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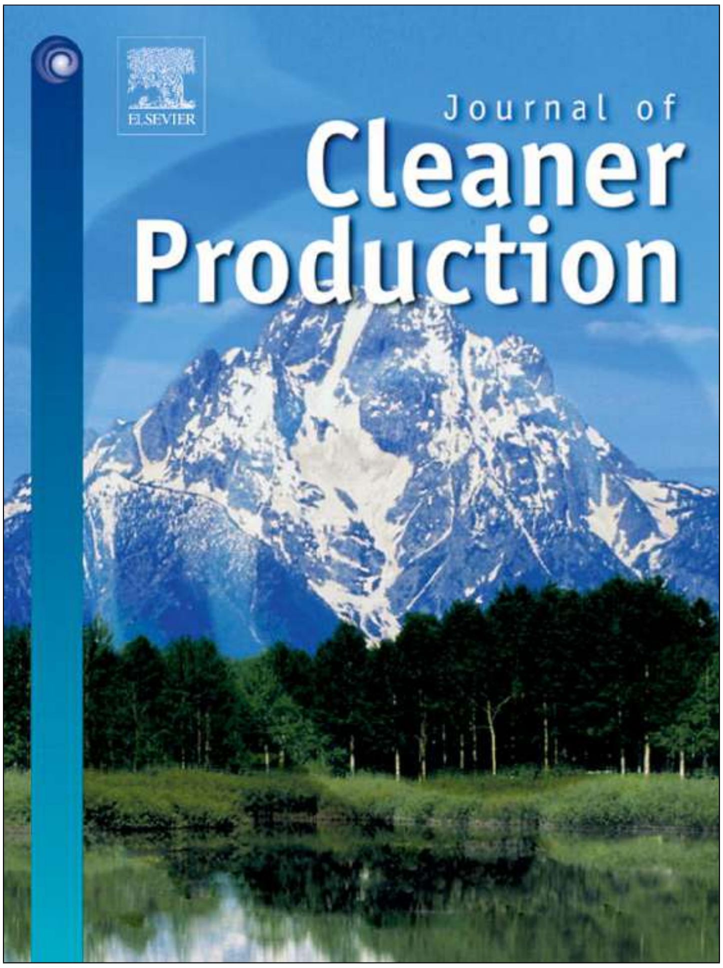

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Review

A critical assessment of lubrication techniques in machining processes: a case for minimum quantity lubrication using vegetable oil-based lubricant

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ABSTRACT

In this study, a review of the available literature on lubrication techniques during machining processes was conducted. Factors such as workpiece material, tool material and machining conditions were observed to be vital to the performance of any of the techniques. The performance and drawback of each technique were highlighted based on the machining conditions. It concludes by making a case for minimum quantity lubrication (MQL) method using vegetable oil-based lubricant in different machining processes, as a way of addressing the environmental health issues and cost associated with the application of lubricant in machining processes.

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1. Introduction

The cooling application in machining processes plays a very important role as many operations cannot be carried out efficiently without cooling (Yildiz and Nalbant, 2008). The high temperature generated in the region of the tool cutting edge has a controlling influence on the wear rate of the cutting tool and on the friction between the chip and the tool during machining process. The maximum temperature occurs along the tool face at some distance from the cutting edge (Boothroyd and Knight, 2005). The tool acts as the heat sinks into which the heat flows from the flow zone and a stable temperature gradient is built within the tool. The amount of heat loss from the flow zone into the tool depends on the thermal conductivity of the tool, tool shape and the cooling method used to lower its temperature (Trent and Wright, 2000). The heat generated during a cutting operation is the summation of plastic deformation involved in chip formation, the friction between tool and workpiece, and between the tool and chip (Shaw, 1996). Much of this heat remains in the chip, but a portion is conducted into the tool and the workpiece (Stephenson et al., 1995). Research reports have shown that reducing cutting temperature is important since a small reduction in temperature will greatly increase cutting tool life (Tuholski, 1993). Without the use of cutting fluid, the heat carried away from the cutting zone is decreased, resulting in an increase in tool and workpiece temperature (Yerkes and Dorian, 1999).

It has been established that the cost of machining is very strongly dependent on metal removal rate (MRR), but increase in MRR can lead to the shortening of tool life due to increase in friction and heat generation at the tool cutting zone. Many of the economic and technical problems of machining are caused directly or indirectly by this heating action (Trent and Wright, 2000). In an earlier report, Taylor (1907) had demonstrated that heat played a part in machining process. High cutting temperatures in machining always result in aggressive adhesion wear at the tool surface (Liu and Chou, 2007). Conventionally, cutting fluid is used to cool and lubricate the cutting process, thereby reducing tool wear and increasing tool life (Shane Hong, 2001).

It has been estimated that the cost of cutting fluids is approximately 7–17% of the total cost in machining process (Klocke and Eisenblaetter, 1997). As cutting fluid is applied during machining operation, it removes heat by carrying it away from the cutting tool/workpiece interface (Silliman and Perich, 1992). This cooling effect prevents the tool from exceeding its critical temperature range beyond which the tool softens and wears rapidly (Bienkowski, 1993). Hence, cutting fluids are used for cooling and lubrication purposes in machining process. However, reports have it that the application of conventional cutting fluids (mineral based cutting

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fluid) creates several techno-environmental problems such as environmental pollution, due to chemical disassociation of cutting fluids at high cutting temperatures; biological problems to operators, water pollution and soil contamination during disposal (Howes et al., 1991; Byrne and Scholta, 1993). Hence, the increasing consciousness for green manufacturing globally and consumer focus on environmentally friendly products have put increased pressure on industries to minimize the use of cutting fluids. Any attempt to minimize or avoid the use of coolant can only be addressed by replacing the functions normally meant for the coolants with other methods. Therefore, an alternative to conventional cutting fluids techniques such as high pressure coolants (HPC), cryogenic cooling, solid lubricants, air/gas/vapour coolant and minimum quantity lubrication (MQL) or near dry machining (NDM) have been reported by different researchers to have addressed the shortcoming of conventional cutting fluid application. Therefore, this review assesses the various lubrication techniques in machining processes by identifying their performances and drawbacks and then makes a case for MQL technique using vegetable oil-based lubricant.

2. High pressure coolant (HPC) technique

High pressure coolant (HPC) delivery is an emerging technology that delivers a high pressure fluid to the tool and machined material. Ojmertz and Oskarson (1999) were the first researchers who started publishing on this technology when they applied it to Inconel 718 material. This technique was developed to replace the conventional process; it aimed at upgrading conventional machining using the thermal and mechanical properties of a high pressure jet of water or emulsion directed into the cutting zone. The general principle of this technique involved the use of range of pressure at certain flow rate directed into the cutting zone. Application of HPC depended on the type of equipment available either employing pressures higher than 150 MPa and flow rates lower than 6 l/min, while using a small nozzle or employing lower pressures up to 30 MPa and higher flow rates that can reach 50 l/min with larger nozzles (Wertheim et al., 1992; Diniz and Ricardo, 2007). Available literature shows that this technique has been applied to machining hard-to-cut materials such as nickel based alloys (Inconel 718), Ti–6Al–4V alloys and AISI 1045 steel using different tool materials like coated carbide, cubic boron nitride, TiAlN coated carbide and ceramic (Ezugwu et al., 2005).

HPC has been widely studied in machining processes and most investigated parameters were surface roughness, chip formation and tool life. Rahmath Zareena et al. (2005) evaluated the performance of CBN, binder CBN (BCBN) and PCD tools for high-speed machining of Ti–6Al–4V alloys with high-pressure coolants, and concluded that BCBN tools were more suitable cutting tool materials for machining titanium alloys. Investigation conducted by Mazurkiewicz et al. (1989) showed that high pressure coolants jet could create a hydraulic wedge between the tool and workpiece, which was capable of altering the chip flow conditions. Ezugwu and Bonney (2005) observed that coolant supply at high pressure tended to lift the chip after passing through the deformation zone resulting in reduction in the tool chip contact length/area. Trent (1988), Ezugwu (2005) and Ezugwu et al. (2007) found that the coolant not only offered more efficient cooling characteristics and improved tool wear but also resulted in reduced contact length as the coolant delivery pressure forced the chip away from the tool rake face. Ezugwu and Bonney (2004) found that chip segmentation depended upon the cutting conditions employed and to a greater extent on the coolant pressure. The main cutting force and specific energy were minimal under high-pressure neat oil, while the resultant feed force and the thrust force were minimal under high-pressure water-soluble oil during turning of Ti–6Al–4V (Nandy et al., 2009). Lopez de Lacalle et al. (2000) observed that under high pressure jet turning of titanium, there was a reduction in cutting force and tool tip temperature. Courbon et al. (2009) investigation shows that high pressure jet assisted cooling system is an efficient alternative lubrication solution, which provides better chip breakability and reduction in cutting forces. The application of coolant at high pressure increases tool life by almost 3 times while turning Ti–6Al–4V material (Palanisamy et al., 2009). Despite the reported results from various authors, HPC machining is still not widely used because of the lack of the fundamental level of understanding the process (Ezugwu et al., 2007). Sharma et al. (2009) summarized the performance of HPC under different cutting conditions as follows:

(a) There is increase in tool life with increasing coolant pressure supply, but once a critical value of pressure has been reached, any further increase in coolant pressure will only result in marginal increase in tool life.
(b) Low cutting forces are generated due to improved cooling and lubrication with HPC. Surface finish is optimum and surface is free from physical damages such as tears, laps or cracks in almost all the cutting conditions with HPC during turning of titanium alloy.
(c) With HPC supply, lesser hardening effect as well as microstructural damage was observed on the machined surface due to efficient coolant supply conditions and increased access of the coolant to the chip–tool interface.
(d) HPC supply shortens the length of contact on the rake face of the tool and thus greatly reduces cutting and feed forces.
(e) During machining of aerospace alloys at high coolant pressure, well-segmented C-shaped chips are generated. Thus it is clear that chip segmentation depends, to a great extent, on the coolant pressure employed.
(f) During turning of hard metals with CBN tools, low CBN content tools give better performance under HPC in terms of tool life with reduced notch wear.

3. Cryogenic cooling technique

The application of liquid nitrogen (LN) at −196 °C to the cutting zone for reduction in temperature during machining process is known as cryogenic cooling (Evans, 1991). It is an efficient way of maintaining the temperature of the cutting tool material (Dhar et al., 2002). Cryogenic cooling is an environmentally safe alternative to conventional emulsion cooling. This is because of the fact that as nitrogen evaporates harmlessly into the air, there is no cutting fluid to dispose. Furthermore, the chips generated from this technique have no residual oil on them and can be recycled as scrap metal (Wang and Rajurkar, 2000). Consequently, the technique, if properly employed can provide significant improvement in both productivity and product quality and hence, overall machining economy even after covering the additional cost of cryogenic cooling system and cryogenic fluid (Mirghani et al., 2007; Dhar and Kamruzzaman, 2007). This beneficial effect of cryogenic cooling by liquid nitrogen may be attributed to effective cooling, retention of tool hardness, and favourable interactions of cryogenic fluid with chip–tool and work–tool interface (Paul et al., 2001). However, Dhar et al. (2002) affirmed that the benefit of cryogenic cooling had been more predominant at lower cutting velocity, because at lower velocity, a large portion of the chip–tool contact remains elastic in nature, which is likely to allow a more effective penetration of cryogen at the interface.

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Cryogenic cooling has been widely studied in turning process (Khan and Mirghani, 2008; Venugopal et al., 2007; Dhar and Kamruzzaman, 2007; Paul et al., 2001; Kumar and Choudhury, 2008) using different materials like Ti–6Al–4V alloy, AISI 4037 steel, AISI 1040 steel, AISI 1060 steel, E4340C steel with various cutting tools such as polycrystalline boron nitride (PCBN), carbide inserts, uncoated micro-crystalline K20 tungsten carbide inserts and diamond. In some cases, cryogenic cooling has increased tool life by 4.27 times compared to conventional coolant (Khan and Mirghani, 2008), maximum flank wear reduces 3.4 times as compared to wet turning and 2 times as compared to wet turning (Venugopal et al., 2007), and improved surface finish (Yildiz and Nalbant, 2008) under various machining conditions. The regulation of flow rate and pressure of liquid nitrogen are critical factors in order to get continuous flow of liquid nitrogen without over cooling the workpiece, because more cutting force will be required if over cooling of workpiece material takes place.

4. Solid lubricant technique

Machining with solid lubricants is one attempt to avoid the use of cutting fluid (Shaji and Radhakrishnan, 2003). Graphite and molybdenum disulphide (MoS_2) are the predominant materials used as solid lubricant (Lathkar and Bas, 2000). Other useful solid lubricants include calcium fluoride, cerium fluoride, boron nitride and tungsten disulphites. These materials are in the form of dry powder and are effective lubricant additives due to their lamellar structure. It is a complex lubrication method to select the right solid lubricant for a specific application and it is usually used when liquid lubricants do not meet the advanced requirements of modern technology, such as providing prolonged stationary service. Only few literature are available on this technique (Singh and Rao, 2008; Krishna and Rao, 2008; Rao and Krishna, 2008; Mukhopadhyay et al., 2007). The machining process involving the use of AISI 52100 steel as workpiece material, and ceramic insert tool when graphite and molybdenum disulphide, were used as lubricant. Surface roughness was observed to have decreased with increase of the cutting speed up to 125 from 50 m/min. Decrease in surface roughness value by 8–10% due to graphite and by 13–15% due to molybdenum disulphide was observed (Singh and Rao, 2008). It was observed that rake of flank wear was less with solid lubricant assisted machining compared to wet and dry machining during the turning of EN8 steel workpiece material and cemented carbide tool in the presence of solid lubricants (a mixture of graphite and boric acid with SAE 40 oil). Some of the drawbacks of this technique are poor heat dissipation with low thermally conductive lubricants, such as polymer base films and having higher coefficient of friction and wear than for hydrodynamic lubrication (Miyoshi, 2007).

5. Air/vapour/gas as coolant technique

Podgorkv proposed a new and pollution free green cutting technique with water vapour as coolant and lubricant during cutting process (Godlevski, 1998). The nitrogen gas, liquid nitrogen and compressed air were delivered under pressure and directed into the tool–chip interface via a bespoke nozzle located on the tool holder. Though, this technique has received tool manufacturer's approval to be used in high speed cutting operations, it is not yet certain whether this environment assists the cutting process or if it's popularity is due to the convenient availability of compressed air in the workshop, and its ability to remove cutting chips from the work zone. The result has shown that the application of this technique produced lower cutting force compared to dry and wet cutting. It was equally observed that gas pressure was also an influential factor on the chip breaker (Cakır et al., 2004; Altan et al., 2002). During the turning of ANSI 1045 steel with cemented carbide, cutting force reduced by 20–40% and 10–15% relative to dry and wet cutting respectively, when water vapour, gas and mixture of vapour were used as lubricant.

6. Minimum quantity lubrication (MQL) technique

Minimum quantity lubrication (MQL), also known as near dry machining (NDM), refers to the use of cutting fluids in tiny quantities, which is only about ten-thousandth of the amount of cutting fluid used in flood-cooled machining (Machado and Wallbank, 1997; Rahman et al., 2002). The performance of this technique, like any other techniques in machining processes, depends on the selection of cutting fluid, workpiece material and machining process (El Baradie, 1996; Avuncan, 1998; ASM, 1978).

For instance, Nakamura et al. (2000) and Yoshimura et al. (2003) proposed another type of MQL technique in which a minimal amount of oil is supplied into a cutting point, carried by and mixed with water droplet. When this method is applied in a milling process, the machining force can be reduced more than by the supply of the same amount of oil droplet alone, and the thermal expansion is also suppressed. There are other reports which indicate that MQL in an end-milling process is more effective than in a continuous turning process. This is considered to be possible because lubricant can reach the tool face easily in milling process than turning process (Lopez de Lacalle et al., 2001; Rahman et al., 2001). However, a remarkable reduction of machining costs can be obtained in MQL technique especially when vegetable oil-based lubricant is used as cutting fluid. This is because the quantity of lubricant used in MQL is small.

The effect on environment, health issues and cost are all relevant when considering the choice of a lubricant and application methods. As the law of restrictions on environmental issues becomes stronger, the public awareness in environmental issues has been constantly growing. In 1983, the National Institute of Occupational Safety and Health (NIOSH), estimated that 1.2 million workers around the world were exposed to the chronic toxic effects of lubricants (Sales et al., 2001; Eichenberger, 1991; Pusavec et al., 2010a,b; Sanchez et al., 2010; Jegatheesan et al., 2009; Marksberry, 2007; Cetin et al., 2011). Bennett and Bennett (1987) found that a source of significant exposure to lubricants was inhalation of aerosols. Greaves et al. (1997) showed that chronic bronchitis, asthma, chest symptoms and airway irritation were linked to aerosol exposures of metalworking fluids (MWFs) as low as 0.41 mg/m^3. Again, the costs of acquisition, care and disposal of MWFs are two times higher and have to be taken into account when the economic involvements in machining operations are compared. About 17% increase in cost has been associated with the use and disposal of MWFs in machining automobile components (Khan et al., 2009). Flooding of fluid leads to various drawbacks like increase in overall cost of cutting and problem of disposal of fluid, etc.

Minimum quantity lubrication (MQL) seems to be a good alternative for effective cooling during machining process (Kendall, 1998). Brockhoff and Walter (1998) observed that the total manufacturing costs would be lower as compared to the cost of traditional overhead flood cooling using large amount of water-miscible MWFs. Erdel (1999) successfully demonstrated a method in the use of minimization of MWFs called near dry machining (NDM), where a very small amount of MWFs in a flow of compressed air can be approximately 10,000 times less than overhead conventional flood cooling. MaClure et al. (2001) observed that the concept of MQL had been suggested as a means of addressing the issues of environmental intrusiveness and occupational hazards associated with airborne cutting fluid particles on

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factory shop floors. The method equally reduces machining floor space; eliminates coolant pump, coolant testing, coolant treatment and coolant disposal, and allows the operator to observe the performance during machining (Boothroyd and Knight, 2005). The MQL technique consists of a mixture of drops of cutting fluids (neat oils or emulsions) in a flow of compressed air, generating a “spray” which is directed to the cutting region of work as lubricant and coolant. This makes it possible to reduce the quantity of MWFs to be used in any machining processes.

Machado and Wallbank (1997), Heisel et al. (1998) and Weingaernter et al. (2000), are among other researchers who have investigated this technique in several processes and proved that it could be a feasible alternative, depending the on cutting conditions, pulverization parameters and type of cutting fluid used. Stäbler et al. (2003) had suggested that water mixed cooling lubricants and their concentrates, lubricants with organic chlorine or zinc containing additives and lubricants that have to be marked according to the decree on hazardous materials are not applicable for MQL. This suggestion by the authors not to use water mixed cooling lubricant in MQL application has been proved wrong. Good results have been obtained when Dhar et al. (2006) used water soluble cutting fluid which was supplied at flow rate of 60 ml/h and mixed with compressed air prior to being impinged on the cutting zone at a high speed, while turning AISI 4340 steel with uncoated carbide tool.

6.1. Research reports on MQL technique

MQL technique has been studied in many machining processes such as turning (Wakabayashi et al., 1998; Dhar et al., 2006; Davim et al., 2007; Kamata and Obikawa, 2007; Autret and Liang, 2003; Chen et al., 2001; Diniz et al., 2003; Varadarajan et al., 2002; Machado and Wallbank, 1997; Vikram et al., 2007; Vasu and Reddy, 2011), drilling (Braga et al., 2002; Filipovic and Stephenson, 2006; Davim et al., 2006; Heinemann et al., 2006); milling (Rahman et al., 2001, 2002; Lopez de Lacalle et al., 2006; Su et al., 2006; Liao and Lin, 2007; Jun et al., 2008; Fratila, 2009; Fratila and Caizar, 2011); grinding (Baheti et al., 1998; Hafenbraedl and Malkin, 2000; Silva et al., 2005; Li and Chou, 2010; Tawakoli et al., 2009, 2010a,b, 2011; Shen, 2008). Each of these studies highlighted one or more advantages of using this technique in machining processes under different lubricants. However, MQL technique using vegetable oil as lubricant is still a relatively new research area that needs to be explored and this study will therefore highlights the gap that needs to be filled.

6.2. Types of MQL technique

MQL technique is distinctly grouped into two systems namely internal supply of the medium via channels built into the tool, and external supply via nozzle fitted separately in the machine area as shown in Fig. 1(a) and (b). While Fig. 2 shows the basic differences between external and internal feed during application.

Each of these systems has specialized areas of application. The external system is mostly used in sawing, end and face milling and turning operations. It could equally be used in machining operations such as drilling, reaming or tapping with limitations. External supply of the medium is appropriate only up to length/diameter ratios of $l/d < 3$ and also present problems in the case of machining tasks requiring the use of multiple tools with widely varying lengths and diameters, e.g. when deep hole drilling. An internal supply of the medium via the spindle and tool is applicable in drilling, reaming and tapping operations with larger l/d ratios and good for tools with very different dimensions. The positioning errors of nozzle are eliminated in the internal supply system (Suzuki, 2002). In this supply, the lubricant is continually available at the critical points during the entire processing sequence. This makes it possible to drill very deep holes and use very high cutting speeds. In an automated production, manual setting of system parameters are not required for this internal system.

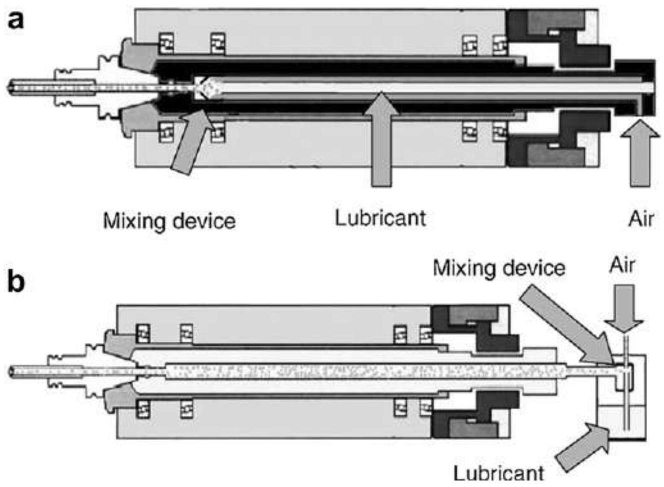

Fig. 1. MQL-feed systems (a) internal (b) external nozzles (Attanasio et al., 2006).

6.3. MQL mixing methods

In the inside nozzle equipment, pressurized air and cutting fluid are mixed into the nozzle by a mixing device. Metalworking fluid performs the lubrication action, while the pressurized air that reaches the cutting surface performs the cooling action. This mixing method has several advantages as mist and dangerous vapours are reduced and the mixture setting is very easy to control. The mixture is obtained in a mixing device positioned in a specific tank for outside nozzle method. In this method, lubrication between workpiece and tool can also be achieved (Attanasio et al., 2006). Control over the amount of lubricant dispensed is important because different processes require different amount of lubricity. Example, milling is a surface operation and it requires a minimum amount of lubricity, deep-hole drilling is a different operation requiring a different level of lubricity. Another third level of lubricity is required for tapping and thread cutting operations because of their high surface pressure. Therefore, the objective of

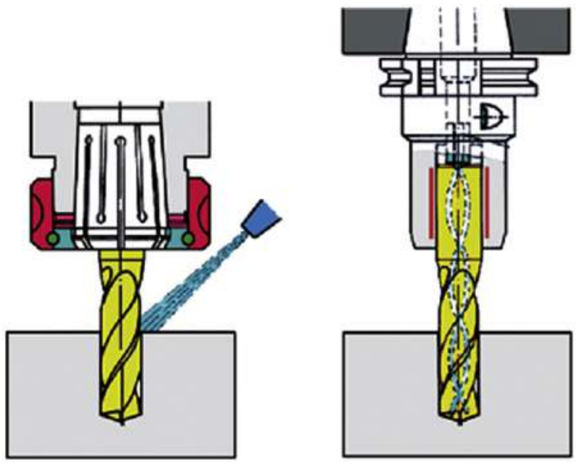

Fig. 2. External and internal feed (DGUV, 2010).

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an MQL mixing system is to deliver a precise amount of aerosol. The diameter of the aerosol particulates is held to a precise tolerance to maintain optimum wetting and lubrication properties in machine designed for MQL, lubricity can be controlled using a parameter in the part program that varies in the aerosol's amount and duration. The CNC program controls the dosing valve that provides the precise amount of lubricant (Quaile, 2004).

6.4. Cutting tools for MQL technique

MQL-compatible tools are a basic prerequisite for efficient machining. On one hand, dry machining and minimum quantity lubrication are based on reduced heat development, and on the other hand it depends on rapid heat dissipation via the chips. The tool is a vital system element for minimum quantity lubrication. MQL-compatible tools are optimized to these requirements with respect to cutting materials and tool geometry. MQL-compatible coatings and geometries that assist chip removal and combat overheating are recommended. MQL-compatible coating which can facilitate chip removal and increases process reliability are required. In addition, friction between chip and cutting face is reduced due to the thermally insulating hard material layers and polished tool surfaces. For optimizing the lubricant supply, tools with elliptical cooling channels that increase the cross section of the cooling channel are recommended (DGUV, 2010). Fig. 3 shows the three common shapes of MQL cutting tools.

6.5. Vegetable oil based lubricants

The use of vegetable oils as cutting fluid has displayed excellent lubrication properties in laboratory investigation (Fox and Stachowaik, 2007). A comprehensive review of the application of vegetable oil-based metalworking fluids in machining ferrous metals by Lawal et al. (2012) shows that a better performance can be achieved during machining processes using vegetable oil-based metalworking fluid. It was observed that, without additives, vegetable oils outperformed mineral based oils in antiwear and friction (Asadauskas et al., 1996, 1997), scuffing load capacity (Kozma, 1997) and fatigue resistance (Odi-Owei, 1988). A fully formulated vegetable oil lubricant, in comparison to mineral oil counterparts, will display a lower coefficient of friction (Arnsek and Vizintin, 2000; Krzan and Vizintin, 2003a,b), equivalent scuffing load capacity (Hohn et al., 1999; Arnsek and Vizintin, 1999) and better pitting resistance (Arnsek and Vizintin, 2001), but also poorer thermal and oxidative stability. Vizintin et al. (2000) noted that at extreme loads, vegetable oil-based lubricants became significantly less effective. One of the notable conclusions made by Sharma et al. (2009) for the performance of MQL/NDM technique under different cutting regime to be effective was the use of vegetable oil, ester oil, or equivalent synthetic MWFs. This is because of the vegetable oil's superior lubrication and better performance at high pressure.

Fig. 3. Cutting tools for MQL (DGUV, 2010).

7. Recent research on MQL technique using vegetable oil – lubricant

7.1. Turning process

Khan et al. (2009) reported that an average chip–tool interface temperature increased with increase of cutting speed and feed rate during the turning process of AISI 9310 low alloy steel using uncoated carbide tool. The authors conducted an experiment that involved the use of vegetable oil lubricant using MQL technique, wet and complete dry cutting to justify the relationship between average chip–tool interface temperature, cutting speed and feed rate. The process parameters used were cutting velocity (223, 246, 348 and 483 m/min), feed rate (0.10, 0.13, 0.16 and 0.18 mm/rev) and depth of cut (1.0 mm). An improved surface roughness of about 31.6% was obtained for vegetable oil MQL over wet cutting and about 18% was obtained for dry cutting over wet cutting as shown in Fig. 4. The drastic deterioration of surface roughness under wet machining compared to dry cutting was possibly due to electrochemical interaction between tool and workpiece. The authors found that when machining with MQL, the form of ductile chips did not change appreciably, but their back surface appeared much brighter and smoother. The colour of the chips became much lighter i.e. blue or golden from burnt blue depending on the cutting velocity and feed rate, due to reduction in cutting temperature by MQL. The gradual growth of average principal flank wear, the predominant parameter to ascertain the expiry of tool's life was observed under all environments. One of the conclusions made by the authors was that, as there was a reduction of flank wear, there was a significant increase in the machining of AISI 9310 low alloy steel with carbide insert under vegetable oil lubricant.

In another development, Itoigawa et al. (2006) examined the effects and mechanisms in minimal quantity lubrication machining of aluminium alloy during turning process with polycrystalline diamond (PCD) tools. The machining conditions involved in the experiment are shown in Table 1.

It was observed that when rapeseed oil was used as lubricant for both MQL and oil-in-water (O-in-W), the light load condition of O-in-W cutting exhibited low and steady friction over the whole cutting length ratio range. The cutting force for cutting speed of

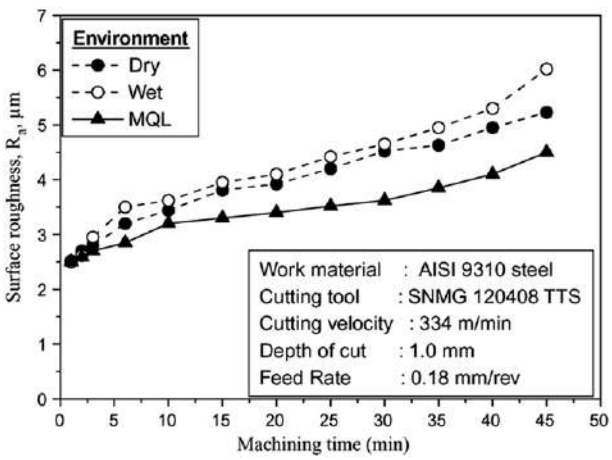

Fig. 4. Variation in surface roughness with progress of turning steel by SNMG insert under different cooling conditions at cutting velocity 334 m/min and feed rate 0.18 mm/rev (Khan et al., 2009).

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Table 1
Test conditions (Itoigawa et al., 2006).

Cutting conditions	1	2
Cutting speed (m/min)	200	800
Feed rate (mm/rev)	0.05	0.2
Axial travelling length (mm)	3	10
Environment	MQL (oil-in-water, rapeseed oil and synthetic ester)	MQL (oil-in-water, rapeseed oil and synthetic ester)

200 m/min and feed rate of 0.05 mm/rev increased from 700 to 750 N for the whole cutting length ratio for O-in-W condition. While for the same range of cutting length ratio the cutting force increased from 810 to 1200 N for MQL. This shows that within the same cutting length ratio, there was 6.6% increment for O-in-W condition and about 32% increment for MQL conditions. Similar trend of increment was noted when cutting speed and feed rate were increased to 800 m/min and 0.2 mm/rev respectively for the O-in-W and MQL conditions. There was much better specific performance in the tests of a synthetic ester developed for aluminium alloy for O-in-W condition. MQL with rapeseed oil has only a small lubricating effect and MQL, with synthetic ester, without water, shows a better lubrication effect.

7.2. Drilling process

Rahim and Sasahara (2011) studied the potency of minimum quantity lubricant palm oil (MQLPO) and minimum quantity lubricant synthetic ester (MQLSE) during drilling of titanium alloys with carbide drill coated with AlTiN along with other cutting environments. The study involved two stages of experiment. The first stage involved the use of cutting speed of 60, 80 and 100 m/min, feed rates of 0.1 and 0.2 mm/rev. while the second stage involved drilling of hole of a depth of 10 mm at the constant cutting speed of 60 m/min and feed rate of 0.1 mm/rev. The following are the tool's life criteria (i) average flank wear, VB(av) = 0.2 mm, (ii) maximum flank wear, VB(max) = 0.3 mm, (iii) corner wear = 0.3 mm, (iv) chipping = 0.2 mm, (v) catastrophic failure and (vi) cutting distance = 440 mm (due to the shortage of workpiece material) were used to evaluate the tool life performance. Thrust force, torque and workpiece temperature were measured and compared for all the cutting conditions. The authors observed that flood condition had the lowest torque among the other conditions tested and air blow condition did not reduce the drilling torque as much as the other coolant-lubricant conditions with the highest torque value of 14.4 N m. The effect of various cutting speeds and feed rates on MQL conditions showed that thrust force and torque decreased with an increase in the cutting speed. While both MQLSE and MQLPO recorded the lowest thrust force of 2318 N and 1954 N at the cutting speed of 100 m/min, and feed rate of 0.1 mm/rev, which translated into a reduction of 27% and 19% for MQLSE and MQLPO respectively. MQLPO induced the lowest torque at the cutting speed of 100 m/min and feed rate of 0.1 mm/rev, which indicated a 32% reduction when the cutting speed increased from 60 to 100 m/min. The MQLSE cutting conditions were measured at two points and it had the lower temperature than the air blow cutting condition with a reduction of 15% and 6.5% respectively. MQLPO condition recorded at the two locations recorded the lowest temperature in comparison to the MQLSE and air blow cutting conditions.

Table 2
Experimental machining variables (Kelly and Cotterell, 2002).

Machining variables	Test A	Test B
Cutting speed (V_c) (m/min)	105	25
Feed (f) (mm/rev)	0.15	0.30

Table 3
Methods of coolant application (Kelly and Cotterell, 2002).

Lubrication	Description
Flood lubrication	A general-purpose mineral soluble oil, Hysol G, at a concentration of 4% was used at a flow rate of 5.2 l/min
Mist lubrication	A unit manufactured by Uni-MIST was used and set with the following parameters: delivery pressure, 6 bar gauge, lubrication consumption, 20 ml/h. The lubricant used was a vegetable oil
Compressed air	Using the Uni-MIST unit but without the lubricant reservoir 6 bar gauge compressed air was directed at the tip of the drill
Dry	Machining was carried out without any form of lubrication or cooling

The authors reported that the flank wear rapidly grew and suffered from excessive chipping during the second experimental set up. A significant reduction in tool life for a drilling time of 48 s or 110 mm for the air blow conditions was equally recorded. The flank and corner wear rate was gradual and grew progressively for MQLSE and MQLPO. MQLPO condition produced lower tool wear rate in comparison with MQLSE condition. The flood condition also showed superior performance by having the lowest flank wear and corner wear in comparison to air blow conditions. MQLPO exhibited the lowest tool wear rate than MQLSE and air blow conditions compared to flood condition. An increment in tool life was achieved by MQLPO, MQLSE and flood conditions compared to the air blow condition at the cutting speed of 60 m/min and feed rate of 0.1 mm/rev.

Similarly, Kelly and Cotterell (2002) have investigated the role of different coolant application methods in the drilling of a 30 mm aluminium alloy (ACP 5080 plate) of Brinell hardness of 85 using a 10 mm high speed steel twist drills. The parameters studied were cutting forces, temperature, surface finish and dimensional accuracy at two different cutting speeds and feed rates as shown in Table 2. Summary of methods of coolant application is shown in Table 3.

It was observed that there was a considerable reduction in torque while machining with mist (vegetable oil) and flood lubrications

Table 4
Grinding conditions (Sadeghi et al., 2009).

Grinding mode	Plunge surface grinding, down cut
Grinding wheel	Al_2O_3 (91A4618AV)
Grinding machine	FAVRETTO MB100 CNC surface grinder
Wheel speed (V_s)	$V_s = 15$ m/s
Work speed (V_w)	$V_w = 20, 30, 40$ m/min
Depth of cut (DOC)	$A = 0.002, 0.005, 0.007$ mm
Environments	Wet and MQL
Conventional wet grinding fluid	Soluble oil (Blaser BC35) in a 5% concentration
MQL flow rare	$Q = 20,40,50,60,70,100,140$ ml/h
Air pressure	$P = 3,4,5,6$ bar
MQL oil	Vegetable oil, synthetic oil, Behran cutting oil 34 and Behran cutting oil 53
Workpiece material	Ti–6Al–4V (50 mm × 20 mm × 10 mm)
Dresser	Six point diamond dresser
Dressing depth	Total depth of dressing (a_d) = 0.03 mm
Dressing speed	$V_d = 5$ mm/s

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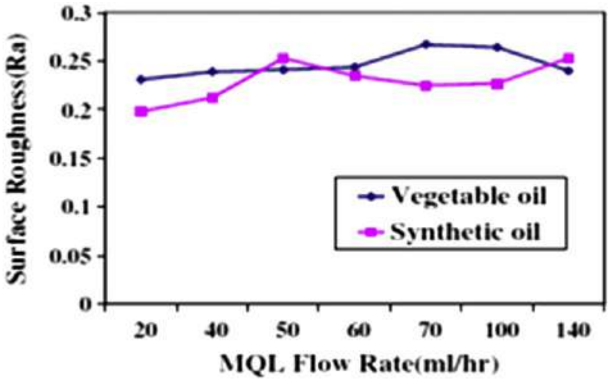

Fig. 5. Effects of MQL modes on surface roughness (grinding experiments were conducted with $V_w = 40$ m/min, $V_s = 15$ m/s, DOC = 0.005 mm and (a) $P = 4$ bar, (b) $Q = 60$ ml/h) (Sadeghi et al., 2009).

compared with compressed air and dry machining. An increase in temperature for all methods of coolant application prior to breakthrough was noted; this may be as a result of reduction in capacity of the workpiece to conduct heat away from the drill point. The temperature increased as cutting speed and feed rate increased, but it was a slight increment for both flood and mist lubrications. The surface finish for flood application was superior in the lower cutting speed and feed rate range. There was an increase of 76.4% of surface roughness associated with flood lubrication for an increase in machining parameters, while all other methods of lubrication show a reduction in surface roughness as follows: mist (vegetable oil) (11.5%), compressed air (12.3%) and dry cutting (25.9%). The dimensional accuracy for flood and mist lubrications was within the tolerance for both machining parameters, which is in agreement with BS 328 standard. It was observed that the average hole size was outside the tolerance range for mist lubrication, when higher feed and speed range were used.

7.3. Grinding process

Sadeghi et al. (2009) have examined the application of minimal quantity lubrication in grinding of Ti–6Al–4V titanium alloy using vegetable and synthetic oils as lubricants. The examination was carried out with aluminium oxide (Al_2O_3) grinding wheels with grinding conditions shown in Table 4.

The authors examined the surface quality of Ti–6Al–4V titanium alloy material using both vegetable and synthetic esters oils during MQL applications. The conventional wet grinding was also used to evaluate the cutting performance of fluid. It was observed that the application of synthetic oil in MQL grinding gave a better surface finish than vegetable oil as shown in Fig. 5 and that at 140 ml/h flow rate, the surface roughness values of both types of oil were the same.

The analysis of surface morphology and microstructure shows that MQL provided lubricant in the cutting zone, thereby producing a very good surface particularly at small wheel depth of cut. The

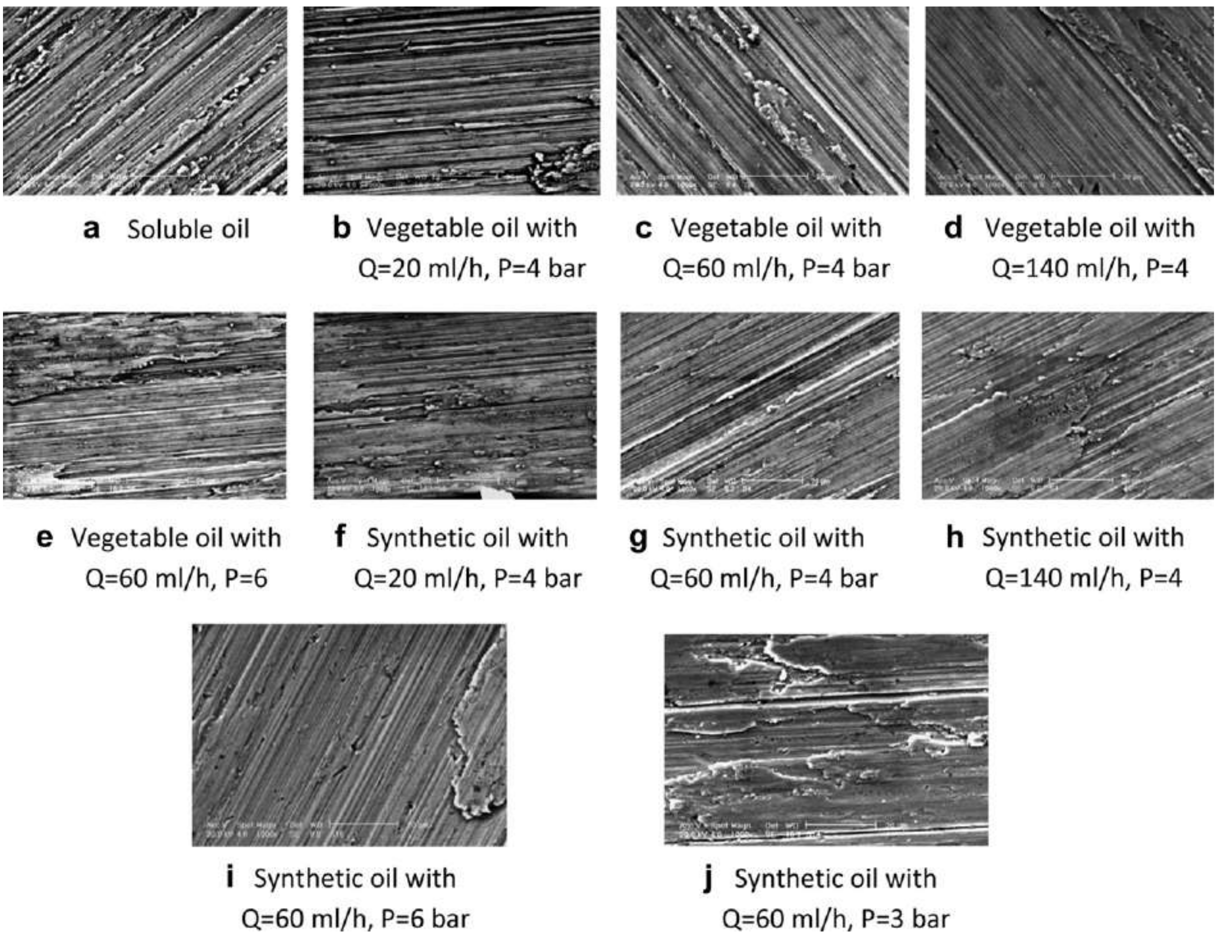

Fig. 6. Surface conditions and metallurgical analysis of surface obtained when grinding with $V_w = 40$ m/min, $V_s = 15$ m/s, DOC = 0.005 mm (Sadeghi et al., 2009).

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Table 5
Cutting conditions (Li and Chou, 2010).

Work material	SKD 61 steels (hardness: HRC38)
Spindle speed (rpm)	20,000, 30,000 and 40,000
Feed (μm/rev)	1.0, 1.5 and 2.0
Depth of cut (μm)	300
Air supply	25 and 40 l/min at 0.5 MPa
Lubricant supply (ml/h)	1.88, 3.75 and 7.5

beneficial effect of finish MQL grinding with vegetable oil compared with wet grinding condition are shown in Fig. 6. The surface finish produced by surface grinding of Ti–6Al–4V with MQL using compressed air pressure at 6 bars was also excellent as shown in Fig. 6(e) and (i).

The authors noted that the subsurface alterations produced by various lubricant and conditions were minimal when the workpiece surface integrity analysis was carried out. There was no significant difference between the condition tested when Al_2O_3 grinding wheel was used with conventional cooling and MQL technique. MQL technique induced lower softening at the outer layers of the ground surfaces, while on the other hand, the profiles show that layer thickness, which undergone work softening when MQL was used, was smaller than those generated when the conventional cooling was applied. When MQL technique with vegetable oil was used, softening was smaller and the micro hardness of surface layer was higher than MQL with synthetic oil.

7.4. Milling process

Li and Chou (2010) investigated the performance of the minimum quantity lubrication technique in milling of SKD 61 steel (with hardness of HRC38) with uncoated carbide end mill on the micro-milling system. Vegetable oil was chosen as the cutting fluid and the cutting conditions for the experiment are shown in Table 5.

The study, which involved two stages of experiments, first studied the performance of MQL technique in milling with respect to dry cutting on the basis of tool wear, surface roughness and burr formation. While the second stage studied the effects of tool materials, oil flow rate and air flow rate on tool performance in MQL technique. In the first stage of the experiment, there was gradual tool flank wears of the micro-tools under different feeds at the spindle speed of 30,000 rpm for both dry and MQL conditions as shown in Fig. 7.

It was observed that the tool life decreased when feed rate decreased under both dry and MQL conditions. It was also observed that application of MQL in near micro-milling can significantly

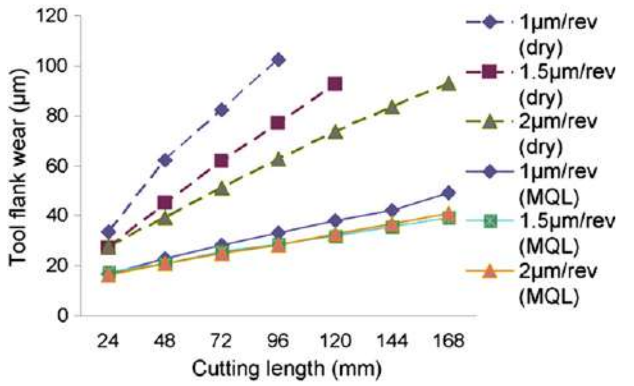

Fig. 7. Tool flank wears at different feeds under dry and MQL conditions (spindle rotational speed is 30,000 rpm) (Li and Chou, 2010).

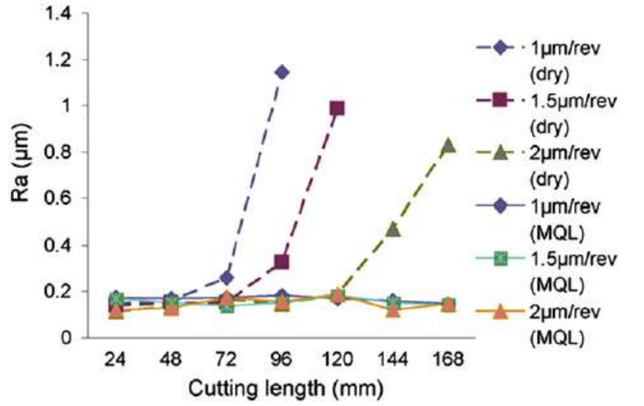

Fig. 8. Surface roughness for different feeds under dry and MQL conditions (spindle rotational speed is 30,000 rpm) (Li and Chou, 2010).

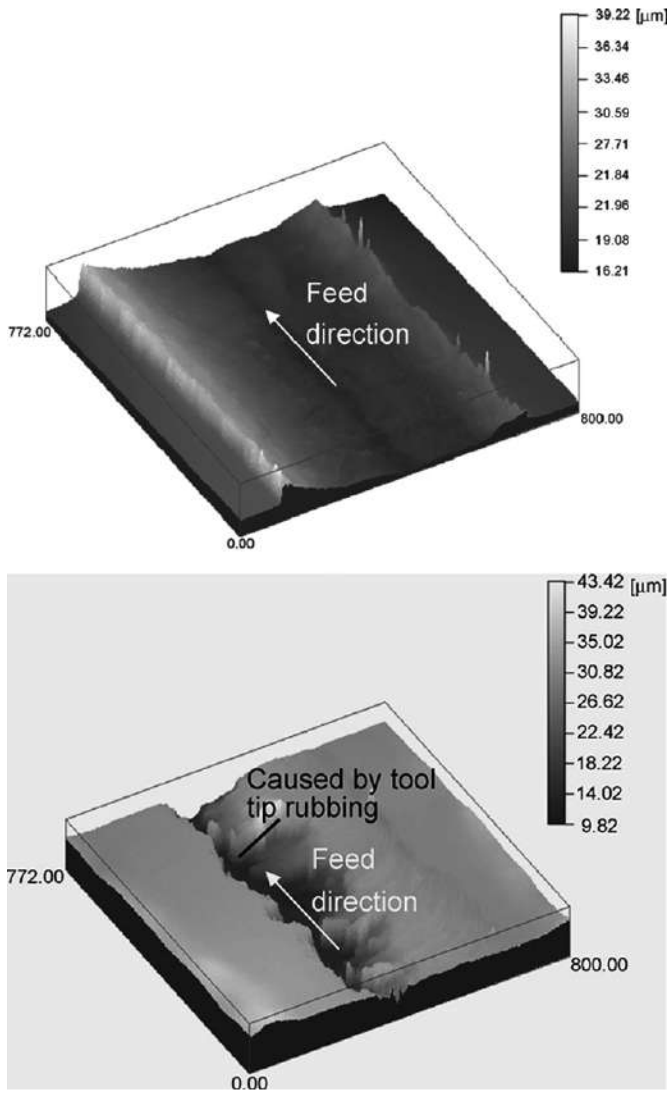

Fig. 9. (i) Surface profile for the machined surface under MQL condition (spindle speed = 30,000 rpm, feed = 2 μm/rev and cutting length = 168 mm) (Li and Chou, 2010). (ii) Surface profile for the machined surface under dry condition (spindle speed = 30,000 rpm, feed = 2 μm/rev and cutting length = 168 mm) (Li and Chou, 2010).

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Table 6
Composition of different tool materials for second stage cutting tests (Li and Chou, 2010).

Tool	Element			
	W	Co	C	O
A (%)	69.2	20.18	9.20	1.39
B (%)	76.7	13.35	8.80	1.06

Tool materials Electronic Data System (EDS) quantitative results.

extend the tool's life under different feed rates. After cutting 96 mm long, the reduction of tool flank wear lengths in MQL cutting compared to dry cutting were 67.65%, 62.66% and 54.59% under the feed rates of 1.0, 1.5 and 2.0 μm/rev respectively. The surface roughness did not change much for all cutting tests under MQL environment as shown in Fig. 8. The values of surface roughness (Ra) varied between 0.1 and 0.2 μm and it did not change with respect to the cutting lengths or the feed rates.

In dry milling, the values of surface roughness increased with respect to the cutting lengths under all feed rates. In dry cutting, it was found that larger burrs were observed for small feed of 1 μm/rev, followed by the feed rate of 1.5 and 2.0 μm/rev. The burr formation was not strongly affected by the increase in cutting lengths under MQL slot as only small burrs were observed in all cutting tests. It was seen from the relationships among tool wear, surface roughness and burr formation that the diminished burr formation under MQL conditions was partly due to the low tool wear in MQL machining. Fig. 9(i) and (ii) shows the surface profile under MQL and dry conditions.

The second stage of the experiment was performed under the spindle speed of 30,000 rpm and the feed rate of 1.0 μm/rev using two different tungsten carbide tools. The tools have the same tool geometry but different cobalt content as shown in Table 6. The tool wear progression for different lubricating conditions and tools are shown in Fig. 10. It was observed that the tool wear rates for Tool A were higher than those of Tool B. The MQL reduced the tool wear rates for both Tool A and Tool B.

It was observed that when the oil flow rates of 1.88, 3.75 and 7.5 ml/h were used in addition to the supply of air without any oil, the tool wear progressions were similar with when the oil flow rate decreased from 7.5 to 1.88 ml/h. The use of only air in near micro-milling did not improve the tool's life compared with that of dry cutting. It showed that lubricating effect of oil under MQL was important for long tool life of micro-tools. The different air flow rate on tool life in dry and MQL cutting indicated that the tool wear rate

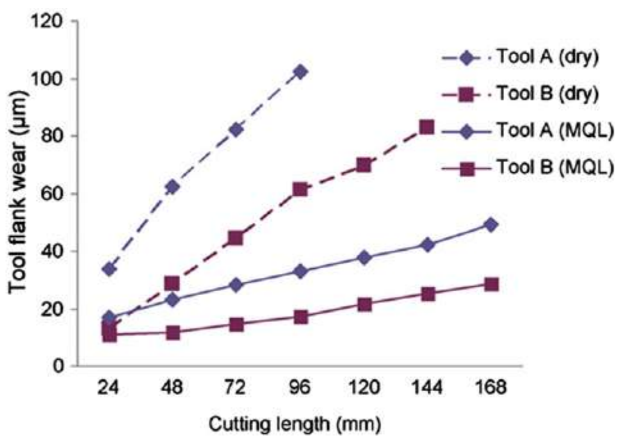

Fig. 10. Tool wear progression for different tool materials (spindle speed = 30,000 rpm and feed = 11 μm/rev) (Li and Chou, 2010).

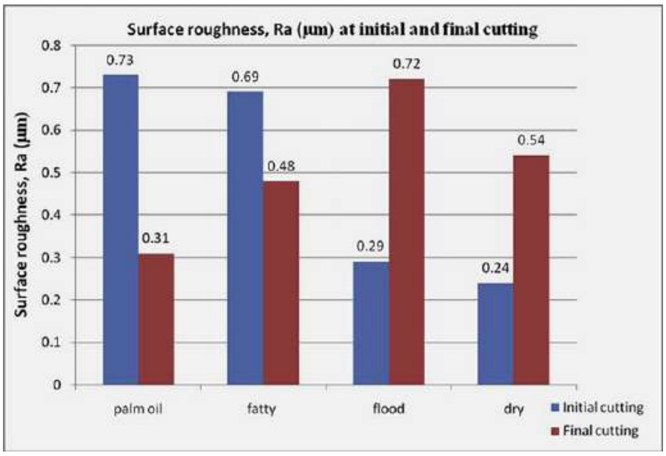

Fig. 11. Surface roughness at initial and final cutting for end milling stainless steel (Sharif et al., 2009).

for dry cutting was maximum followed by MQL with 25 l/min and 40 l/min air flow.

In a related development, Sharif et al. (2009) evaluated the feasibility of vegetable oil based palm oil as a cutting lubricant through the use of minimum quantity lubrication (MQL); during end milling of hardened stainless steel (AISI 420), using coated carbide tool materials (TiA1N and A1TiN). The study involved the use of the following lubricants: fatty alcohol, palm olein, palm olein with additive A and palm olein with additive B (identity of additives A and B were not declared by the authors). Cutting forces, tool life and surface roughness were evaluated under the following machining conditions; cutting speed (100, 130 and 160 m/min), feed rate (0.05 mm/tooth), axial depth of cut (12 mm) and radial depth of cut (1 mm). It was noticed that the tool wear progression was gradual for palm oil and fatty alcohol, while for the dry and flood cutting, the tool wear progressed rapidly. Initial rates of tool wear for palm oil and fatty alcohol showed similar trend and increased drastically after the average wear reaching 0.1 mm. Three distinct stages of wear were observed namely, the (i) primary wear, (ii) normal (secondary) wear, and (iii) sharp (tertiary) wear. The rate of wear was high with dry cutting and cutting with flooded coolant. However, with palm oil and fatty alcohol coolant, the rate of wear was rather low.

The highest tool life achieved was 160.27 min for palm oil lubricant, followed by 137.74 min for fatty alcohol, 39.86 min for flood cutting and 35.16 min for dry cutting. The surface roughness for palm oil and fatty alcohol was 0.73 μm and 0.69 μm at initial stage and finally improved to 0.31 μm and 0.48 μm respectively. However, for dry and flood coolant conditions, the surface roughness was 0.24 μm and 0.29 μm at the initial stage and finally increased to 0.54 μm and 0.72 μm respectively as shown in Fig. 11.

The effect of MQL technique on surface roughness and tool flank wear in end milling Inconel 718 at different speed combinations, using high speed super cobalt tool, were examined by Thamizhmanii et al. (2009). The authors observed that tool life increased by 43.75% when MQL technique with sunflower oil was used as lubricant, compared to dry cutting and surface roughness by dry milling, was higher than MQL milling.

However, MQL technique did not show much significant contribution at low cutting speeds. Similarly, Zhang et al. (2012) examined tool life and cutting forces in end milling of Inconel 718 under dry and minimum quantity cooling lubrication cutting conditions. They found that tool life under MQL cutting condition is 1.57 times as much as that under dry cutting conditions, which

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implies that the supply of the cryogenic compressed air and the micro-droplets of the biodegradable vegetable oil can significantly reduce tool wear rate and extend tool life.

8. Conclusions and future research

Although it is impossible to rank the performance of lubrication techniques in machining processes, because its performance depends on the type of machining process (machining conditions), workpiece material and cutting tool material. However, a critical analysis of the available literature on this subject shows that MQL technique stands out among other techniques. Unlike high pressure coolant, whose application is still not widely used because of lack of basic understanding of the entire method, MQL technique application cuts across different machining processes, workpiece material and cutting tool material. Again, most of the reported works in the application of high pressure coolant technique have largely been restricted to hard-to-cut materials.

The application of cryogenic cooling technique has shown improved productivity and product quality. However, the initial cost is high and the benefit of cryogenic cooling technique has been predominantly at low cutting speed as improved surface finish and reduction of tool wear have been reported. In this technique, the regulation of flow rate and pressure of liquid nitrogen are critical factors in order to get continuous flow of liquid nitrogen without over cooling the workpiece. Furthermore, the technique offers a situation whereby there is no cutting fluid to be disposed as nitrogen generated evaporates into the air and chips from this technique have no residual oil on them and therefore can be recycled as scrap. On a general note, the performance of MQL technique in different machining processes still offers better results especially when vegetable oil-based lubricant is used in term of cost, performance and environmental related issues.

Solid lubricant technique is a complex lubrication method because it requires the selection of the right lubricant for a specific application. It becomes an alternative method when liquid lubricant does not meet the advanced requirement of modern technology such as prolonged stationary service. Although, the application of this technique has shown improved surface finish and reduced flank, it still remains as an alternative method to other means of lubrication techniques, especially MQL.

Air/vapour/gas lubricant technique has received tool manufacturer's approval to be used in high speed cutting operation. Nevertheless, more research still needs to be carried out, because it is not yet certain whether this environment assists the cutting process or if its popularity was due to the convenient availability of compressed air in the workshop and its ability to remove cutting chips from the work zone. Therefore, there is the need to conduct more researches on different machining processes, workpiece and cutting tool materials using this method of lubrication technique to be able to substantiate its contribution to machining performance and environmental issues.

Literature have shown that MQL technique using vegetable oil-based lubricant in any machining processes offers the best alternative in combating the environmental problems or challenges posed by mineral oil based lubricants. Apart from addressing environmental problems, it has been established by researchers that MQL technique using vegetable oil lubricant exhibit better machining performances. MQL also shows favourable cost reduction due to reduced cost of cutting fluid management. However, factors such as types of workpiece material, machining process, cutting tool material and machining conditions still remain critical variables in determining the performance ability of MQL technique with vegetable oil lubricant. Much still need to be done to address the application of MQL technique using vegetable oil lubricant in machining processes, especially in grinding process to determine the grinding ratio, roughness values and wheel wear rate; as only few literature are available on this technique when using vegetable oil as lubricant. Machining of materials such as aluminium and medium carbon, which are sensitive to surface finish due to the tendency of the material to create built up-edge on the tooling, needs further investigation under MQL technique. The generation of mist particle from the lubricant and their characteristics need to be investigated for a whole range of machining processes and conditions. These generated mist particles may not be an issue when vegetable oil lubricant is used in MQL technique as the mist particle generated cannot pose any danger to the environment. The summary of the performance of MQL technique using vegetable oil-based lubricant from the available literature is hereby presented:

1. An improved surface roughness of about 31.6% was reported for MQL with vegetable oil based lubricant over wet and dry cutting during turning process of AISI 9310 low alloy steel with uncoated carbide tool under specified machined conditions.
2. Better lubrication was achieved with MQL synthetic ester compared to MQL rapeseed oil during turning of aluminium alloy with polycrystalline diamond tool.
3. The MQLPO recorded the lowest thrust force by 27% compared to 19% recorded for MQLSE during drilling process of titanium alloy with carbide drill coated with AlTiN tool. Generally, MQL conditions showed that the thrust force and torque decreased with an increase in cutting speed.
4. The analysis of surface integrity of Ti–6Al–4V titanium alloy showed no significant difference between MQL technique and conventional method of cutting fluid application in grinding process.
5. There were reduction of tool's flank wear length in MQL cutting by 67.65%, 62.66% and 54.59% compared to dry cutting for feed rates of 1.0, 1.5 and 2.0 μm/rev respectively for 96 mm cutting length, while milling SKD 61 steel with uncoated carbide.

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