cooling lubrication conditions [149]



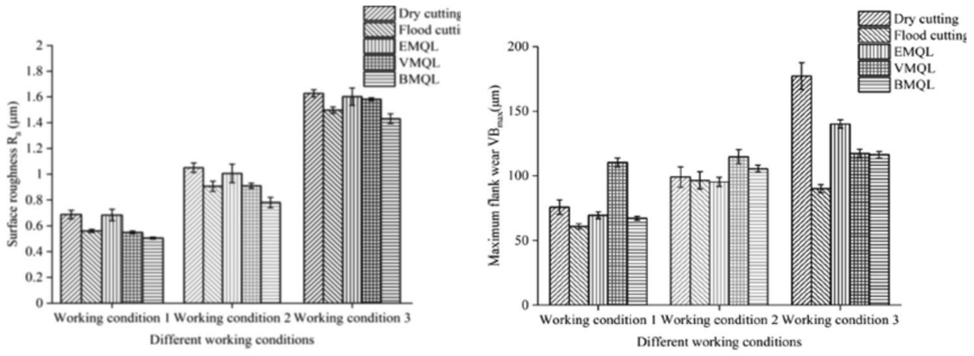
roughness, tool wear, and coefficient of friction. Moreover, Liu et al. [146] studied a performance evaluation of blended castor oil and ethanol under MQL delivery for AISI 304 steel. Surface roughness, tool wear, and surface hardness analyses were performed under the comparison of dry, flooded, castor oil MQL (VMQL), ethanol MQL (EMQL), and blended coolant (BMQL) methods. They found that BMQL reduced overall surface roughness by more than 4.5% in comparison to other cooling methods. It was also found that BMQL reduced the flank wear and crater wear of the carbide tool by 7.72% as shown in Fig. 41.

De Moraes et al. [151] studied the performance of two types of commercially available cutting fluids in pure form and diluted form for the grinding process of SAE 52100 steel under the MQL cutting fluid delivery technique. Different ratios of fluid dilutions were used, namely 1:0 (pure oil), 1:1 (50% water), 1:3 (75% water), and 1:5 (83% water) for MQL fluid system, while 1:32 (97% water) dilution of cutting fluid was used for flooded system as performance comparison. The authors concluded that the MQL system was viable as an alternative method of coolant delivery to replace flood coolant system due to the factor of extremely low amount of coolant required and ease of disposal of contaminated cutting fluids. The author also found that increase of water content in the diluted oil (83% water content) improved the surface quality of the workpiece and reduced the temperature, wheel clogging, scratches, plowing, and rubbing during machining process.

Conventional cutting fluids are effective ways to cool and lubricate the cutting zone; however, they also result in several ecological problems. One of which are they often generates airborne mists, smoke, and other particles in the workshop's atmosphere. Due to the toxicity nature of the mists, conventional cutting fluids create health problems for the machining operators and lead to environmental pollution. Exposure to conventional cutting fluid had resulted in 80% of occupational infection among the contractors [152]. The potential severe health problems including respiratory diseases, lung cancer, genetic disease, and dermatological problems are suffered by machine operators who frequently expose to conventional cutting fluids [153]. According to report by the International Agency for Research on Cancer (IARC), petroleum-based cutting fluids lead to occupational skin cancer as it contains carcinogenic heterocyclic and polyaromatic rings [154]. Besides, the growth of bacteria in the cutting fluids obviously lead to the presence of microbial populations, especially endotoxins in the workplace atmosphere. Thus, proper disposal plan is needed for conventional cutting fluid due to their toxicity and nonbiodegradability traits. Due to above reasons, disposal cost of conventional cutting fluids is higher than the biodegradable cutting fluids. In fact, additional space is also required for storing and processing of contaminated conventional cutting fluids [155]. Moreover, for all the reasons mentioned, biodegradable fluids that are capable of being broken down by bacteria or microorganism without causing harm to the environment are generally chosen [156]. One of the suitable candidates for biodegradable cutting fluids is natural vegetable oil.

4.2 Vegetable oil used as cutting fluid in machining

Due to rising awareness and concern of health and safety, the demand for alternative replacement for conventional cutting lubricants for manufacturing industries has been ongoing for several years. Most of the oils used in MQL in recent days consist of synthetic fatty alcohols obtained from vegetables and mineral oils [157, 158]. However, researchers have been indulging in various possibilities of lubricant types which contain biodegradable and stable characteristics under decent loads for longer service life of the lubricant. Based on the law restriction, the harmful contents of cutting oil are required to be minimized or removed to an acceptable level to reduce the adverse environmental impact. Therefore, sustainability and biodegradability of the cutting fluids are important aspects to be considered in manufacturing industries. One of the more viable options are natural oils, specifically vegetable oils such as coconut, rapeseed, sunflower, castor, canola, and palm oils due to their properties of having



a) b)

Fig. 41 Comparison of machining performance of different metal-working conditions such as ***a*** surface roughness and ***b*** flank wear analysis [146] the ability to provide superior lubrications during metal and alloy machining while being biodegradable, non-toxic, and easily obtainable anywhere in the world. Table 5 shows the summary of works by various authors on the use of vegetable oil in machining.

Agrawal and Patil [160] reported that vegetable oil was a potential replacement of conventional cutting fluid on M2 steel machining under the MQL technique. Furthermore, they recommended that aloe vera oil was the most suitable vegetable oil as it produced better surface roughness and tool wear in steel machining while also being environmentally friendly. Ghatge et al. [161] concluded that coconut and neem oil demonstrated promising results in improving machinability of stainless steel, producing better surface roughness and lower tool wear when compared to mineral oil. Another study by Mahadi et al. [159] showed that boric acid-aided palm kernel oil yielded better surface roughness compared to conventional mineral-based oil in MQL turning of AISI 431 steel. They suggested that vegetable oil was able to reduce the environmental impact as well as the risk of health and safety of operators. As shown in Fig. 42, Fernando et al. [167] used coconut oil-based metal cutting fluids as MQL coolant in AISI 304 stainless steel turning. They determined that surface finish and tool wear were improved using coconut oil-based cutting fluid in comparison to standard emulsion mineral oil.

Moreover, Lal Virdi et al. [168] found that nanofluid vegetable oil MQL for Inconel 718 grinding performed the best with reference to surface roughness, machining energy, and coefficient of friction when compared to dry and flooded machining. Khunt et al. [169] concluded that vegetable oil-based MQL (sunflower oil) were able to effectively improve

Table 5 Process parameter used during MQL machining using vegetable oil-based cutting fluids

Ref	Material	Machining process	Lubrication	Cutting speed (m/min)	Feed rate (mm/min)	Depth of cut (mm)	Responses
[159] (2017)	AISI 431 steel	Turning	MQL	150, 200	0.16, 0.24	0.5, 1.0	Surface roughness
[160] (2018)	M2 steel	Turning	MQL	52.36, 83.78, 130.90	0.18, 0.27, 0.36	0.2, 0.4, 0.6	Surface roughness, tool wear
[161] (2018)	AISI 2205 stainless steel	Turning	MQL	100, 150, 200	0.1, 0.2, 0.3	0.4, 0.8, 1.2	Tool wear, surface roughness, cutting temperature
[162] (2019)	Ti-6Al-4V ELI alloy	Grinding	Dry, MQL	22	3000	0.1	Specific grinding energy, coefficient of friction, surface roughness, grinding forces
[163] (2020)	Ti-6Al-4V alloy	EDM	Dielectric Fluid	–	–	–	Surface roughness
[164] (2020)	AISI H13 steel	Grinding	MQL	39.25	10	15	Surface roughness, grinding temperature, grinding force, specific energy.
[165] (2020)	SAE 1045 steel, 6061-T6 aluminum	AFM	Abrasive Flow	–	–	–	Surface roughness
[166] (2020)	7050-T7451 aluminum	Milling	Wet	150	0.012	0.060	Cutting force, tool wear, surface roughness

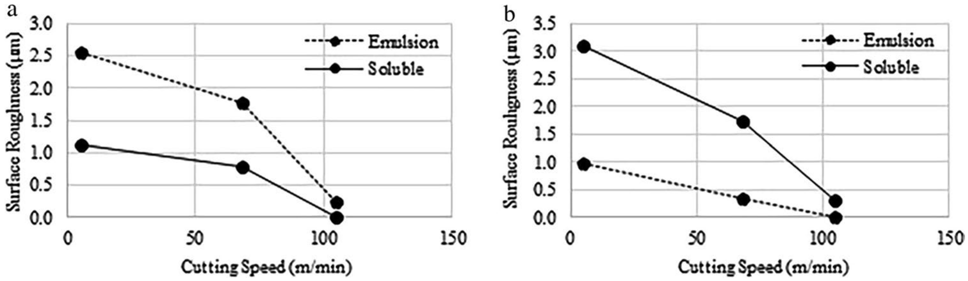


Fig. 42 **a**, **b** Surface roughness performance of coconut oil MQL delivery on AISI 304 stainless steel turning [167]

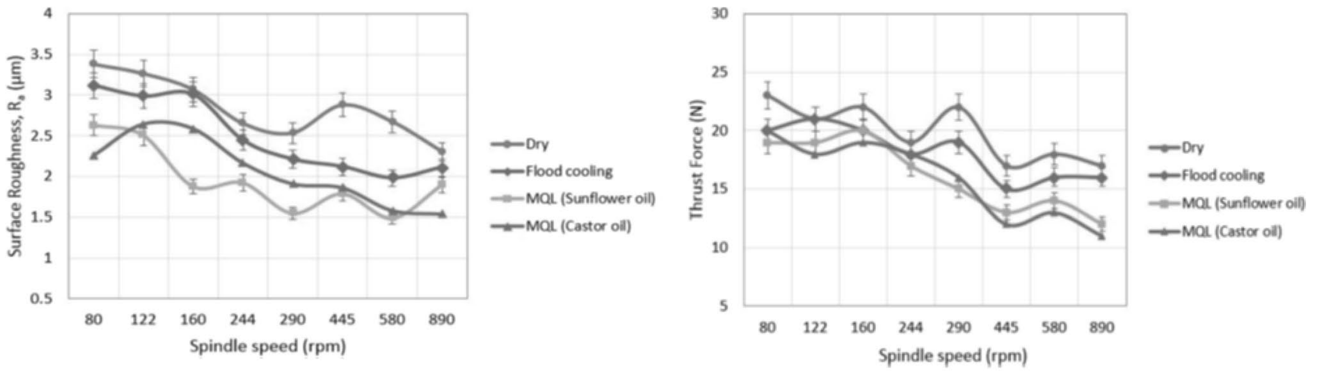
thrust force, torque, and surface roughness at higher cutting speed during drilling as shown in Fig. 43. Moreover, they reported that vegetable oil-based metal-working fluids have the potential as an effective alternative metal-working fluid over castor oil for flood cooling or MQL that can effectively enhance machining performance during drilling operations.

In terms of vegetable oil application in titanium alloy machining, there are several investigations performed by various authors. For example, Deiab et al. [170] found that vegetable oil specifically rapeseed oil in both MQL and MQCL setups was the most sustainable option over synthetic coolants. Rao et al. [171] used coconut oil in the development of novel cutting tool in titanium alloy turning where positive results were obtained in terms of tool wear, cutting temperature, and surface roughness. Moreover, Singh et al. [162] found that nanographene additive-aided canola oil reduced grinding energy and achieved green manufacturing due to its high content of fatty acids, high heat capacity, and decent fluid viscosity. The usage of jojoba oil with the addition of nanoparticles in Ti-6Al-4V alloy hard turning was investigated by Gaurav et al. [172] where conclusions were made that jojoba oil showed promising results in cutting force, surface roughness and tool wear improvements. Singaravel et al. [163] investigated the use of vegetable oils such as sunflower, canola, and jatropha oils as dielectric machining fluids in titanium alloy EDM machining. Conclusion was made that vegetable oil was suitable replacement for conventional dielectric fluids with similar properties. Moreover, vegetable oils were eco-friendly and biodegradable, showing sustainable machining. Furthermore, Awale et al. [164] used groundnut oil as MQL lubricant in AISI H13 steel grinding to determine its effect on grinding temperature, surface roughness, specific energy, and grinding force. At 4 bar of pressure, 200 ML/H flow rate and diameter of 50 mm settings showed the best performance in the grinding process. Munhoz et al. [165] analyzed the surface roughness (Ra, Rq, and Rz) of aluminum 6061-T6 and medium carbon steel SAE 1045 workpieces under abrasive flow machining process using oiticica vegetable oil with mixture of abrasive particles. They found that the developed paste based on the oiticica oil used on the machining of steel and aluminum was able to reduce the surface roughness and chip accumulation.

In another research completed by Chanes De Souza et al. [166], the authors studied the influence of fatty acid content in vegetable oil-based (VO) MWFs on the lubrication film formation in micromilling process of aluminum alloy. High-oleic fatty acid (HOFA) and mild-oleic fatty acid (MOFA) based sunflower oil were used in the micromilling process with the combination of cutting parameters of 150 m/min cutting speed, 0.012 mm/z feed per tooth, and 0.060 mm depth of cut. The authors concluded that HOFA produced better lubricating film which resulted in improved protection compared to MOFA. They also found that VO-HOFA and VO-MOFA showed similar tool wear performance and improved surface finish of micromilled aluminum alloy in comparison to commercial emulsion as shown in Fig. 44.

4.3 Palm oil as MQL cutting fluid in metal machining

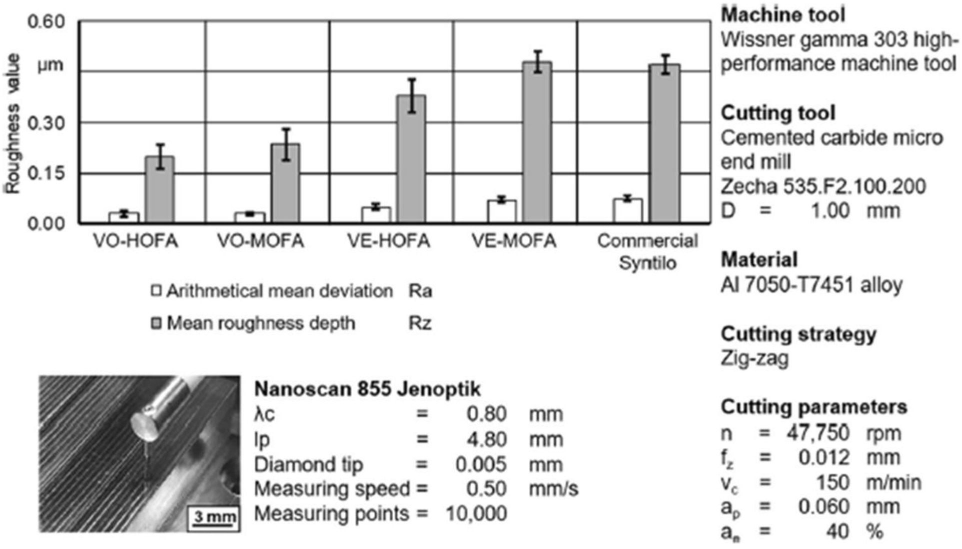
Palm oil, commercially known as *Elaesis quineenis*, is one of the main agricultural crops produced in Malaysia which thrives in a hot tropical climate [173]. Therefore, due to the exquisite amount of oil palm crops, palm oil production has become Malaysia's largest export and production for decades. According to statistics, Malaysia exported a total of 17.3 million tonnes of the total world oil palm production in year 2020 and 18.4 million tonnes in the year 2019 as shown in Fig. 45. Therefore, Malaysia is known to be one of the largest palm oil production and export countries in the Southeast Asia region together with Indonesia [174]. Palm oil contains approximately 50% saturated fatty acids, 40% monosaturated fatty acids, and 10% polyunsaturated fatty acids. Palm oil and its components are generally used



a) b)

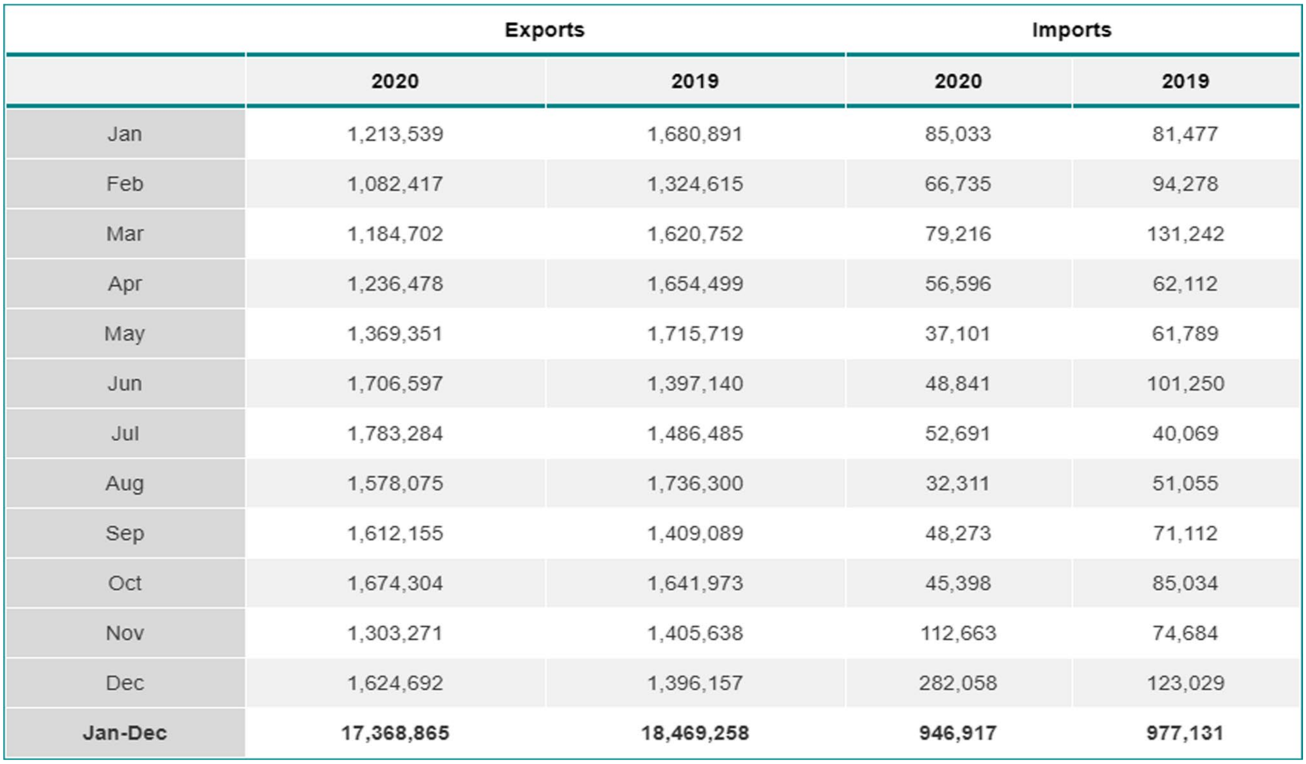
Fig. 43 **a**, **b** Resultant surface roughness and thrust force from dry, flooded, synthetic oil MQL, and vegetable oil MQL [169]

Fig. 44 Surface roughness of micromilled Al7050-T7451 aluminum alloy using different lubricants [166]



in production of daily living product and foods such as vegetable-based cooking oil, soaps, shortenings, and confectionery products. The versatility and adaptability of palm oil to different applications are the result of its chemical composition [175].

In previous research works performed by various authors, palm oil had been proved to be a promising potential replacement to synthetic oils which is more superior to conventional cutting fluids in machining industries [177–180,181]. Palm oil is one of the recent choices from list of vegetable oils to be studied as potential low cost, efficient cutting fluids for MQL-assisted machining. It is considered an environmentally friendly vegetable-based oil with the high potential to be used as cutting fluid due to its high content of triglycerides and polarity which contribute to good heat absorption film for heat removal from tool workpiece area [182]. Rahim



	Exports		Imports	
	2020	2019	2020	2019
Jan	1,213,539	1,680,891	85,033	81,477
Feb	1,082,417	1,324,615	66,735	94,278
Mar	1,184,702	1,620,752	79,216	131,242
Apr	1,236,478	1,654,499	56,596	62,112
May	1,369,351	1,715,719	37,101	61,789
Jun	1,706,597	1,397,140	48,841	101,250
Jul	1,783,284	1,486,485	52,691	40,069
Aug	1,578,075	1,736,300	32,311	51,055
Sep	1,612,155	1,409,089	48,273	71,112
Oct	1,674,304	1,641,973	45,398	85,034
Nov	1,303,271	1,405,638	112,663	74,684
Dec	1,624,692	1,396,157	282,058	123,029
Jan-Dec	**17,368,865**	**18,469,258**	**946,917**	**977,131**

Fig. 45 Malaysia's monthly palm oil trade statistics 2020 [176]

and Sasahara [135] reported that PO-MQL produced better overall performance in terms of preserving tool life in Ti alloys machining compared to synthetic oil. The utilization of PO-MQL allowed for lower generated temperatures and thrust forces due to formation of thin lubrication film from its triglyceride contents between the tool–workpiece interfaces. It was concluded that PO was a viable candidate for substitution of synthetic oil as MQL fluids due to its biodegradability and excellent lubrication performance. In another study done by Li et al. [183], it was concluded that PO-MQL was able to generate the lowest temperature and cutting forces which lead to tool life improvements due to the presence of unsaturated fatty acid and viscosity properties compared to other vegetable oils. A recent study by Sen et al. [184] on synergistic effect of silica nanoparticles and pure palm oil in the machining performance of Inconel 690 showed that 1% addition of silica deposits in palm oil (1%-MQNGL) was able to substantially improve surface roughness, reduce resultant cutting force and cutting temperature, and enhance tool life due to the formation of tribo-film between the tool–workpiece interface as shown in Fig. 46.

Sen et al. [185] investigated alumina-enriched palm oil-based MQL lubrication condition on the wear behavior of Ti-Al-N-coated solid carbide tools in end milling of Inconel 690 where 0.9% alumina-deposited palm oil (0.9%-MAPO), flooded coolant, and pure palm oil (MPO) were used as metal-working fluid. They concluded that 0.9%-MAPO were able to improve coated solid carbide tool wear by 19.35% over flooded cooling and 10.71% over MPO cooling respectively.

5 Summary

As machining represents a major part of manufacturing industries in terms of producing quality products, it involves the machine parameters, lubricants, and the environment. Due to the focus on ecological pollution and health and safety issues, manufacturing industries were required to implement environmentally friendly machining techniques in their operations. Therefore, minimum quantity lubrications have been gaining significant attention throughout the years due to its capability as a cooling delivery solution to enhance the heat transfer and lubrication performance for machining operations. This paper represents a comprehensive review of published articles concerning on the recent progresses on application of MQL in different metal machining techniques, the machining performance of MQL, and the sustainability characteristics of MQL lubrication delivery using synthetic oil and vegetable oil in various machining

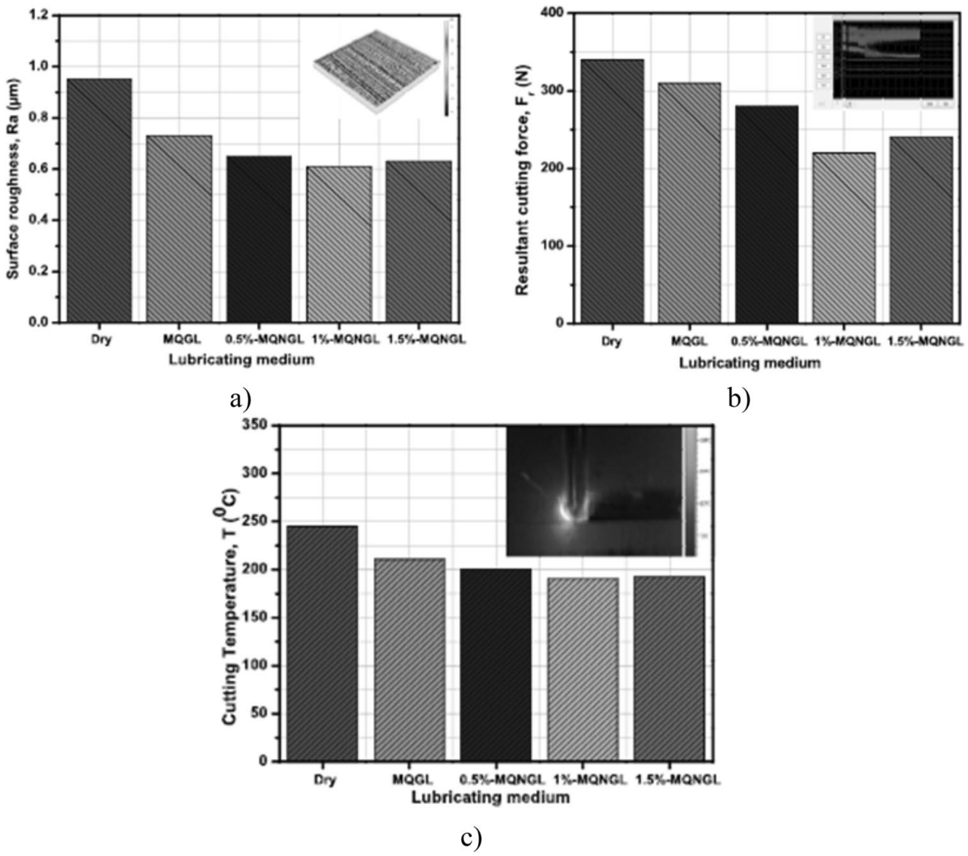


Fig. 46 **a**–**c** Machining performance comparison between dry and MQL Inconel 690 machining [184]

process such as drilling, milling, grinding, and turning. The summary is outlined as follows:

1. In terms of sustainable manufacturing, the MQL method shows significant improvements for manufacturing industries in terms of environmental friendliness and compliance to health and safety regulations. It is a more cost-efficient method of cooling and lubrication as a metal-working fluid, and it generally reduces the usage of coolants by more than half the amount used in flooded cooling as shown in Table 6. Due to excellent heat removal and dissipation capability of the MQL method, similar or lower resultant surface roughness and cutting temperature can be achieved under MQL environment with the combination of optimum machining parameters such as cutting speeds, feed rates, and depth of cuts as compared to dry and flooded machining conditions.
2. The natural properties of vegetable-based metal-working fluids provide similar or more superior lubrications during any metal, alloys, or hybrid composites machining due to its biodegradable, non-toxic, and easily disposable natures. These vegetable oils can also further enhance the effect of MQL delivery as a cost-saving and eco-friendly method of lubrication and cooling. A summarized view of usage of vegetable oil-based metal-working fluids in MQL machining is shown in Table 7.
3. Tool wears such as flank wear, crater wear, and built-up edges on cutting tools along with machining forces and coefficient of friction were significantly reduced by using minimum quantity lubrication due to better penetration of machining fluid at the tool–chip interaction zone.
4. The paper not only showed the potential advancements of MQL methods but also focused on using cryogenic liquids and vegetable-based oils in MQL delivery to improve the performance of various machining operations.
5. Palm oil has good potentials to be an alternative cutting fluid in MQL machining to the conventional and commercially available metal-working fluids. Table 8 summarizes the current usage of palm oil in machining processes as lubricant. However, it is noticed that there is a lack of research in using palm oil as cutting fluid which triggers the need of additional investigations to be done to further explore its capabilities.

Table 6 Benefits for using MQL cooling delivery methods in different machining operations

References	Machined material	Machining process	Mode of lubrication	Findings
Praveen et al. [105]	EN 47 chrome-vanadium steel	Turning	Dry, MQL	MQL improved surface roughness by 48% in comparison to dry machining
Mishra et al. [104]	EN 24 high tensile steel	Turning	MQL	MQL provided significant cooling and lubrications resulting in improvement of surface roughness and reduced machining costs
Abas et al. [118]	6026-T9 aluminum	Turning	Dry, MQL	Increase in tool life and better surface quality of machined workpiece under MQL compared to dry machining
Javidikia et al. [120]	6061-T6 aluminum	Turning	Dry, wet, MQL	Increased productivity and tool life and improved surface roughness under MQL coolant delivery
Gutnichenko et al. [124]	Inconel 718 alloy	Turning	Dry, MQL	Improvement of tool life, machining stability, and surface finish of alloy
Ni et al. [128]	TC4 alloy	Milling	MQL	UVA-assisted MQL improved surface roughness up to 30% and machining force up to 55% while also reducing machining time
Shukla et al. [97]	6061 aluminum	Drilling	Dry, wet, MQL	Vegetable oil-based MQL improved surface finish and tool wear over dry and wet machining
Khatri et al. [141]	Ti-6Al-4V titanium alloy	Milling	Dry, wet, MQL	Significant improvement of edge chipping and adhesion tool wear was observed under MQL machining
Xu et al. [144]	CFRP/Ti-6Al-4V Hybrid	Drilling	Dry, MQL	MQL produced better geometrical accuracy of drilled holes, while reducing energy consumption, and better tool wear compared to dry drilling

Table 7 Summary of vegetable oil-based cutting fluids in MQL machining

References	Machined material	Machining process	Mode of lubrication	Findings
Mahadi et al. [159]	AISI 431 steel	Turning	MQL	Improvement of surface roughness by 7.21% using boric acid powder-aided palm kernel oil compared to conventional mineral-based oil
Singh et al. [162]	Ti-6Al-4V ELI alloy	Grinding	MQL	Machining performance under nanoadditive-based canola oil machining fluids was improved over synthetic fluid-based MQL, soybean, and olive oil-based MQL
Gaurav et al. [172]	Ti-6Al-4V titanium alloy	Turning	Dry, MQL	Nanoparticle-enhanced jojoba vegetable oil showed significant improvement reduction of cutting force, surface roughness, and tool wear ranging from 35 to 47% in comparison to commercially available mineral oil
Virdi et al. [168]	Inconel 718 alloy	Grinding	Wet, MQL	Nanofluid-aided sunflower oil MQL lowered grinding energy, coefficient of friction, and surface roughness in Inconel 718 grinding while being able to effectively clean the machining area over flooded cooling
Souza et al. [166]	7050-T7451 aluminum alloy	Milling	Wet	Higher surface quality and lower active mill force on micromilled aluminum alloy was obtained under HOFA vegetable-based oil due to its superior lubrication performance
Munhoz et al. [165]	6061-T6 Aluminum, SAE 1045 steel	AFM	Abrasive Flow	Vegetable oil-based paste reduce overall surface roughness of machined material over commercial paste
Fernando et al. [167]	AISI 304 stainless steel	Turning	MQL	Coconut oil improved overall surface finish and cutting tool wear compared to standard mineral oil
Khunt et al. [169]	6063 aluminum alloy	Drilling	Dry, Wet, MQL	Lowest surface roughness, thrust force, and torque were obtained vegetable oil based at higher cutting speed over commercially available castor oil

Table 8 Summary of usage of palm oil as a cutting fluid in machining

References	Machined material	Machining process	Mode of lubrication	Findings
Rahim and Sasahara [135]	Ti-6Al-4V titanium alloy	Drilling	Dry, MQL	Palm oil performed better in comparison to synthetic oil in terms of improving tool life and cutting temperature.
Li et al. [183]	GH4169 nickel-based alloy	Grinding	MQL	Palm oil generated low grinding force and machining temperature compared to several other vegetable-based oil.
Sen et al. [184]	Inconel 690 alloy	Milling	Dry, MQL	Resultant cutting force, cutting temperature, tool life, and surface roughness of milled 690 alloy were improved substantially under palm oil–silica-based MQL lubrication compared to dry milling.
Bai et al. [80]	Grade 45 steel	Milling	MQL	Palm oil showed lowest milling force and the best surface finish in the milling of grade 45 steel over synthetic, cottonseed, castor, peanut and soybean oil.
Abdollah et al. [181]	Carbon chromium steel	Tribological test	Wet	HBN-palm oil-blended lubricant showed lower coefficient of friction compared to commercially available mineral oil-based lubricants, resulting in reduced wear rate and smooth steel ball's surface.

Availability of data and materials Not applicable as it is a review paper.

Author contribution Gary Wong: formal analysis, investigation, writing—original draft. Sumaiya Islam, Moola Mohal Reddy, Neamul Khandoker, Vincent Lee Chieng Chen: conceptualization, resources, supervision, writing—review and editing, project administration, funding acquisition.

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Declarations

Ethics approval Not applicable as it is a review paper.

Consent to participate On behalf of all authors, the corresponding author agrees to participate as required.

Consent for publication On behalf of all authors, the corresponding author agrees to publish.

Competing interests The authors declare no competing interests.

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