A review on localised and multi-point aerosol application in minimum quantity lubrication machining

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Abstract: The minimum quantity lubrication (MQL) is prominent among the environmentally friendly machining techniques. Localised cooling and lubrication at multiple locations in the cutting zone is the latest development to improve efficacy and further trim down the consumption of metalworking fluid. The paper consolidates the strategies to use the MQL cutting fluids at the specific locations, *vis-à-vis* rake face, flank face and back of the chip. A critical analysis is made on cutting fluids, cooling strategies, process parameters, and their effect on quality. The latest developments and future directions in the framework of the hybrid lubrication method, hybrid cutting fluid and numerical modelling are presented.

Keywords: environmentally friendly machining; cutting fluid; nanofluids; tool face; multi-point injection; hybrid lubrication; hybrid cutting fluid; minimum quantity lubrication; MQL.

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1 Introduction

Conventional machining operations like turning, milling and drilling use cutting fluids to increase machining efficiency. The cutting fluids are not only hazardous to human health, but their disposal also causes environmental problems like water contamination and air and soil pollution. With the introduction of stricter standards setup by the international bodies like the International Organization for Standardization (ISO) and Occupational Health and Safety Advisory Services (OHSAS), manufacturing industries are obliged to pursue alternative methods (Avram et al., 2011). Figure 1 explains the current industrial scenario wherein the challenges are the collective outcomes of environmental and product quality issues. The challenges as mentioned above promoted environmentally friendly machining concepts, as brought up in reviews submitted at various times such as Weinert et al. (2004), Kundrák et al. (2006) and Dixit et al. (2012). These concepts consider it essential to develop a machining process that can minimise the use of traditional cutting fluids or can replace them entirely with environmentally friendly cutting fluids to reduce the energy consumption and maximise the efficiency of the cutting tools.

Figure 1 Industrial scenario

The environmentally friendly machining strategies can be categorised in several ways (Figure 2). Complete removal of cutting fluids by dry machining has shown a promising

scope. However, the superalloys and other difficult-to-machine materials prove to be challenging for the dry machining. Complete removal by the change in cutting fluid, e.g., cryogenic machining, solid lubricants, and biodegradable lubricants can provide alternate solutions (Krishna and Rao, 2008). Vegetable oil-based cutting fluids and synthetic esters are some of the biodegradable alternatives that are used with the current machine tools. In the system-based approach, consideration can be directed towards injecting an appropriate quantity of cutting fluid only at the locations where it is mostly required. Research related to the use of minimum quantity lubrication (MQL) during machining has shown that only a small amount of cutting fluid, when appropriately applied, is enough to give comparable performance to that of flood cooling and even better in some cases. MQL, which is likewise termed as near dry machining (NDM), uses a minimal quantity of cutting oil mixed with carrier gases like air, N_2 or CO_2 . A considerable amount of research in MQL focuses on turning, drilling, milling and grinding (Sharma et al., 2015)

Figure 2 Environmentally friendly machining strategies

Owing to increased popularity, reviews on various aspects of MQL machining have been published. A review on the application of MQL in various machining operations such as turning, drilling, and milling is presented by Sharma et al. (2015). Boubekri et al. (2010) reviewed economic, environmental, and technical aspects of MQL technology and compared them to traditional flood cooling and lubrication techniques. Lawal et al. (2013) and Srikant et al. (2014) consolidated literature on MQL using vegetable oil and nanofluids, respectively. A comparison between the conventional cutting fluids with that of nanofluid-based cutting fluids in MQL machining processes is presented (Sharma et al., 2016).

Despite previous consolidation efforts, new methods are quickly emerging. To minimise the amount of oil in MQL, the selection of the point of the application becomes a significant factor. The rake and flank face are the two main locations that experience maximum tribological and thermo-mechanical changes. Several research efforts have been made to realise the outcome of localised cooling and lubrication at flank and rake face; a combination of the two has also been investigated. The knowledge on this issue is scattered and need consolidation for reference of the end-users. The present article is an attempt in the same direction. The article focuses on two significant aspects, namely, the

efficacy of different MQL cutting fluids and their localised application. The subject matter is analysed from the perspectives of cooling and lubrication strategies, MQL parameters, and their effect on quality. Subsequently, a discussion on the latest developments and future directions is provided.

2 Cutting fluids in MQL

The essential attributes that qualify a lubricant include – boiling and freezing point, viscosity index, kinematic viscosity, pour point and flashpoint. Since the cooling and lubrication in MQL is achieved with a small quantity of the oils, their physical and chemical properties play a significant role. In terms of environmental friendliness, the secondary performance of the cutting fluids should be considered, which includes environmental compatibility, oxidation stability and storage stability (Suda et al., 2002). The following section gives insight into some of the commonly used cutting fluid in MQL.

Figure 3 Influence of feed rate and lubrication strategies on tool life using synthetic ester (see online version for colours)

Source: Aoyama et al. (2008)

2.1 Synthetic ester

Synthetic esters are obtained from the esterification of the biodegradable material, refining the animal fats and vegetable oils. The ester develops an oxide layer which acts as a protective cover on the tool surface during MQL machining. The protective layer results in increased tool life and improved surface finish of the workpiece (Liao and Lin, 2007). The protective layer of oxide is maintained at higher speed and feed rates (Figure 3) (Liao et al., 2007). Aoyama et al. (2008) showed the effectiveness of synthetic ester as a lubricant in the MQL application. The effectiveness of synthetic ester can be improved by adding extreme pressure (EP) additives. Suda et al. (2004) developed a multifunctional fluid by adding organo-phosphorus (an EP) compound with synthetic

polyol ester that can be used as a lubricant in the machine tools as well as a cutting fluid. The effectiveness of MQL using synthetic ester depends on different carrier gases, such as nitrogen, oxygen, and argon present in the air (Figure 4) (Wakabayashi et al., 2007). Improvement in the performance was observed when nitrogen and argon were used as carrier gases with a base fluid. A small number of microdroplets of water added with the oil mist could enhance the tribological condition during machining.

Figure 4 Comparison of the effect of various carrier gases on thrust force during drilling (see online version for colours)

Source: Wakabayashi et al. (2007)

2.2 Vegetable oil

Vegetable oils are mixtures of long-chain fatty acids. The flash point, viscosity, and boiling point of the vegetable oils are higher than the mineral oil. Consequently, the vegetable oils generate less smoke, offer more lubricity, and do not quickly vaporise. These attributes make the vegetable oils the potential candidates for MQL. Various vegetable oils, namely soybean, high oleic soybean, sunflower, rapeseed, palm, rice bran, jatropha, olive, castor, neem, linseed and coconut, are used for machining with MQL. The advantages of vegetable oils are shown in Table 1. MQL can improve the machining condition by reducing the cutting zone temperature, enabling favourable chip formation, improving tool life as well as the surface finish when vegetable oil is used as a lubricant.

Table 1 Pros and cons of vegetable oil as lubricants

<i>Advantages</i>	<i>Disadvantages</i>
Better biodegradability	Low thermal stability
Lower level of environmental pollution	Oxidative stability
Easily compatible with additives	High freezing point
Comparatively lower production cost	Corrosive nature
Wide range of manufacturing options	
Less harmful as compared to other cutting oils	
Flashpoints are considerably high	
Less volatile	
Viscosity indexes are higher	

Source: Shashidhara and Jayaram (2010)

Leppert (2011) analysed the effect of different cooling and lubrication strategies, i.e., vegetable oil-based MQL, dry cutting, and flood cooling on the surface finish, profile bearing ratio, topography and cutting forces. The experimental results showed that machining parameters, i.e., speed and feed, can significantly influence the effectiveness of the lubrication process. The improvement in the tool life, surface finish, and burr formation can be achieved with the use of vegetable oil as a lubricant in MQL micro-milling operations (Li and Chou, 2010). The effect of air flow rate is more significant than the oil flow rate in improving tool life (Figure 5). The effects of using different speeds and feeds on surface roughness for different cutting lengths are shown in Figure 6.

Figure 5 Effect of different lubrication conditions on tool wear in MQL with vegetable oil (a) varying flow rate of oil and (b) varying flow rate of air (see online version for colours)

Source: Li and Chou (2010)

Figure 6 Effect of cutting length and surface roughness at, (a) various rotational speed (b) feeds (see online version for colours)

Source: Braghini et al. (2009)

The enhancement in tool life can be obtained by using the neat vegetable oil in MQL when compared with the cutting in dry and flood cooling conditions (Braghini et al., 2009). With the use of a small quantity of vegetable oil-based lubricant supply (7 ml/hr), a substantial reduction in corner and flank wear could be achieved (Obikawa et al., 2006). The pressure of the injected air could play a significant role in the MQL application since it is responsible for atomising and transporting the oil from the nozzle to the tool-workpiece and the tool-chip interface.

Bruni et al. (2006) showed the effectiveness of using vegetable oil-based cutting fluids in MQL, during the finish turning of AISI 420B stainless steel with wiper technology cutting insert. Drilling titanium alloys (Ti-6Al-4V) using palm oil can improve the performance as compared to a synthetic ester by limiting the temperature generated during machining, reducing the cutting and thrust forces, improving the power specific cutting energy and prolonging the tool life (Rahim and Sasahara, 2011).

2.3 Mineral oil

MQL with mineral oil mixed with compressed air can give a comparable result in terms of cutting and thrust forces, tool wear, and quality of machined holes as that of flood cooling (Braga et al., 2002). An enhancement in the machined surface quality and tool life can be achieved using a minimal quantity (2 ml/min) of mineral oil in MQL hard turning because of lower cutting temperature and cutting forces (Varadarajan et al., 2002). The performance of coated tools, i.e., single-coated and nano-coated tools, can be improved while using the MQL as it can reduce the wear mechanisms like delamination, attrition and abrasion (Figure 7) (Liew, 2010).

Figure 7 Comparison of flank wear for (a) TiAlN and (b) TiAlN/AlCrN-coated carbide inserts

Note: a – attrition and abrasion, c – cracking and f – fracture.

Source: Liew (2010)

2.4 EP additives

The machining performance can be improved by adding EP additives with cutting fluid as they reduce tool wear. The addition of additives with the base cutting fluid improves the effectiveness at high pressure and temperature conditions. The EP additives have also been used with MQL fluids. Jayal and Balaji (2009) used mineral oil and natural esters mixed with EP additives (Sulphur-based) as a lubricant in the MQL turning of AISI-1045. The results suggested that the injection of cutting fluid position and its type significantly affect the tool life and cutting forces. Although flood cooling could enhance the machining performance in terms of improvement in tool life and cutting force reduction, MQL machining was able to reduce the cutting force and increase tool life as compared to dry cutting. Attanasio et al. (2006) showed that the EP additives in ester oil could improve the tool life in turning process. Kishawy et al. (2005) used synthetic phosphate ester mixed with EP additives in an MQL system for high-speed milling of A356 aluminium alloy. The adhesion and adhesive tool wear could be reduced by using the MQL technique.

2.5 Nanofluids

The nanofluids are colloidal suspensions of nanoparticles in a fluid such as water or oil. They show enhanced heat transfer, thus are found useful in machining applications. Several substances like graphene, MoS_2 , Al_2O_3 , SiO_2 , multiwall carbon nanotube, graphite, copper, copper oxide, boric acid, etc. have been investigated as additives in nanofluid for MQL applications. These nanoparticles in different concentration can be mixed with various carrier fluids to obtain potential nanofluids; many of which are listed in Sharma et al. (2016). The impact of nanoparticles on thermal conductivity improvement of nanofluid fluids can be visualised from Figure 8. The scatter plot generalises the impact of additive size and volume fraction to understand the impact on thermal conductivity of representative combinations of additives and carrier fluid available in Hegab (2018). Small to medium-sized nanoparticles improve the thermal conductivity while the thermal conductivity increases with increase in volume fractions. Smaller size additive particles improve the thermal conductivity because of the increase in the surface area.

Considerable improvement in terms of cutting force reduction, improved surface finish, low cutting temperature, and increase in tool life can be achieved by using nanofluid in MQL operation, as compared to directly apply the base fluid as the cutting fluid in MQL (Vasu and Reddy, 2011). Nam et al. (2011) studied the influence of nanofluids as a lubricant in the MQL system on the micro-drilling of aluminium 6061. The paraffin oil and vegetable oil were used as the base fluid, and nano-diamond particles were mixed with them at different concentrations to form the nanofluids. The developed cutting fluids showed significant improvement in the quality of the drilled holes. Considerable reduction in average torque and average thrust force was observed using different concentrations of nanofluids as compared to compressed air cooling. Since the viscosity of vegetable oil is two to three times higher than the paraffin oil, more nanoparticles are required for vegetable oil to become evenly distributed in the liquid medium and to obtain the desired cooling and lubrication effect. The use of surfactant with the nanofluids can further improve its effectiveness since it can effectively disperse the particles evenly within the base fluid volume (Musavi et al., 2019). One of the issues

with the use of nanofluids in MQL operation that needs further examination is occupational hazards. A large proportion of the MQL fluid is not recovered as atomised mixtures directly spread in the surrounding environment. In addition to the occupational hazards, the cost of nanofluid is also very high. Special efforts are required to prevent the nanoparticles in spreading in the environment by collecting them after they accomplish their role in the machining.

Figure 8 Impact of nanoadditive size and volume fraction on the thermal conductivity of nanofluids (see online version for colours)

3 Cooling and lubrication approaches in MQL

The three main heat generation regions in the cutting zone – the primary shear zone, the secondary shear zone, and the tool contact with the freshly machined surface (Figure 9). The unique effect of cooling and lubrication at these three zones can be attributed to different reasons. At the primary shear zone, cooling and lubrication result in chip curl, and reduction in cutting forces, while at the secondary shear zone, cooling and lubrication facilitate smooth flow of chip and reduce crater wear. At the tool contact with the freshly machined surface, cooling and lubrication reduce the flank wear and improve the surface quality.

Figure 9 Schematic of chip formation mechanism

A proper selection of cutting fluid and the ability to direct the fluid to the proper locations are vital for its optimal usage. Since a very small quantity of cutting fluid is used in MQL system, hence it becomes imperative to inject it in the proper location during the cutting operation. In recent times, the focus has also been on understanding the effect of applying small quantities of lubricants only at the cutting zone instead of spraying it anonymously. During the metal cutting operation using a single-point cutting tool, there are three ways that a cutting fluid can be applied, as shown in Figure 10, namely, at the rake face, at the back of the chip, and the flank face.

Figure 10 Schematic representation of the multi-point cooling system

Source: Banerjee and Sharma (2019)

Figure 11 Effect of tool wear on different cutting conditions, (a) principle flank wear
(b) auxiliary flank wear

Source: Dhar et al. (2007)

3.1 MQL at the rake face

The use of applying cutting fluid at the rake face of the cutting tool is reported in the literature. A substantial decrease in flank wears (both auxiliary and principle) was reported in the work of Dhar et al. (2006) (Figure 11). The application of MQL showed its superiority over wet and dry cutting. Surface roughness also reduced by using the MQL technique (Figure 12).

Figure 12 Comparison of surface roughness values under different lubricating conditions

Source: Dhar et al. (2007)

Figure 13 Variation in forces under dry and MQL conditions, (a) cutting force (b) feed force

Source: Dhar et al. (2007)

Improvement in terms of reduction in cutting force and feed force at various cutting speeds was also observed by Dhar et al. (2007) (Figure 13). Tasdelen et al. (2008) investigated the influence of different cooling and lubricating environment, i.e., MQL, cooling using compressed air, and cooling using emulsion-based cutting fluid on the tool-chip contact length. Although their study revealed that MQL and cooling using compressed air both could reduce the contact length as compared to dry cutting, the wet cooling provides the minimal tool-chip contact length.

Khan et al. (2009) suggested that the considerable reduction in cutting zone temperature can be achieved by injecting cutting fluid in the form of aerosol at the rake face. Improvement in tool life as well as in surface finish was also observed by using MQL. Musavi et al. (2019) also showed that the use of surfactant in nanofluids at the rake face could improve the surface finish, as compared to the nanofluids without surfactant.

3.2 *MQL at the back of the chip*

Itoigawa et al. (2006) showed that by keeping the nozzle position just above the cutting position, a considerable reduction in the specific cutting force could be achieved. The amount of cutting force reduction was comparable to that of flood coolant, and in some cases, the results were even better. Jayal and Balaji (2009) suggested that injecting the cutting fluid at the back of the chip can enhance the tool life as well as effectively reduce the cutting force compared to dry machining (Figure 14 and Figure 15). Addition of EP additives with MQL oil can further enhance its performance in certain conditions.

Figure 14 Effect of various lubricating conditions on tool life for, (a) PVD coated flat-faced inserts (b) PVD coated grooved inserts

Source: Jayal and Balaji (2009)

3.3 *MQL at the flank face*

The effectiveness of injecting the MQL mist at the tool-workpiece interface, i.e., at the flank face is reported in the literature. Obikawa et al. (2009) examined the influence of nozzle distance from the tool-workpiece interface (flank face). Investigation revealed that

the cutting fluid sprayed from the oblique position with specially covered design nozzle could provide a better spray pattern. An improved spray pattern can, in turn, help to provide better lubrication and cooling effect. In another work, Obikawa et al. (2008) investigated the efficacy of a micro-litre (less than 1 ml/hr oil consumption) lubrication technique by injecting cutting fluid through the specially designed nozzles attached to the tool holder. Effectiveness in performance was achieved in terms of lower surface roughness and prolonged tool life. The position of the injecting nozzle and its design plays a vital role in achieving the desired results from the proposed system. A predictive model was developed by Li and Liang (2007), where the influence of injecting the cutting fluid in the flank face of the cutting tool on cutting forces was analysed during the MQL environment. A model for predicting the cutting forces was developed by considering the material properties and boundary lubrication approach.

Figure 15 Effect of various lubricating conditions on cutting force at 400 m/min for, (a) PVD coated flat-faced cutting inserts (b) PVD coated grooved cutting inserts

Source: Jayal and Balaji (2009)

Figure 16 Position of the nozzle at, (a) the rake face (b) flank face

Source: Attanasio et al. (2006)

3.4 MQL combined at rake face and flank face

The benefits of cooling at individual zones can be enhanced by simultaneous application of cutting fluid at the rake face and flank face. Attanasio et al. (2006) showed that the injecting the cutting fluid independently at the flank face of the tool could reduce the tool wear as compared to injecting at the rake (Figure 16). The work of Kamata and Obikawa (2007) suggested that the simultaneous application of cutting fluid at the rake and the flank face of the tool can significantly improve the tool life and surface finish during the turning of Inconel 718. A proper air-oil mixture is required to obtain better performance.

In the work of Leppert (2011), the influence of applying the MQL at the rake and the flank face of the tool during the turning of C45 steel was reported. The performance of the MQL was compared with that of dry cutting and flood cooling conditions. An improved performance was observed in terms of cutting forces surface roughness and surface waviness reduction.

3.5 MQL at the flank face, rake face and back of the chip

Very few works are available in the literature wherein the MQL fluid is simultaneously applied on the flank face, rake face, and back of the chip. The work of Banerjee and Sharma (2015) reported the effect of injecting MQL fluid at the multiple locations. The effects were analysed in terms of reduction in cutting force and surface roughness. The injection of MQL fluid at the multiple locations, especially simultaneously on the rake face and back of the chip, reduced the cutting force and surface roughness. Li and Seah (2003) investigated the influence of injecting compressed air at the rake face, flank face, and above the chip separately, during the turning operation of SiC-aluminium metal matrix composite. The pressurised air was used as a cutting fluid, keeping the air pressure like that of the conventionally applied MQL. Applying pressurised air individually at all these three places can be highly beneficial in reducing tool wear (Figure 17). Studies have also revealed that injecting air at the rake face can provide maximum benefits. Figure 18 shows that pressure plays a crucial role in reducing the amount of tool wear. Also, higher pressure results in reduced tool wear.

Effect of nozzle positions was reported in the work of Bonfá et al. (2019). A comparison of injecting cutting fluid at the flank position, auxiliary flank position, and in the overhead position (back of the chip) was made. The improved performance was observed in terms of low tool wear when the nozzle position was kept at the flank position as compared to dry cutting and other two nozzle positions.

It can be inferred on localised cooling methods that injecting the cutting fluid with optimal pressure and oil quantity can affect the tool life, surface roughness, chip morphology, and cutting forces during the machining operation. The coolant nozzle position plays a significant role in obtaining a beneficial machining condition. The placement of the nozzle at the rake or flank face has individual benefits which are further augmented by simultaneous use at both rake and flank in terms of lower forces and surface roughness (Masoudi et al., 2018). The location-specific cooling not only useful in single-point cutting but also the milling cutters with multiple inserts exhibit a reduction in tool wear rate when MQL is applied to inserts (Werda et al., 2017).

Figure 17 Effect of application of pressurised air at three different locations on flank wear

Source: Li and Seah (2003)

Figure 18 Effect of air pressure applied to the rake face on flank wear

Source: Li and Seah (2003)

3.6 Interplay between machining parameters and nozzle position

The MQL process is controlled by air/fluid pressure and flow rate in combination with machining parameters, i.e., feed rate, depth of cut and cutting speed. The right selection of MQL parameters can significantly reduce the friction between tool-chip interfaces. The sliding speed followed by MQL parameters affects the friction coefficient. Chip morphology and degree of serration are also affected by using different lubricating conditions. The effectiveness of MQL is more pronounced at severe machining conditions such as higher cutting speed and feed rates. Extremely high speeds, as well as excess oil supply, lead to a rough machined surface and excessive wear of the tool because of the slurry made of worn tool particulates, workpiece material and oil. The

slurry increases the friction at the interface. An optimal oil-flow rate with moderate cutting speed and air pressure is adequate for lubrication and cooling. Excess pressure reduces the droplet size and increases their numbers which generate secondary droplets that lead to a reduction in heat dissipation capability.

The relationship between the nozzle position can be realised by analysis of a typical case of MQL machining of normalised 100Cr6 steel using ester oil with EP additive (Table 2). The mist supplied on the flank face provides more tool life compared to that achieved by supplied on the rake face or the dry cutting. The supply at the flank face assists the mist reaching the cutting zone and thereby achieving longer tool life even at greater cutting lengths. In comparison with the dry cutting, the MQL remains more effective at higher feed rates.

Table 2 Effect of nozzle position on the rake face and the flank face in terms of tool wear

<i>Lubrication</i>	<i>Feed rate (mm/rev)</i>	<i>Cutting length (mm)</i>	<i>Mean tool life (min.)</i>
Dry	0.20	50	10.04
		200	10.10
	0.26	50	8.17
		200	7.86
MQL of rake	0.20	50	9.75
		200	9.48
	0.26	50	8.58
		200	9.36
MQL of flank	0.20	50	10.36
		200	11.44
	0.26	50	9.16
		200	9.68

Source: Attanasio et al. (2006)

4 Latest developments and future directions

The research in MQL in the last few years has exponentially grown, which more often relates to the assessment of new cutting fluids, e.g., the jojoba oil is recently reported to be for the first time as base oil in nanofluid for the MQL machining (Gaurav et al., 2020). The remarkable breakthroughs in recent times are the hybridisation of cooling methods and cutting fluids. The application of the hybridised fluids at a specific location in the cutting zones, as discussed in the previous sections, would pave the way to one of the future directions of research in MQL.

4.1 Hybrid metalworking fluid

The hybridisation of metalworking fluids or fluid with solid substances enhances the effectiveness of metalworking fluid; for example, when graphite is mixed with mineral oil, the surface finish significantly improves. The graphite powder helps in chip removal. In combination with the ease of chip removal, the spread of graphite powder on the

finished surface significantly improves the surface finish by minimising the effect of rubbing by the auxiliary flank (Muaz and Choudhury, 2019). The hybridisation also brings in tribological phenomenon different from those that are present in the conventional MQL. One of such examples is the mixing of phosphonium and ammonium-based ionic liquids with vegetable-based metalworking fluid (Sani et al., 2019). The ionic liquid promotes physisorption (physical absorption of lubricant molecules caused by Van der Waals forces) in addition to the chemical reaction of the ionic fluid with the metal. The resulting metal oxide tribofilm improves the machining performance in terms of reduction in cutting forces, specific cutting energy, cutting temperatures, friction coefficient, tool-chip contact length and chip thickness.

Another aspect of hybridisation is blending or dilution of metalworking fluid by adding substances like water or different oils. The cooling capacity of the lean MQL fluid is enhanced by diluting the base oil with water. The dilution improves the cooling capacity without additional cost. The preliminary results of oil-water amalgamation are favourable to the extent that the emergence of new research on the MQL technique is anticipated (de Moraes et al., 2019). The preliminary investigations suggest a wide range of dilution, for example, 1:5 (de Moraes et al., 2019) to 3:2 (Liao et al., 2017), that means the degree of dilution merits further investigations. The performance of MQL mist is also improved innovative methods like electrostatic atomisation (Lv et al., 2018), wherein the atomisation is achieved by forces. In time to come, the electrostatic atomisation could prove pathbreaking in achieving micro level localised lubrication by electrically directing the mist stream.

4.2 Hybrid cooling and lubrication techniques

Several environmentally friendly machining techniques have simultaneously grown along with MQL, e.g., cryogenic cooling, CO₂ and cold air. These techniques have individual merits and limitations. Hybridisation of the cooling-lubrication techniques has added value to the overall machining performance; for example, a combination of MQL and cryogenic cooling [known as CryoMQL (Pereira et al., 2017)] overcomes the limited tool life due to cryogenic cooling. In the CryoMQL process, the CO₂ is first heated over the critical point in a pressurised tank with oil and then injected to the cutting zone. In a typical condition, the CryoMQL can achieve 30% and 10% improvement over the tool life obtained with cryogenic and MQL machining, respectively. The cryogenic and MQL hybridisation is also achieved by multi-point injection, i.e., MQL and cryogenic fluids are supplied by different nozzles (Sartori et al., 2017). Like the CryoMQL, the multi-nozzle hybrid cryogenic MQL also improves the tool life; however, the MQL yields smoother surface than the hybrid cryogenic MQL. On a similar line, MQL with compressed cold air (MQCL) is a perfect example of hybridisation. The MQCL impacts the chip formation and separation mechanism. The chips are produced with the smooth backside, thin cross-section, and reduced curl radius (Benjamin et al., 2018). Easy separation of chips leads to a decrease in cutting temperatures and cutting forces, along with an increase in tool life. The location (rake and flank) also plays a role in hybridised cooling, for example, MQL hybridised with cryogenic carbon dioxide (CMQL) and supplied at the flank face improves the tool wear and surface finish in comparison with CO₂ and MQL supplied to the rake and flank faces (Bagherzadeh and Budak, 2018). The reduction in contact length and higher thermal efficiency of CMQL plays a vital role in improving its performance.

4.3 *Multi-point injection*

Despite the advantages of supplying the MQL mist at specific locations, as discussed in previous sections, a universal mandate on the selection of the specific location is not possible. The application points (e.g., rake or flank) act as minor or major contributors to a specific outcome rather than becoming entirely beneficial or entirely detrimental. The collective benefits of simultaneously applying the mist at a different location with independent control on flow rate and pressure motivated the distributive cooling through multi-point injection. The multi-point injection allows the simultaneous but individual supply and control of fluid to the specific locations (Banerjee and Sharma, 2016, 2018, 2019). The oil distribution factor defines the proportion in which the oil is distributed between the rake and flank faces. Focusing the total oil quantity at the flank face can provide better surface finish; but if the supply is distributed, e.g., 25% of oil is focused at the flank face and rest at the rake face, cutting energy can be minimised.

The multi-point cooling with external nozzles needs precise control over the nozzle location. This problem is resolved in a recent investigation wherein an embedded double jet nozzle is designed (Zaman and Dhar, 2019). The tool holder is drilled with holes and embedded with specially designed nozzles for the supply of the mist. The arrangement helps in reducing the cutting temperature and improving the surface finish and tool life in addition to the saving of time spent in nozzle adjustment (Zaman and Dhar, 2019). The multi-point cooling is further augmented by providing in more than one streams of mist at rake or flank faces. Supplying the mist by three nozzles at the flank face significantly improves the wear performance (Alagan et al., 2019). The multi-point injection could be investigated in future for the use of different base oils in the individual streams or blending of different oils to enhance the performance.

4.4 *Modelling of MQL machining*

The selection of a cooling method or strategy is still an open question. More often, the investigations until now are designed to improve the machining performance through experimental evaluation. These investigations also attempt to indirectly understand the associated physical phenomenon through analysis of the results. Modelling of MQL phenomenon is lesser investigated because of increased complexity associated with flow pattern, and lesser-known modelling parameters such as heat transfer and friction coefficients. Current investigations cover one or two of the multiple phenomena that are simultaneously present in the MQL, namely, fluid dynamics, tribology and mechanical aspects. The outcomes of the modelling investigation could part of the associated phenomena, e.g., Vazquez et al. (2014) performed a computational fluid dynamics analysis of MQL micro-milling to divulge the flow order disorder that results insufficient cooling and lubricating condition. The numerical simulation of MQL is still to develop. Moreover, the simulation of location specific MQL or multi-point MQL is a computationally highly challenging task. Additionally, the monitoring of such complex systems to generate validation data (for example, intricate flow pattern due to multiple interfering mist streams) could be a multi-disciplinary research challenge for the future.

5 Conclusions

The article reviews the localised and multi-point cooling and lubrication approaches used in machining with MQL. The article consolidates the scattered knowledge on the topic and concludes as follows:

- 1 MQL machining has been keenly investigated in the recent past from various aspects including cooling and lubrication strategies, MQL parameters and their effect on quality. Various studies have compared MQL with other machining processes and proposed it as a viable and environmentally friendly alternative.
- 2 Recent works show that because of environmental concerns, the use of oil-based lubricants (mineral oil) is going obsolete. Synthetic esters and vegetable oil-based cutting fluid usage are becoming more prevalent. Use of additives and nanofluids has shown promising results, but occupational hazards associated with the use of nanofluid need to be further examined for large-scale industrial applications.
- 3 The application of MQL mist at a specific location, namely rake, flank, and back of the chip impacts the machining performance. The flank face application helps in enhancing the tool life while the rake face influences the chip separation. The choice of the placement for the mist application may induce a major or minor impact on one or more process outcomes. The simultaneous application at different locations improves the overall machining performance.
- 4 The advantages of localised cooling and lubrication can be augmented by simultaneous multi-point injection of mist. The individual supply of mist can be individually controlled so that the optimal results can be obtained with the minimum possible consumption of oil. New tool holders are designed to realise the multi-point injection.
- 5 The MQL research is expected to grow in three directions, namely hybridisation of cooling methods, use of hybridised fluids, and modelling of MQL machining process. Coupling of thermal, fluid flow, and plasticity model will pave the way for future research in MQL provided the computational capability required to address the inherent complexity is made available.

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