Prabha Materials Science Letters
Vol. 3, No. 2, 191-203, 2024
https://doi.org/10.33889/PMSL.2024.3.2.012

Ram Arti
Publishers

A Short Review on Minimum Quantity Lubrication Method in Machining Applications

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(Received on March 25, 2024; Revised on May 18, 2024; Accepted on May 20, 2024)

Abstract
To maximize production while reducing environmental effect, the machining industry is always looking for new, sustainable, and cost feasible ways. One approach that shows promise in this area is Minimum Quantity Lubrication (MQL). The MQL approach is briefly reviewed in this work with an emphasis on its use in machining. At the beginning of the study, a basic introduction of the MQL method is given, and then its effect on tool wear, surface roughness, cutting temperature and the energy consumption is reviewed. In brief, this paper discusses MQL's lubrication methods, benefits, drawbacks, and applications in different machining operations. The outcomes demonstrated that the MQL efficacy is also affected by tool material, workpiece material, cutting conditions, and lubricant type. Therefore, it is worth to mention that this review emphasizes MQL's sustainability in machining lubrication. By balancing its pros and cons, this study hopes to help readers understand MQL and its potential to optimize machining operations in many industries.

Keywords- Machining, MQL, Sustainable manufacturing, Cutting fluids.

1. Introduction

The use of abundant coolants and lubricants stands out when the studies on the machining of engineering materials are examined (Demirpolat et al., 2023; Gupta et al., 2023b; Srinivas et al., 2023). In particular, the dangers of chemical and petroleum-based lubricants and coolants used in traditional cooling for the environment and human health have become more evident (Kuntoğlu et al., 2023; Ross et al., 2023), and new lubrication and cooling conditions have begun to be developed to reduce these effects (Binali et al., 2023b; Etri et al., 2023). Minimum Quantity Lubrication (MQL) is among the best alternatives (Binali et al., 2023a; Gupta et al., 2023a). In machining, MQL means sending the cutting fluid to the cutting tool-workpiece contact area by pulverizing it with compressed air (Gürkan et al., 2020; Ross et al., 2023). Compared with dry machining, machining using the MQL method increases tool life (Cönger et al., 2024; Shyam et al., 2021), reduces cutting temperatures (Ross et al., 2022b; Şirin and Kivak, 2021), reduces surface roughness (Gupta et al., 2022; Ross et al., 2022c), etc. Additionally, the properties of the cutting fluid play an important role in machining performance (Bedi et al., 2020; Öndin et al., 2020). The MQL method not only reduces the amount of cutting oil used but also reduces production costs. It is also considered to have less negative impact on human health and the environment (Sarıkaya et al., 2016). The use of vegetable-based cutting and cooling fluids as an alternative to chemical and petroleum-based cutting fluids is becoming more common day by day. Majak et al. examined the effects of using vegetable-based cutting fluids under MQL condition in turning AISI 304 stainless steel. They used palm, coconut and sunflower oils as cutting fluids and concluded that sunflower oil gave the best surface quality and that sunflower oil was the most suitable oil for sustainable manufacturing among these three oils (Majak et al., 2020). The effects of the MQL method and the vegetable-based oils used on many issues such as machining, part surface quality and cost, processing parameters, tools and energy usage should be investigated. The effects of the MQL method and the vegetable-based cutting fluids used on many issues such as machining, part surface quality and cost, machining parameters, cutting tools and energy use are continuing to be investigated. Roy et al. (2019) examined the use of the MQL method in various machining processes. It has been concluded that the MQL method, in which vegetable-based cutting fluids are used, gives better results in reducing the temperatures in the cutting zone, increasing tool life and reducing surface roughness compared to dry and traditional cooling conditions. It has also been concluded that the use of graphite as nanoparticles has a positive effect on tool life and surface quality because it reduces cutting forces and heat in the cutting zone. Yazid et al. (2011) examined the turning of Inconel 718 alloy using the PVD (Physical Vapor Deposition) method and the MQL method with a TiAlN coated WC cutting tool. Better surface roughness values were obtained using the MQL method compared to the dry machining condition. Babu et al. (2017) examined the turning of AISI 410 stainless steel with uncoated tungsten carbide tools under dry, conventional and MQL lubrication/cooling conditions. In the study, 3 nozzles were used in the MQL system. As a result of the experiments, it was stated that the MQL condition is an effective method on tool life and cutting forces. The MQL method provided an improvement of 9% and 51% in surface roughness and 18% and 19% in cutting forces, respectively, compared to dry and conventional conditions. Additionally, less wear occurred on the cutting tool in the MQL condition compared to the other two conditions. The reason for this is that the friction between the cutting tool and the workpiece decreases in the MQL method. Rajaguru and Arunachalam (2020) performed a turning operation of super duplex stainless steel under dry, conventional and MQL lubrication/cooling conditions. They stated that they detected fewer surface cracks in the samples processed using the MQL method, and the reason for this was the lower surface residual stress in connection with the decrease in cutting forces in the MQL condition. In the study, it was observed that the MQL method reduced cutting tool wear by 33.08% compared to the dry condition. In addition, a 29.06% improvement in surface roughness was observed in conventional cooling and 54.69% in the MQL method compared to the dry cutting condition.

The primary objective of lubricating systems is to mitigate heat generation by establishing a thin protective film between the cutting tool and metal chips, hence reducing friction at the cutting zone (Korkmaz et al., 2022; Ross et al., 2022a). The dry and other conventional or sustainable machining methods have both benefits and drawbacks. Regarding dry machining, several advantages may be enumerated (Korkmaz et al., 2019), including cost-effectiveness (in terms of lubrication and cleaning expenses), mitigation of thermal shocks, reduction of environmental pollutants, and prevention of health issues (Korkmaz and Gunay, 2018). With the use of the MQL method, the use of chemicals and petroleum-based oils is reduced (Dixit et al., 2012). In addition, vegetable-based cutting fluids are also used in the MQL method (Baldin et al., 2021; Srinivas et al., 2021; Touggui et al., 2021). However, the herbal cutting fluids used may not provide the desired performance at high temperatures, feed and cutting speed values, and their structure may deteriorate and become unusable (Usha and Rao, 2020). These deteriorations and deficiencies can directly cause the workpieces not to be produced with the desired features (Günay and Korkmaz, 2024). As a result of all these negativities, it may be necessary to apply extra machining or machining-free shaping methods to bring the parts to the desired form (Alparslan and Bayraktar, 2021). As a result, products cannot be manufactured at the desired time, costs increase, and ecological damage increases due to the use of more energy and refrigerant (Günay and Meral, 2020). In order to eliminate all these losses or reduce costs, studies are being carried out to increase the performance of the vegetable cutting fluids used in the MQL method (Çakır Şencan et al., 2021), instead of returning to the traditional lubrication/cooling method (Mergen and Kafkas, 2023), which is known to be harmful to the environment and human health (Gupta et al., 2024).

One illustration of a mist-assisted lubrication technique is the near-dry lubrication method, which is sometimes referred to as the MQL, as shown in **Figure 1**. The proposed technique involves the integration of a small amount of lubricant with the air that is released from the output of an air compressor (Li et al., 2016). This aligns with the nomenclature of the procedure, indicating that it pertains to MQL. A nozzle, which is a part of a MQL system, is responsible for directing pressurized air into the specific region where the workpiece and the tool are situated as shown in **Figure 1** (Pervaiz et al., 2022). The prevailing conditions result in variations in air pressure ranging from 0.1 to 0.8 MPa, contingent upon the specific requirements. The flow rate of the liquid at usage spans a range of 20–1200 mL/h (Hamran et al., 2020).

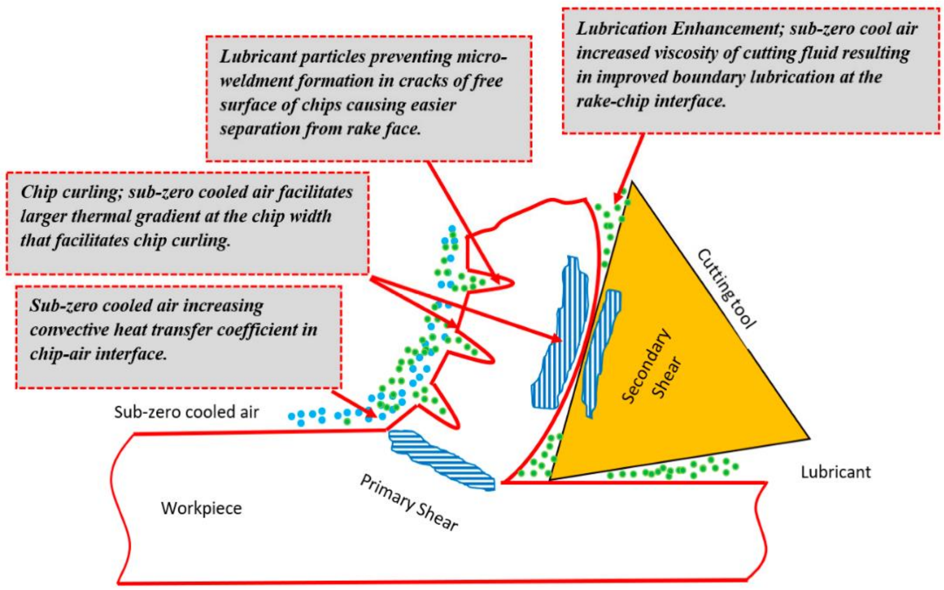

Figure 1. Schematic of MQL mechanism (Pervaiz et al., 2022).

The traditional approach to MQL entails employing a combination of air and oil to produce aerosol. MQL may be classified into two distinct groups based on the supply system: internal supply systems and external supply systems. The categorization of these supply systems is contingent upon the specific characteristics of the application being employed. The MQL system has many components, including a cutting fluid container, a compressor, tubing, a spray nozzle, and a flow control system (Rahim and Dorairaju, 2018). To improve the surface roughness, it is necessary to handle the bottleneck problem of adjusting the position parameters of the nozzle, such as the target distance, incidence angle, and elevation angle. When it comes to sustainability, MQL demonstrates more cost-effectiveness and environmental friendliness in comparison to flood cooling. The application of Minimum Quantity Lubrication (MQL) in machining operations yields improved outcomes in terms of cutting forces, surface integrity, temperature, and tool lifespan when compared to both dry and wet machining techniques. MQL places tool wear as a primary indicator for evaluating the performance of machinability. The coming sections will provide a detailed explanation of MQL and its use for enhancing machining performance.

2. Tool Wear Improvement with Lubricated Conditions

Khan et al. (2018) concluded that the MQL system outperforms both dry and wet cooling systems in terms of machining performance after completing an experimental investigation on the grinding of AISI D2 steel using a MQL system. Furthermore, it was asserted that the grinding methods conducted on a diverse range of alloys yielded consistent outcomes. Synthetic ester oils are more efficient than vegetable oils as the base fluid for MQL. Synthetic ester oils are gaining popularity due to their enhanced heat stability, oxidation resistance, and lubricating properties. The materials possess a molecular structure that facilitates enhanced load-carrying capacity and reduced frictional capacity, hence leading to improved machining efficiency. Furthermore, synthetic esters exhibit enhanced resistance to degradation under elevated temperatures, therefore guaranteeing consistent lubrication even in the presence of challenging machining conditions. Due to these characteristics, they are particularly suitable for use in MQL applications, which necessitate lubrication that is both efficient and reliable to enhance tool longevity and machining efficiency. MQL has excellent performance in terms of crater wear. The primary reason for this is the tribological and heat transfer effects that take place during the first process, as opposed to dry and wet machining. The mist has the capability to infiltrate the cutting zone, hence mitigating the generation of elevated temperatures. The conducted experiments aimed to compare the outcomes with MQL and revealed that MQL resulted in a reduction in tool wear (Sultana and Dhar, 2022). Szczotkarz et al. (2020) conducted a study to examine the advantages of using the MQL and MQCL techniques alongside the extreme pressure and anti-wear (EP/AW) approach. The goal was to minimize wear in the turning of 316L stainless steel tools coated with AlTiN. The active medium employed in the MQCL approach was a blend of water and an emulsified mineral oil derived from a concentrate. Conversely, the MQL technique employed vegetable oil as the active medium to augment the lubricating characteristics of the cutting fluid. When conducting a comparison between the MQCL+EP/AW methodology and dry machining, it was seen that the use of the MQL method led to a decrease of roughly 9% and approximately 21% in the level of cutting tool wear, respectively as shown in **Figure 2**.

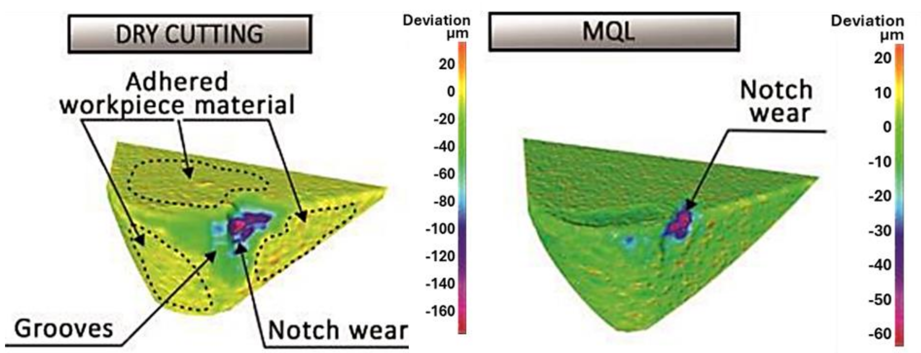

Figure 2. Minimizing tool wear by MQL method in the turning (Szczotkarz et al., 2020).

Salur et al. (2021) conducted a study on the milling of AISI 1040 steel to evaluate tool wear, focusing specifically on the results obtained from MQL and dry machining techniques. After executing the experiment, it was revealed that the MQL conditions yielded the most significant outcomes in terms of flank wear. Chinchanikar and Choudhury (2014) successfully identified the wear pattern of carbide-coated tools during severe turning under MQL and dry conditions. By employing MQL at elevated cutting rates of 150 mm/min, a notable increase in tool longevity was seen throughout the cutting procedure. The superior cooling provided by MQL effectively disperses heat generated during high-speed machining, hence preserving the tool's hardness and minimizing thermal-induced wear. Furthermore, the lubricant facilitates the smooth evacuation of chips, hence minimizing the likelihood of chip recutting. In order to enhance the lubricating and cooling characteristics of the material, the incorporation of solid lubricant in the form of particles into MQL was undertaken. Saha et al. (2021) conducted a study to examine the wear characteristics of the micro-milling tool. The study encompassed an examination of the tool form, stress distribution, lubrication, and tribology, conducted under both dry and MQL conditions. The application of MQL resulted in a decrease in the measured coefficient of friction at the contact between the chip and the tool, resulting in a range of values between 0.50 and 0.60. Firstly, the novel micro-mill tool exhibits rapid abrasive wear within a cutting range of 15 millimeters. As a consequence of rapid wear, the edge radius exhibited an increase from 1.3 to 3.69 mm under dry conditions and 3.44 mm under MQL conditions. Prior to the coating delaminating and the substrate being visible, the tool progressively diminished its adhesive properties until a cut length ranging from 45 to 80 mm. This event happened subsequent to the preceding stage. The extension of this progressive wear regime, which did not need adhesive, was influenced by both the utilization of MQL oil and the increase in cutting speed. The utilization of MQL resulted in increased normal stresses in the plowing-dominant region, hence increasing the tool's susceptibility to edge chipping. In contrast, dry cutting did not exacerbate these pressures.

3. Surface Quality Improvement with Lubricated Conditions

The increasing importance of sustainable development has coincided with a gradual rise in the adoption of cutting fluids derived from vegetable oil. The influence of six distinct cutting fluids on the surface roughness and cutting force of AISI 304 L steel during the turning process has been examined by researchers. In the present study, it was shown that a workpiece exposed to biodegradable vegetable oil exhibited a higher surface quality compared to a workpiece exposed to mineral oil or semi-synthetic oil (Cetin et al., 2011). In their study, Elmunafi et al. (2015) investigated the application of castor oil as a cutting fluid for the aim of turning hardened AISI 420 steel. The efficacy of MQL castor oil surpasses that of dry cutting in terms of surface roughness, cutting force, and tool longevity. Liu et al. (2021) performed a review study to examine the influence of different volume ratios of castor oil and alcohol on the processing quality. The optimal volume ratio of oil to alcohol for achieving a smooth surface was determined to be 35% and 65%, respectively. The aforementioned ratio yielded the minimum surface roughness. The plant-derived cutting fluid is environmentally safe, and the vegetable oil-based mixed cutting fluid has the potential to achieve exceptional processing performance when the volume ratio is tuned. Furthermore, the integration of MQL technology with biodegradable vegetable oils may be achieved by this particular procedure. Tazehkandi et al. (2015) examined the cooling and lubricating methods employed during the machining of Inconel 706. They specifically focused on the use of compressed air and biodegradable vegetable oil. Based on the experimental results, this approach reduces both the cutting force and the cutting temperature, leading to an enhancement in surface quality, as shown in **Figure 3**. The consumption of cutting fluid is reduced as a consequence of this. As a consequence, there is a mitigation of environmental concerns, a decrease in expenses associated with processing, and a rise in overall productivity.

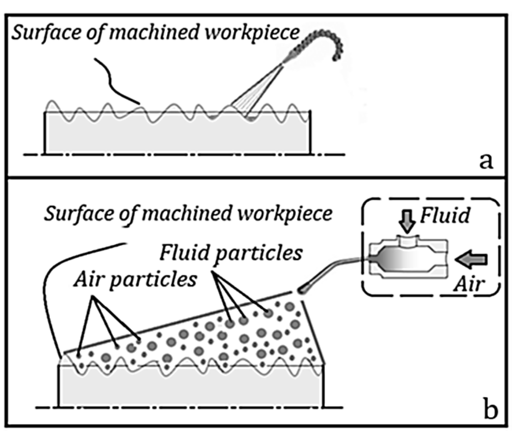

Figure 3. Surface quality improvement by lubrication method, a) flood mode, b) MQL mode (Tazehkandi et al., 2015).

4. Cutting Temperature Decrease with Lubricated Conditions

The cutting temperature is a crucial evaluation parameter in machining operations, as it significantly impacts both the surface quality of the machined surface and the wear resistance of the tool (Abukhshim et al., 2006). It provides a reflection of the cooling and lubricating capabilities across different cutting settings. The cutting temperature for the first, second, fourth, sixth, and eighth experimental groups was determined using an infrared thermal imager, as seen in **Figure 4**.

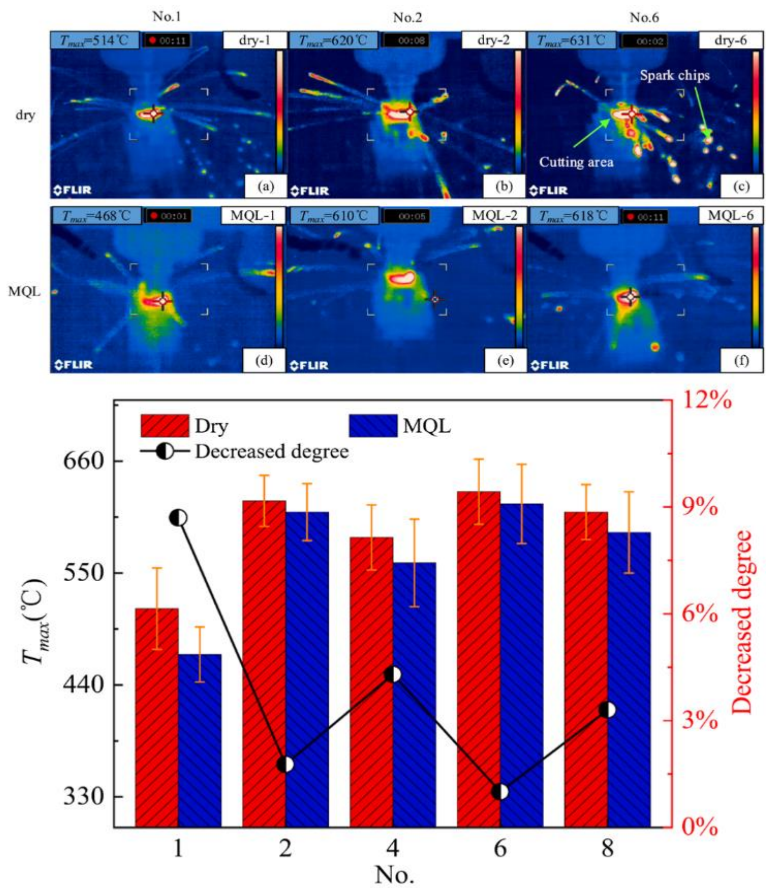

Figure 4. The decrease of cutting temperature under lubrication conditions (Du et al., 2024).

The aforementioned result aligns with the findings reported by Yu et al. (2022). The observed trend indicated a positive correlation between the milling temperature and the rise in cutting parameters. A plausible hypothesis for this phenomenon is that the augmentation of cutting parameters resulted in a rise in the quantity of material that was eliminated. Consequently, this phenomenon gives rise to increased levels of shear and friction, finally culminating in the accumulation of thermal energy. In addition, the chip is expelled from the cutting zone through the utilization of a high-pressure and high-speed fluid generated by the MQL system. This process furthermore aids in the decrease of the cutting temperature (Danish et al., 2023). In the context of MQL conditions, it is consistently observed that the temperature at which cutting takes place is lower than the temperature at which dry cutting occurs. The initial group exhibits a temperature decrease of around nine percent, hence highlighting the prominent cooling effect. Based on the initial group as the benchmark, the comparison demonstrates that the decrease in MQL cutting temperature diminishes as the cutting parameters increase. This conclusion is derived from the comparative analysis.

This observation implies that an augmentation in cutting parameters poses a challenge for MQL droplets to effectively infiltrate the contact zone between the tool and the chip. Consequently, the formation of the lubricating layer is rendered more challenging, leading to a reduction in the cooling efficacy (Liu et al., 2021). **Figure 4** displays a depiction of the temperature distribution for the initial, subsequent, and final experimental groups. The results suggest that an increase in the temperature of the cutting process leads to an expansion of the high-temperature zone and a corresponding increase in the quantity of spark chips generated. In contrast to MQL, dry cutting yields a higher amount of spark chips and a considerably bigger high-temperature zone. The findings of Mia (2018) indicated that MQL has the capacity to effectively decrease the temperature of both the tool and the chip with high efficiency.

5. Energy Consumption Decrease with Lubricated Conditions

It is stated that the industrial business frequently uses machine tools to precisely cut materials into a wide range of complex shapes (Makhesana et al., 2022). Yıldırım et al. (2019) have reported that machine tool attachments exhibit a substantial level of energy consumption. These supplementary components encompass supplementary cooling systems, machining settings, machining circumstances, and analogous elements. Pimenov et al. (2018) found that the machine tool consumes less energy during the cutting process, as opposed to doing other tasks. Consequently, the measurement of energy must be conducted on a per-component basis. Based on the findings of Yildirim et al. (2020) stated that the advanced manufacturing sector is presently seeking sustainable alternatives to achieve cost reduction, adoption of environmentally friendly cutting fluids, enhancement of product quality, and augmentation of productivity. In addition, the implementation of environmentally friendly methods has been found to positively impact machining performance, namely in terms of tool wear, surface roughness, and especially energy/power consumption as in **Figure 5**.

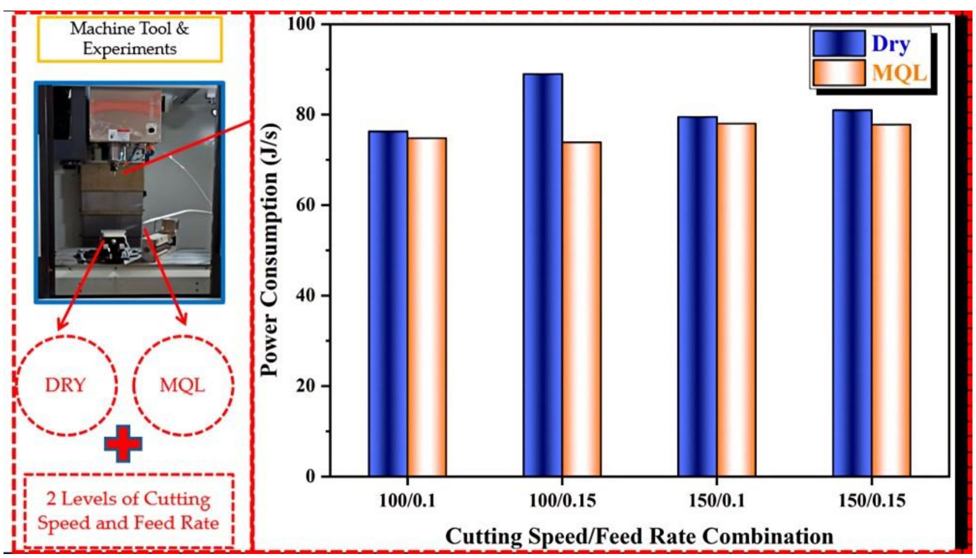

Figure 5. Effects of MQL method in energy consumption (Salur et al., 2021).

Bustillo et al. (2020) observed that emerging sustainability trends are resulting in reduced expenses, decreased waste, and minimized environmental harm in relation to the utilization of mineral oil. Iqbal et al. (2016) stated that the biodegradable oil-based MQL is an environmentally friendly method of lubrication that utilizes a pressured cooling/lubrication medium to deliver both cooling and lubrication. Jamil et al. (2020) showed the application of biodegradable MQL in the machining of challenging-to-cut materials.

Based on the results obtained, it can be inferred that enhanced lubrication possesses the capacity to reduce the energy and cutting forces necessary, alongside mitigating surface roughness. The utilization of MQL facilitated the release of a small quantity of oil mist, leading to the evacuation of the chip. This lubrication process subsequently prolonged the lifespan of the tool, enhanced the quality of the surface, and mitigated the environmental consequences associated with machining processes reliant on mineral oil. In this study, Hadad et al. (2012) investigated the cutting temperature and energy partition in the machining of AISI-52100 in both dry and MQL conditions. The study concluded that the use of lubricant, which reduced the forces and adhesion between the tool and workpiece, led to a substantial decrease in the heat generated during MQL. Iqbal et al. (2018) conducted a study to assess the effects of dry ice and MQL on the machining process of titanium alloy. The researchers reached the determination that the utilization of dry ice significantly influences both the cooling efficiency and the sustainability of the operation.

6. Conclusions, Challenges and Future Scope

While oil and chemical-based lubricants and coolants used in the machining of engineering materials harm both the environment and human health, they are also disadvantageous in terms of cost. The MQL method reduces cutting temperature and surface roughness while increasing tool life. It also ensures that less amount of cutting oil is used and production costs decrease. At the same time, it reduces the negative effects on both human health and the environment. These advantages and disadvantages can be explained as follows.

- The Minimum Quantity Lubrication (MQL) method balances environmental sustainability, cost-effectiveness, and machining performance, making it a potential machining process. MQL increases tool life, surface finish, energy efficiency, and waste reduction by supplying lubrication directly to the cutting zone. These benefits boost manufacturing productivity and competitiveness while addressing environmental and resource problems.
- However, MQL implementation in machining operations is difficult. Selecting lubricants that cool and lubricate the cutting zone while being compatible with machining materials and processes is difficult. Providing regular and precise lubricant distribution without nozzle clogging or machining errors is also difficult. To optimize machining performance, MQL parameters including cutting speed, feed rate, and lubricant flow rate must be carefully considered.
- Despite the current limitations, the field of MQL in machining applications holds promising prospects. Further investigation and enhancement are required to address the limitations of MQL. Subsequent investigations may provide lubricants and nozzle technologies that are specifically designed for MQL (Minimum Quantity Lubrication) applications, therefore enhancing the accuracy and reliability of lubricant delivery. Investigate the potential synergistic effects of MQL (Minimum Quantity Lubrication) and additive manufacturing and AI (Artificial Intelligence) in order to discover novel methods for enhancing machining operations. The advancement of MQL research and innovation, leading to more sustainable and efficient machining, will be facilitated by collaboration among academia, industry, and government organizations.

Conflict of Interest

No potential conflict of interest was reported by the author(s).

Acknowledgments

No acknowledgement was reported by the author(s).

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