# MINIMUM QUANTITY LUBRICATION ASSISTED TURNING - AN OVERVIEW

UPADHYAY, V.; JAIN, P. K. & MEHTA, N. K.

***Abstract:*** *Minimum Quantity Lubrication, which relies on total use without residue, has been gaining popularity as a new alternative for flood cooling. This chapter presents an overview regarding the various aspects of Minimum Quantity Lubrication/Near Dry Machining followed by a comprehensive literature review to provide an outline of developments and outcomes of various studies. Further, a sequential procedure for determining the rational operating parameters was demonstrated to achieve enhanced effectiveness of aerosol during machining. Finally, the chapter was concluded with some guidelines for further research.*

***Key words:*** *minimum quantity lubrication, near dry machining, turning, machinability*

**Authors´ data: Upadhyay**, V[ikas]; **Jain**, P[ramod] K[umar]; **Mehta**, N[arinder] K[umar], Mechanical and Industrial Engineering Department, Indian Institute of Technology Roorkee, Uttarakhand, India, vikasupadhyay.agra@gmail.com, pjainfme@iitr.ernet.in, mehtafme@iitr.ernet.in

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## 1. Introduction

Green manufacturing is one of the major research and development theme in manufacturing sector in recent years due to the challenges raised by increased environmental awareness, and strict protection laws and health regulations for occupational safety. The main environmental and occupational health hazard problems in metal cutting industry are related to the use and disposal of cutting fluids, which are used to reduce force and power, increase tool life, improve surface finish and chip removal, and reduce thermal distortion and subsurface damage (Devries, 1992). Use of cutting fluid provides numerous advantages in machining but suffers from serious drawbacks of operator health hazard as well as environmental and economical problems. Improper disposal of cutting fluids pollutes land, water, and air and thus disturbs the whole environment (Jiang et al., 2008). Contact of cutting fluid with skin and inhalation of its vapour causes skin and respiratory problems due to presence of various additives such as emulsifiers, biocides, rust inhibitors, stabilizers, etc. In addition, cutting fluid particles remain suspended in the environment for a long period (Sutherland et al., 2000) and thus affect other employees, which are not in direct contact with cutting fluids (Benett and Benett, 1985). National Institute of Occupational, Safety and Health (NIOSH), 1983 estimated that 1.2 million workers are potentially exposed to the hazardous/chronic toxicology effects of metal working fluids. NIOSH recommended exposure limit of 0.5 mg/m$^3$ for 10-hour time weighted average (TWA) for no requirement of respiratory protection (Sutherland et al., 2000; Khan et al., 2009). However, the oil mist levels on shop floor are quite high; oil mist level of 1-56.5 mg/m$^3$, 0.8-50 mg/m$^3$ and 20-90 mg/m$^3$ was reported for flood type of cooling in automobile manufacture, manufacture of steel products and automotive plants respectively (Benett and Benett, 1985). Also, the use of coolant fluid costs from 7 to 17% of the total manufacturing cost of work-piece (Weinert et al., 2004) and requires additional time for work-piece/tool/machine cleaning (Dhar et al., 2006a). Moreover, a study conducted by Sutherland et al. (2000) reveals that 12-80 times more cutting fluid mist was generated with wet turning, than cast iron dust in dry turning.

Consequently, dry machining turned out to be the field of interest for many researchers to deal with above-mentioned challenges. Dry machining was found successful with some materials such as cast iron but less effectiveness was noticed when high production rates and machining efficiency is required. Tools with high heat resistance and wear resistance are required for dry machining. New tool coatings were found helpful to some extent, as the machining cannot be still performed at the same rate as with cutting fluids (Canter, 2009). In addition, for continuous high speed machining of some materials such as superalloys and titanium, cooling is necessary (Sreejith and Ngoi, 2000) to improve tool life and surface finish. So, Near Dry Machining (NDM)/Minimum Quantity Lubrication (MQL)/Micro-Liter Lubrication (μLL) emerged out as a plausible solution to aforementioned problems as it reduces the drawbacks associated with flood cooling and dry machining and even can perform better than flood cooling. The concept of MQL was emerged nearly a one and a half decade ago to meet out the strict environmental regulations, issues related to operator health hazard and cost related to use of coolant. MQL has been successfully applied in various machining operations such as turning (Dhar et al., 2006a), drilling (Kelly and Cotterell, 2002), milling (Kishawy et al., 2005) and grinding (Sadeghi et al., 2009). Applications of MQL has resulted in better tool life, improved surface finish, better chip forms and reduced cutting forces (Varadarajan et al., 2002; Khan et al., 2009).

## 2. Minimum quantity lubrication

In MQL process, oil is mixed with high-pressure air and the resulting aerosol is supplied near to the cutting edge. This aerosol impinges at high speed on the cutting zone through the nozzle. Air in the aerosol provides the cooling function and chip removal, whereas oil provides lubrication and cooling by droplet evaporation. The flow of lubricant in MQL process varies from 10 to 100 ml/h and air pressure varies from 4 to 6.5 $Kgf/cm^2$ (Silva et al., 2005). Different ranges for flow rate were also reported in literature such as 50 to 500 ml/h (Dhar et al., 2006a) and 2 to 300 ml/h (Zhong et al., 2010). However, in industrial applications consumption of oil is approximately in the range of 10-100 ml/h (Kamata and Obikawa, 2007). When the flow rate of cutting fluid in MQL is less than or equal to 1 ml/h it is termed as Micro-Liter Lubrication (μLL) (Obikawa et al., 2008). As the quantity of cutting fluid in MQL is very less (in ml/h instead of l/min) in comparison to flood cooling, the process is also known as Near Dry Machining. If oil is used as fluid medium in NDM, better lubrication is obtained with slight cooling effect whereas, when emulsion, water or air (cold or liquid) were used, better cooling is achieved with slight/no lubrication so, the processes were termed as Minimum Quantity Lubrication and Minimum Quantity Cooling respectively (Weinert et al., 2004). NDM can be classified on the basis of method of aerosol spray and aerosol composition as shown in Figure 1. Detailed description is available with Astakhov, 2008.

In MQL, cooling occurs due to convective and evaporative mode of heat transfer and thus is more effective than conventional wet cooling in which cooling occurs due to convective heat transfer only. In addition, cutting fluid droplets by virtue of their high velocity penetrates the blanket of vapor formed and provides more effective heat transfer than wet cooling (Varadarajan et al., 2002). However, according to Astakhov, 2008 aerosols do not acts as lubricants or boundary lubricants as they do not have access to the tool-chip and tool-work-piece interfaces due to too low penetration ability. In addition, the cooling action due to droplet evaporation is also small due to very small flow rate of oil. MQL action on forming chip is also negligibly small as compared to high pressure water soluble metal working fluids due to low mass of aerosol. Astakhov, 2008 suggested that the application of MQL enhances the Rebinder effect and thus reduces the work due to plastic deformation. Possible parameters and machining conditions affecting the performance of MQL assisted machining are illustrated in fishbone diagram as shown in Figure 2.

As little quantity of cutting fluid was utilized in MQL process, the cutting fluid should possess significantly higher lubrication qualities than mineral oil. Vegetable

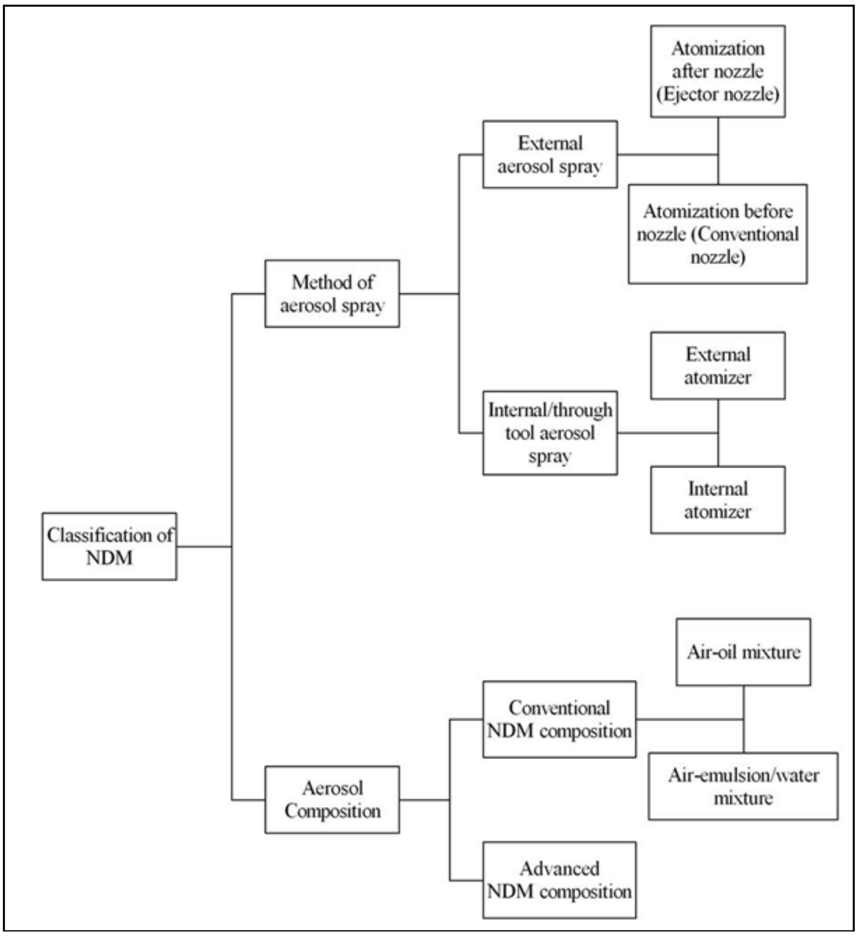


Fig.1. Classification of Near Dry machining (Astakhov, 2008; Weinert et al., 2004)

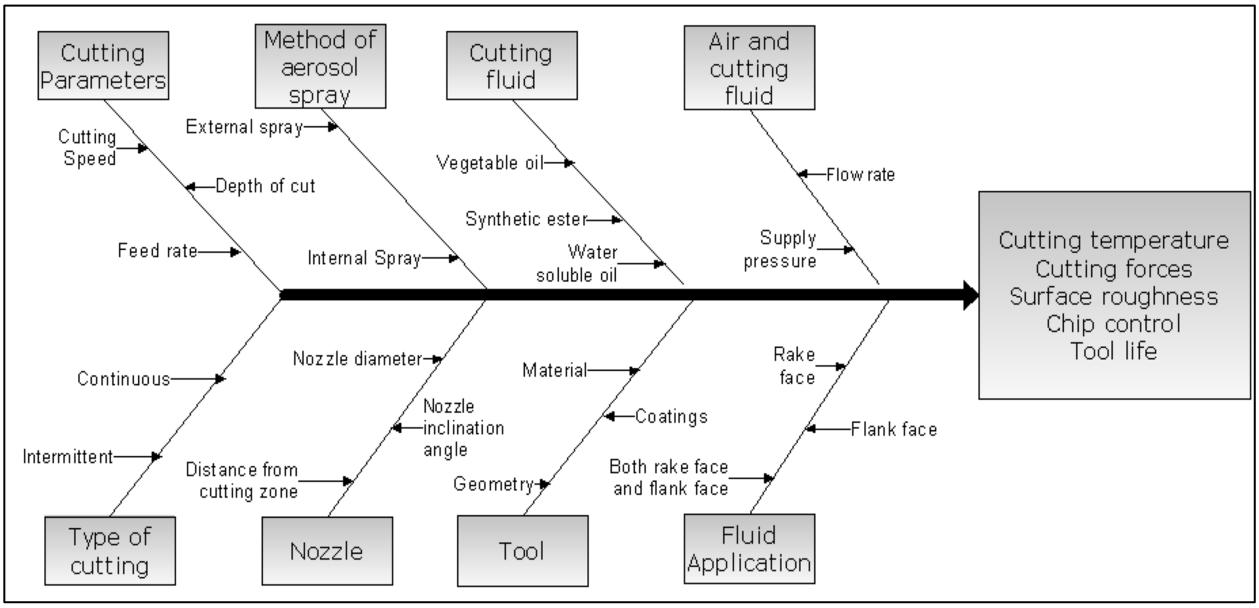


Fig.2. Fishbone diagram showing cause and effect in MQL assisted machining

oil and synthetic ester oil are two viable alternatives. Vegetable oils are nontoxic as they are based on extract from plants. Molecules of these oils are long, heavy and dipolar in nature and provides greater capacity to absorb pressure. Higher viscosity index provides stable lubrication in operating temperature range and higher flash point provides opportunity to increase metal removal rate due to reduced smoke formation and fire hazard (Krahenbuhl, 2002). Wakabayashi et al. (2006) introduced some synthetic esters, synthesized from a specific polyhydric alcohol. These synthetic esters have high biodegradability, excellent oxidation stability, good storage stability, and satisfactory cutting performance. Investigated synthetic esters were suggested as satisfactory MQL cutting fluid on the basis of cutting performance and optimal fluid for MQL machining on the basis of biodegradability, oxidation and storage stability.

Some studies reported that application of MQL results in zero airborne mist levels as the oil mist either vaporizes or clings to the work-piece or chips (Dasch and Kurgin, 2010). However, Dasch and Kurgin (2010) found MQL mist level comparable to wet application and proportional to the volume of oil entering the system. So, mass concentration and particle size as well as composition and physical state of mist requires serious attention.

A MQL supply system typically consists of a compressor, container for cutting fluid, fluid supply pump, mixing chamber, nozzle, separate pipes for supply of cooling lubricant and air for their independent adjustment. However, the components of the MQL system may vary depending upon the type of fluid delivery system and atomization. The schematic diagram of the experimental set-up fabricated at Machine Tool Laboratory, Indian Institue of Technology Roorkee is presented in figure 3. An air compressor was used to increase pressure of air. In order to deliver metered supply of air at desired pressure, pressure regulator and flow meter are fitted in air supply line. The pressurized air from nozzle can be directed either on rake or flank face or on both face depending upon experimental requirement. A fluid chamber fitted with a pump was used to store and deliver the coolant to the nozzles. A commercially available medical infusion set consisting of flexible tube and roller type flow controller was used to control the supply of cutting fluid to the nozzle. Commercially available gas welding nozzles were used to impinge aerosol at high velocity in the cutting zone. The inlet side of nozzles was modified by installing a fabricated chamber of Perspex having separate passages for air and coolant.

Advantages of MQL assisted machining are: fluid supplied to the cutting tool is consumed at once so there is no need of fluid monitoring, maintenance or disposal (Dasch and Kurgin, 2010); reduction in solid waste by 60%, water use by 90%, and aquatic toxicity by 80% due to delivery of lubricants in air instead of water (Clarens et al., 2008); decreased coolant costs due to low consumption of cutting fluid; reduced toxicity and hazardous effects as mostly vegetable oils are used which are nontoxic and biologically inert (Khan et al., 2009); reduced cleaning cost and time due to low residue of lubricant on chip, tool and work-piece (Attansio et al., 2006); better visibility of cutting operation (Attansio et al., 2006).

## 3. Review of literature

This section provides the review of previous research work carried out in the area of MQL assisted turning to highlight the outcomes. This review was conducted material wise to provide a comprehensive overview of reserach outcomes for a particular work-material.

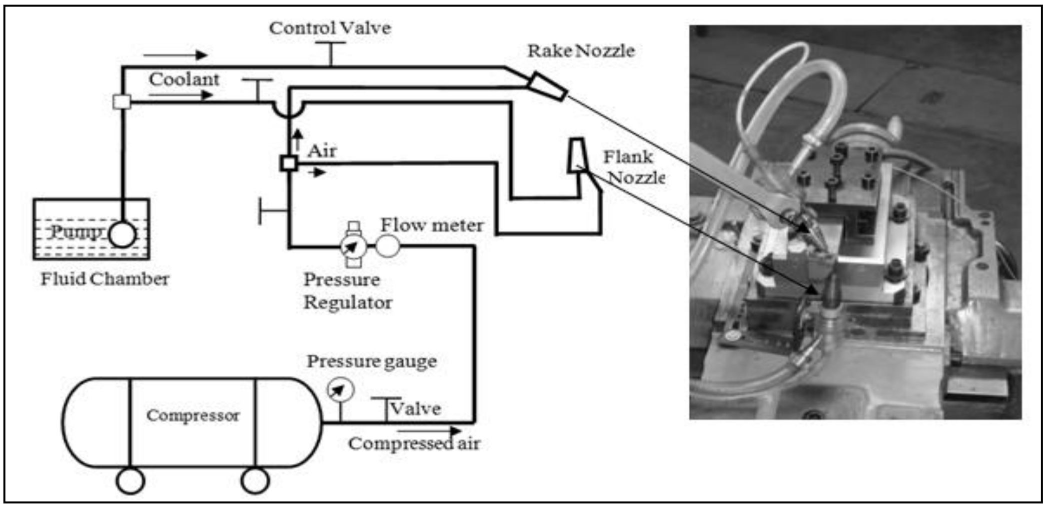


Fig.3. Schematic diagram of MQL set-up

*3.1 MQL assisted hard turning and turning of Steel*

*3.1.1 MQL assisted hard turning of Steel*

Varadarajan et al., 2002 investigated hard turning of AISI 4340 with P30 or equivalent substrate with TiC, TiN and TiCN coatings under minimal cutting fluid application. Coolant rich (60%) lubricant fluid with minimal additives at 2 ml/min delivery rate, 20 MPa injection pressure and 600 pulses/min was used in investigation. Lower cutting force and reduced tool chip contact length, surface roughness and cutting temperature were reported as compared to dry and flood cooling. Also high cutting ratio, improved tool life and better chip control is achieved. Better machinability is attributed to fragmentation of cutting fluid in tiny droplets, which penetrates the blanket of vapors by virtue of their high velocity and reaches the cutting zone. Furthermore, the cooling was more effective due to convective and evaporative mode of heat transfer.

In another study on hard turning of AISI 4340 with minimal fluid application, Kumar and Ramamoorthy, 2007 evaluated the performance of two nitride-coated tools (TiCN and ZrN) in terms of cutting force, surface roughness and cutting temperature using statistical design of experiments. Exit pressure was the most significant parameter affecting the cutting force followed by depth of cut and feed whereas type of coating has not much influence. Increase in nozzle pressure increases the exit velocity of cutting fluid resulting in better penetration and thus reduction in cutting force. Cutting velocity is the most significant parameter influencing the cutting temperature followed by amount of cutting fluid, nozzle pressure, and frequency of pulses. Surface roughness is most affected by feed and then by nozzle pressure, type of coating and amount of cutting fluid.

*3.1.2 MQL assisted turning of Steel*

Turning of AISI 52100 hardened steel was studied Diniz et al. (2003) using TiN coated CBN inserts under dry cutting, wet cutting and minimum volume of oil (MVO). Mostly similar values of flank wear and surface roughness were obtained with dry and MVO cutting. Values of flank wear and surface roughness were always found better than wet cutting. Based on study, dry cutting was concluded as the best technique for turning of this material. The better performance of dry cutting was attributed to increased cutting zone temperature that caused easier deformation and shearing of chip, reduced cutting forces and vibration, and reduced tool wear.

Attansio et al., 2006 studied tool wear in finish turning of 100Cr6 normalized steel pieces under MQL and dry cutting conditions using triple coated carbide tip (TiN outer layer, $Al_2O_3$ intermediate layer and TiCN inner layer). MQL was applied on rake and flank face of the tool at constant cutting speed of 300 m/min and depth of cut of 1 mm, and at feed rate of 0.2 and 0.26 mm/rev with cutting length of 50 mm and 200 mm. Equal or greater mean removed material was reported with flank MQL as compared to dry and rake MQL. Tool life decreased with feed rate in all cutting conditions however the tool life obtained in flank MQL was highest. Tool life increases in flank MQL with increase in cutting length whereas it does not influence tool life in dry and rake MQL. In rake MQL, lubricant was not able to reach the cutting area as no elements indicating compounds from lubricant were seen on worn surface of tool tip.

Tool wear and surface roughness of AISI-4340 alloy was studied by Dhar et al., 2006b with uncoated carbide insert under MQL conditions. Principal flank wear and auxiliary flank wear were selected to study the tool wear as former affects the cutting force, and latter affects the surface finish and dimensional deviation. Reduced tool wear and improved surface finish was achieved with MQL as compared to dry and wet machining mainly due to effective reduction in cutting temperature.

In another study on same alloy, chip tool interface temperature and dimensional deviation were also monitored along with surface roughness and tool wear. At low cutting speeds the chip makes partially elastic contact with the tool but with increase in cutting speed chip makes fully plastic or bulk contact with the rake face of the tool. So, at low cutting speeds more effective cooling was observed as MQL was dragged due to capillary effect in the elastic contact zone. While, at high cutting speed less reduction in cutting temperature was observed due to reduction in time to remove accumulated heat and due to fully plastic or bulk contact preventing the MQL to reach the hot chip-tool interface. Decrease in feed improves the cooling effect to some extent particularly at low cutting speed possibly due to slight lifting of the thinner chip. About 5 to 10% decrease in average cutting temperature was recorded depending upon the level of cutting speed and feed rate. Reduced dimensional deviation with machining time was observed with MQL as compared to that in dry and wet turning (Dhar et al., 2007). Rahman et al., 2009 reported about 5 to 10% reduction in average cutting temperature in MQL turning of AISI 9310 alloy depending upon the levels of cutting speed and feed.

In MQL turning of AISI-1040 with uncoated carbide, MQL jet was targeted on the rake and flank face of the auxiliary cutting edge to achieve better dimensional accuracy. With MQL application the cutting temperature is effectively reduced and blue colored spiral shaped chips produced under dry and wet conditions became metallic colored and half turn. Also the back surface of chip under MQL is much brighter and smoother indicating the favorable chip tool interaction and elimination of built–up edge formation. Reduced value of chip compression ratio and improved dimensional accuracy was also achieved with MQL (Dhar et al., 2006a). Similar improved results were also reported in MQL turning of AISI-9310 and AISI-1060 alloy by using vegetable oil-based cutting fluid (Khan and Dhar., 2006; Khan et al., 2009). Physics based models for MQL was developed by Li and Liang (2007) to predict the cutting temperature, cutting force, tool wear and aerosol generation rate. The models were validated with the experimental results obtained in turning of AISI 1045 material. MQL was supplied on the flank face of the tool by a 0.762 mm diameter opening in the tool holder. Cutting forces for MQL are found smaller than dry cutting but higher than wet cutting. At lower cutting speeds lubrication was effective but at high cutting speed (228.75 m/min) ineffective lubrication was observed. MQL was most effective in reducing the tangential cutting force among the cutting force components. MQL also reduced the cutting temperature for the entire range of speed and provided a lower wear rate in comparison to dry cutting. However, it was expected that MQL will generate more cutting fluid aerosol than flood cooling due to splash mechanism.

Tasdelen et al. (2008) investigated the affect of different cooling techniques such as MQL, compressed air and emulsion on tool chip contact length in turning of 100Cr6 steel with different engagement times of inserts. Lower contact lengths were observed with MQL and compressed air as compared to dry cutting. However, emulsion assisted cutting provided the shortest contact length. For long engagement times, MQL and compressed air have same contacts lengths, as the cooling effect was mainly from air constituent in aerosol. For short engagement times, lubrication effect of oil drops decrease the friction in the sliding region and overcomes the cooling effect resulting in shorter contact lengths than compressed air. Also at short engagement times, increase in quantity of oil decreases the contact length. More up-curled chips were obtained with emulsion than MQL and air assisted cutting. Chips obtained from MQL and compressed air have almost same radius of curvature. Whereas, chips obtained from dry cutting have largest radius of curvature. Chips obtained in dry cutting were wider than the chips obtained with other methods due to side flow in the shear plane and have side curl due to difference in speed at outer and inner diameter of work-piece. Shorter contact lengths were observed with TiN coated tool due to different friction and temperature distribution in the cutting zone. Effect of oil drops were found even at reduced engagement time for TiN coating than uncoated carbides. On the basis of study it was concluded that for short engagement time machining MQL is very suitable.

A study was conducted by Hwang and Lee (2010) to predict the cutting force and surface roughness and to determine the optimal combination of cutting parameters in turning of AISI 1045. To determine the significant parameters among supplied air pressure, nozzle diameter, cutting speed, feed rate and depth of cut a two level fractional factorial design is employed. It was reported that except supplied air pressure all the parameters significantly affected the surface roughness. Models are then developed for prediction of cutting speed and surface roughness in MQL and wet turning using Central Composite Design. From the validation experiment cutting force equations are found valid whereas surface roughness equations were not appropriate for accurate prediction. The mismatch in experimental and predicted values was attributed to uncontrolled parameters such as work material defect, lathe vibration and measuring errors. Nozzle diameter of 6 mm, cutting speed of 361 m/min, feed rate of 0.01 mm/rev and depth of cut of 0.1 mm were found optimal for MQL turning whereas nozzle diameter of 6 mm, cutting velocity of 394 m/min, feed rate of 0.02 mm/rev and depth of cut of 0.1 mm were found optimal for wet turning considering surface roughness and cutting forces simultaneously. MQL turning was found to be more advantageous than wet turning when only surface roughness and cutting forces were considered.

*3.2 MQL assisted turning of Inconel 718*

Kamata and Obikawa (2007) investigated finish turning of Inconel 718 under MQL with three types of coated carbide tool (TiCN/$Al_2O_3$/TiN (CVD), TiN/AlN superlattice (PVD) and TiAlN (PVD)). Biodegradable synthetic ester was supplied with compressed air on both the rake and flank face of the tool. On the basis of tool life and surface finish, TiCN/$Al_2O_3$/TiN (CVD) and TiN/AlN superlattice (PVD) were found suitable for finish turning of Inconel 718 with MQL. They reported that optimization of air pressure is required for appropriate application of MQL in finish turning of Inconel 718. They also reported that carrier gas plays a vital role in cooling of cutting point as short tool life were obtained with argon gas as compared to air. Increase in cutting speed from 1m/s to 1.5 m/s resulted in drastic decrease of tool life and worse surface finish for both the coatings under MQL condition. Also, increase in lubricant quantity, increased the tool life and surface roughness for TiCN/$Al_2O_3$/TiN coating, whereas it decreased the tool life and surface roughness slightly for TiN/AlN coated tool.

Su et al. (2007) used cooled air (at a temperature of -20$^0$C) with MQL at a pressure of 6 bar in finish turning of Inconel 718 alloy. Application of cooled air and cooled air with MQL resulted in 78% and 124% improvement respectively in tool life over dry cutting. Improvement in tool life was attributed to reduction in cutting temperature resulting in reduced abrasion, adhesion and diffusion wear. Surface roughness was also reduced drastically in both conditions due to reduction in tool wear. Significant improvement in chip shape was also reported as short continuous tubular chips were obtained under both conditions.

Obikawa et al., 2008 observed that control of oil mist flow and decrease in distance between nozzle and tool tip enhances the cutting performance of MQL particularly in Micro-liter lubrication range (oil consumption less than 1 ml/h). Finish turning of Inconel 718 was investigated in micro-liter lubrication (μLL) range with biodegradable ester using three different types of nozzles: ordinary type, cover type for normal spraying and cover type for oblique spraying. Effectiveness of MQL ($e_{MQL}$) was computed by the relation (1)

$$e_{MQL} = \frac{T_{MQL} - T_{dry}}{T_{wet} - T_{dry}} \quad (1)$$

where $T_{MQL}$, $T_{dry}$ and $T_{wet}$ are tool life for MQL, dry and wet turning.

Ordinary nozzle and cover type nozzle for normal spraying are not found suitable for μLL. Values of $e_{MQL}$ decreased to 0.50, 0.47 and 0.36 as oil consumption

(Q) decreased to 1.1 , 0.5 and 0.2 ml/h for ordinary nozzle whereas with cover type nozzle for normal spraying increase in $e_{MQL}$ is 0.22 and 0.18 for Q =0.50 and 0.20 ml/h over ordinary nozzle. The cover type nozzle for oblique spraying provided significant improvement as value of $e_{MQL}$ was 0.80,0.94 and 0.97 for Q =0.2, 0.5 and 1.1ml/h respectively. Good surface finish and tool life of 47 min was obtained at an oil consumption of 0.5 ml/h and cutting speed of 1.3 m/s.

### *3.3 MQL assisted turning of Aluminum alloys*

A study on effects and mechanisms in MQL intermittent turning of Aluminum alloy (AlSi5) was conducted by Itoigawa et al. (2006). MQL was studied with oil and oil film on water droplet using rapeseed oil and synthetic ester as lubricant. MQL with rapeseed oil showed only a small lubrication effect in light loaded machining conditions. MQL with synthetic ester shows a lubrication effect but there was significant tool damage and aluminum pick-up on the tool surface. MQL with water droplets using synthetic ester provided good lubrication. They reported that influence of water for good frictional performance depends not on the film chemi-sorption process but on water’s chilling effect to sustain boundary film strength.

In MQL machining of 6061 aluminum alloy the quantity of adhered material to the tool was more as compared to flooded coolant and less as compared to dry cutting. No considerable reduction in material adhesion and flank wear was observed by increasing the lubricant quantity to two times. Significant increase in flank wear was reported with increase in cutting speed. Cutting forces were found highest under dry cutting and lowest under flooded condition. The variation of cutting forces with different machining strategies is attributed to the amount of adhesion. Surface roughness obtained by MQL is found to lie between dry cutting and flooded condition (Sreejith, 2008).

### *3.4 MQL assisted turning of Brass*

Davim et al. (2007) conducted a study on turning of brass with MQL to study the effect of the quantity of cutting fluid. They compared the cutting power, specific cutting force, surface roughness and chip form with MQL at Q =50, 100, 200 ml/h and with flood cooling at Q =2000 ml/h. Cutting parameters in the experimental test are cutting speed (v) =100, 200 and 400 m/min, feed rate (s) =0.05, 0.10, 0.15 and 0.2 mm/rev, depth of cut (t) =2 mm. Slightly higher cutting power was observed with MQL lubrication at 50 ml/h and flood lubrication at 2000 ml/h whereas almost same power is noticed with MQL at flow rate of 100 and 200 ml/h. This suggests that similar/better cutting conditions can be achieved with MQL as compared to flood lubrication. The specific cutting force is found lower at a cutting velocity of 200 m/min except for fluid lubrication and reported it to be a critical speed for brass machining. At Q =200 ml/h specific cutting force is found to be lowest. Surface roughness decreased with increase in flow rate. Similar surface roughness is observed with MQL at Q =200 ml/h and flood lubrication. Also for all the machining conditions the relation between $R_t$ and $R_a$ was found maintained. Similar chip forms were observed MQL and flood lubrication. In further work by Gaitonde et al., 2008, quantity of lubricant, cutting speed and feed rate were determined for simultaneously minimizing surface roughness and specific cutting force by using Taguchi method and utility concept. They reported that Q =200 ml/h, v =200 m/min and s =0.05 mm/rev are optimal process parameters. Feed rate is found to be most significant factor followed by quantity of MQL lubricant and cutting speed in optimizing the machinability characteristics.

*3.5 MQL assisted turning of Titanium alloy*

Effect of dry cutting, flood coolant, and minimum quantity lubrication were studied in continuous and interrupted turning of Ti-6Al-4V alloy with uncoated carbide inserts. It was reported that in continuous cutting, MQL seems to be more effective than flood cooling at high cutting speed and feed rate due to its better lubrication ability. In interrupted cutting MQL was also found more effective than dry and flood coolant particularly in two slots cutting (Wang et al., 2009).

The main problem with machining of titanium alloys is related to high heat generation at tool-chip interface due to which machining of these alloys is recommended only with copious amount of cutting fluid. As the main concern in titanium alloy machining is to remove the heat generated during the process, Minimum quantity cooling (MQC) seems to be more appropriate than MQL. A sequential procedure for determining operating parameters in MQC assisted turning of Ti-6Al-4V alloy is presented in following section.

## 4. Sequential procedure to determine a rational set of operating parameters

This section presents a sequential procedure to determine a rational set of operating parameters for minimum quantity coolant application during turning of Ti-6Al-4V alloy. Operating parameters of the process can be divided into two subsets: nozzle related parameters and aerosol related parameters. Nozzle related parameters are nozzle tip distance from tool tip, nozzle inclination angles, and nozzle location (on rake face or flank face or on both face) and aerosol related parameters are compressed air pressure, concentration of oil in emulsion, and coolant flow rate per nozzle. The process begins by determining rational value of each of the nozzle related parameters in a sequential manner and then determining the aerosol parameter. The detailed description is as follows.

The first step in the process is to determine the range of various nozzle and aerosol related parameters. The range of parameters for MQC assisted machining of Ti-6Al-4V alloy with the developed experimental setup was fixed with the help of information collected from detailed literature review and pilot experiments.

*Nozzle related parameters*

- *Nozzle tip distance from tool tip*: Nozzle tip distance plays a vital role in aerosol effectiveness as if the distance between tool tip and nozzle distance is too small, coolant drops will not be disported from the aerosol providing reduced performance. If the distance is too large, most of the fluid will be concentrated near the spray axis and only a small quantity will be left in the outer region (Tawakoli et al., 2010). When the nozzle tip distance from tool tip was kept 10 mm, obstruction of chip flow with nozzle was observed so the minimum distance to start with was selected as 15 mm. This distance will be increased in a increment of 5 mm to study the effect of tip distance.

- *Nozzle inclination angles*: The nozzle inclination angle of $45^0$ in horizontal and $45^0$ in vertical plane were suggested as best angles in turning (Ueda et al. 2006). The nozzle inclination angle in vertical plane was kept fixed at $45^0$ for entire experimental study based on literature review, as this angle is not affected by direction of chip flow. However, the inclination angle in horizontal plane may affect the MQC performance depending upon chip flow direction so it is varied between $30^0$ and $60^0$ to determine the appropriate inclination angle in horizontal plane. For initial study, nozzle inclination angle in horizontal plane was kept at $45^0$ as it has been reported to be most effective for reducing the rake surface temperature (Ueda et al. 2006).
- *Nozzle location*: The aerosol can be directed on rake face or flank face or on both face, rake face location of nozzle was selected to start with as it has been used in turning of various steels (Khan et al., 2009; Rahman et al. 2009).

*Aerosol related parameters*

- *Air pressure:* Air pressure plays a vital role in deciding the diameter of tiny droplets in aerosol. Increase in air pressure causes a decrease in droplet diameter and thus helps the aerosol to penetrate in the tool-chip interface. However, beyond a certain value of air pressure, the aerosol effect starts detoriating due to spring back of high speed droplets from the chip tool interface (Liu et al., 2011). The air pressure in MQL varies from 4 to 6.5 kgf/cm$^2$ (Silva et al., 2005), so a value close to the mid level of this range i.e. 5 bar pressure has been selected for investigation.
- *Oil concentration*: The recommended oil concentration in emulsion is 5 to 15% by coolant manufacturer. The minimum concentration, i.e. 5% was selected for the initial experiments.
- *Coolant flow rate*: Starting value of coolant quantity has been selected as 100 ml/hr based on primary knowledge from literature review and preliminary experiments. However, to determine the rational value the coolant flow rate was varied from 25 ml/hr to 150 ml/hr per nozzle.

In the next step, experiments were conducted by varying nozzle tip distance values from 15 to 30 mm in increment of 5 mm while keeping other variables at their predetermined values as discussed in previous section. Based on these experiments rational value of nozzle angle was determined and kept fixed for subsequent experiments. Then, nozzle angle was varied at $30^0$, $45^0$ and $60^0$ and this process was continued until the rational values of all the operating parameters are determined. The entire experimental scheme and sequence of experiments is shown in Table 1.

It is evident from Table 2 that by adopting a sequential procedure to determine the operating parameters, a significant reduction in cutting forces and surface roughness was obtained with final set of operating parameters. The limitation of the approach is that the interaction effects of parameters cannot be studied as it is a one factor at a time approach.

<table>
<tr><th></th><th>Variable Parameter</th><th colspan="5">Fixed parameters</th><th>Selected parameter value</th></tr>
<tr><td rowspan="3">Nozzle position</td><td>ND (mm)</td><td>NA: $45^0$</td><td>NL: Rake</td><td>AP: 5 bar</td><td>OC: 5%</td><td>CFRPN: 100 ml/hr</td><td>Say A</td></tr>
<tr><td>NA(degree)</td><td>ND: A</td><td>NL: Rake</td><td>AP: 5 bar</td><td>OC: 5%</td><td>CFRPN: 100 ml/hr</td><td>Say B</td></tr>
<tr><td>NL</td><td>ND: A</td><td>NA: B</td><td>AP: 5 bar</td><td>OC: 5%</td><td>CFRPN: 100 ml/hr</td><td>Say C</td></tr>
<tr><td rowspan="3">Aerosol related</td><td>AP (bar)</td><td>ND: A</td><td>NA: B</td><td>NL: C</td><td>OC: 5%</td><td>CFRPN: 100 ml/hr</td><td>Say D</td></tr>
<tr><td>OC (%)</td><td>ND: A</td><td>NA: B</td><td>NL: C</td><td>AP: D</td><td>CFRPN: 100 ml/hr</td><td>Say E</td></tr>
<tr><td>CFRPN (ml/hr)</td><td>ND: A</td><td>NA: B</td><td>NL: C</td><td>AP: D</td><td>OC: E</td><td>Say F</td></tr>
<tr><td colspan="3">ND: Nozzle tip distance</td><td colspan="5">NA: Nozzle inclination angle in horizontal plane</td></tr>
<tr><td colspan="3">NL: Nozzle location</td><td colspan="5">AP: Compressed air pressure</td></tr>
<tr><td colspan="3">OC: Oil concentration</td><td colspan="5">CFRPN: Coolant flow rate per nozzle</td></tr>
</table>

Tab. 1. Experimental Scheme

| Cooling environment | | Axial force, N | Radial force, N | Tangential force, N | Surface roughness, μm |
|---|---|---|---|---|---|
| MQC | Initial | 319 | 275 | 621 | 1.95 |
| | Final | 279 | 238 | 549 | 1.79 |
| Flood cooling | | 292 | 234 | 568 | 1.92 |

Tab. 2. Values of cutting forces obtained in MQC and flood cooling assisted turning

## 5. Conclusions and future scope

It is evident from the literature that application of MQL has resulted in better tool life, improved surface finish, reduction in cutting temperature, better chip forms and reduced cutting forces. As number of variables are involved in MQL assisted machining a careful selection of parameters is required to make the process effective and efficient. Proper combination of cutting parameters is must to ensure proper chip removal and evacuation for effective functioning of MQL. Apart from this, method of aerosol spray, distance between nozzle and cutting zone, air and oil flow rate, air pressure, orientation of nozzle all plays a significant role in MQL application. Effectiveness of MQL system also varies with tool material and coatings. So the selection of tool material/coatings should be done after a critical analysis.Moreover, the sequential approach desribed in the present work to determine rational value of operating parameters helps in achieving enhanced process performance. However, to establish MQL as a feasible alternative to flood cooling, research should be directed to also measure the mist level and droplet size as it seems that mist level is assumed lower than flood cooling without knowing the actual mist level. If the mist levels are comparable with wet turning as reported by Dasch and Kurgin (2010) than entire system must be restudied and suitable alteration in terms of method of aerosol spray, aerosol composition, machining parameters, etc. should be taken.

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