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Review Article

A Critical review on Minimum Quantity Lubrication (MQL) Coolant System for Machining Operations

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Abstract

Cooling lubricants and coolant systems have various tasks in metal cutting. Primarily they conduct heat and reduce friction. They ensure a uniform temperature of the work piece and tool and help to maintain tolerances. Supply, preparation, and disposal of cooling lubricants can cause considerable costs. Additionally, these substances pollute the environment. Therefore, it is worthwhile to think about alternatives. A possible solution in searching for the optimum lubrication system is minimum quantity lubrication (MQL), which is becoming increasingly important. This is an alternative between wet and dry machining. In the case of minimum quantity lubrication, the quantity of the applied lubricant is reduced to a minimum. The maximum volume flow rate with MQL is less than 50 ml/hour. Compared to conventional wet machining, where up to 12,000 liters of coolant is used per hour and must be reconditioned again, the user of the MQL system does not need a higher quantity than a few milliliters. The optimum lubrication considerably reduces the frictional heat. With MQL, the machining costs can be reduced considerably. The environment is also protected and possible health risks for the machine operator are reduced. The current paper reviews different types of MQL systems, comparison of MQL coolant system with conventional coolant systems, applications and advantages of MQL coolant system

Keywords: *Minimum quantity lubrication (MQL), machining, coolant system*

1. Introduction

Firstly, the disadvantages of flood coolant are numerous, such as the high running cost of coolant pumps, maintenance of coolant systems, cleaning the work area of the machine tool and, particularly in summer or warm conditions, the unpleasant odour sometimes emitted by poorly maintained coolant systems. It is probably a common viewpoint in the machining industry that machine shops using flood coolant require a high level of maintenance, not only in monitoring coolant condition but also clearing up spills from leaks that present a health and safety hazard in the workplace. Therefore, it would be ideal to implement dry machining, but the adverse effect on tool life, higher temperatures induced and lower performance makes it unsuitable in most cases. Where dry machining is successfully employed, the process performance can be inhibited by the need to balance productivity against surface finish, tool life and maintenance costs. Therefore, even where users have a defined dry cutting process, MQL can potentially assist with extending tool life and increase machining performance in terms of surface finish, cutting forces and process capability.

Minimum quantity lubrication (MQL) has increasingly found its way into the area of metal cutting machining and, in many areas and has already been established as an alternative to conventional wet processing. Minimum quantity lubrication today uses such precise metering that the lubricant is nearly completely used up. Typical dosage quantities range from 5 ml to 50 ml per process hour if lubricant is supplied by means of a minimum quantity lubrication system (MQL system). Application of a targeted supply of lubricant directly at the point of use lubricates the contact surfaces between tool, work piece and chip.

The lubricant is either applied from outside as an aerosol using compressed air or it is shot at the tool in the form of droplets. Another possibility is internal lubricant feed through the rotating machine tool spindle and the inner channels of the tool (Figure 1). The extreme reduction in lubricant quantities results in nearly dry work pieces and chips. Losses due to evaporation and wastage, which may be considerable with emulsion lubrication (depending on the work piece being processed), are inconsequential with MQL. This greatly reduces health hazards due to emissions of metalworking fluids on the skin and in the breathed-in air of employees at their workplaces.

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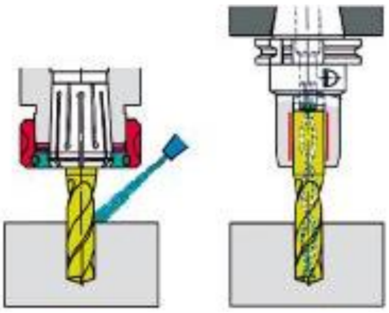

Figure 1 Basic differences between External and internal feeds

Today, the enormous cost-saving potential resulting from doing almost entirely without metalworking fluids in machining production is recognized and implemented by many companies, primarily in the automotive industry. While in the early 1990s small applications (sawing, drilling) were done dry, today it is possible to produce cylinder heads, crankcases, camshafts and numerous other components made of common materials such as steel, cast iron and aluminum using MQL in the framework of highly automated large volume production. Minimum quantity lubrication is a total-loss lubrication method rather than the circulated lubrication method used with emulsions. This means using new, clean lubricants that are fatty-alcohol or ester based. Additives against pollution, e.g. biocides and fungicides, are not necessary at all, since microbial growth is possible only in an aqueous phase. Metalworking fluids do not spread throughout the area around the machine, thus making for a cleaner workplace. Costs generated by conventional flood lubrication (e.g. maintenance, inspection, preparation and disposal of metalworking fluids) are no longer an issue with minimum quantity lubrication. The average percentages of these costs in the overall cost of wet processing are shown in Figure 1.(Maschinenbau et al , 2010)

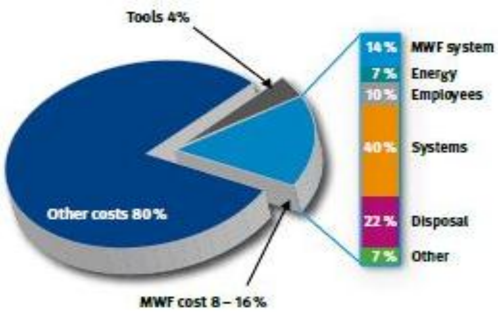

Figure 2 Metal working fluid costs in metal machining

When cost analyses are carried out for new assemblies and systems, investments in metalworking fluid systems (containers, pipelines, pumps, and filtration devices) play a major role. Furthermore, when minimum quantity lubrication is used, there are no costs for cleaning and drying the chips before their disposal or, as the case may be, cleaning the work pieces prior to subsequent processing. The exact percentage of metalworking fluid-specific costs is greatly dependent on the processing method, on the machinery, and on the specific building conditions.

The necessity to machine using less harmful cutting fluids has prompted many researchers to investigate the use of minimum quantity lubrication (MQL). The exposure to such amounts of metal working fluid may contribute to adverse health effects and safety issues, including toxicity, dermatitis, respiratory disorders and cancer.

2. Aims of the MQL Coolant System

The aim of MQL machining is

- Reduction of thermal stresses at the tool point
- Less tool wear
- Effective chip evacuation from deep holes
- Reduction of cooling lubricant requirement
- High cooling and lubrication effect especially in deep
- holes
- Reduction in component cleaning costs
- Reduction in cooling lubricant disposal costs
- Reduction in cost of disposal of scrap contaminated
- with cooling lubricant
- Protection of environment and health through lower
- Emissions

3. Lubricants Used for minimum quantity lubrication

For fault-free, low-emission metal machining when using minimum quantity lubrication, lubricants with very good lubricity and a high thermal rating are best. In industrial manufacturing, synthetic ester oils and fatty alcohols with favorable vaporization behavior and a high flash point are used (S.kurgin *et al 2011)*

- **Synthetic esters** are preferable for all machining processes in which the lubricating effect between tool, the work piece and separation from the chips is of prime importance. Examples of this are threading, drilling, reaming and turning.
- **Fatty alcohols** are preferred for machining processes in which the separation effect rather than the lubricating effect is important. An example of this is the machining of non-ferrous metals.

When choosing a suitable MQL lubricant, the user should take into account the criteria below.

Smell - The smell of the lubricant is not inconsequential. Spraying the lubricant can cause the smell to be intensified.

Sprayability - The lubricant should spray easily and, especially with 1-channel systems, be able to produce a stable aerosol (oil-air mixture).

Additives - The additives should be adjusted to the processing requirements, particularly when processing non-ferrous metals and difficult-to-cut steels.

Residues on machine parts - Despite minimum spray amounts and the use of extraction devices, lubricants may leave residues on work pieces and machine parts. The lubricant should not resinate and should be easy to clean off if necessary.(T.wakabayashi *et al 2006)*

Viscosity range - Practical experience shows that the best results with lubricants (ester or fatty alcohol) are achieved at a viscosity range of 15 to 50 mm^2/s and in some cases up to $100mm^2/s$ at 40 °C. Upper viscosity limits should be discussed with the MQL system manufacturer (check device suitability for spray ability). In general the MQL system and lubricant should be compatible with each other.(F.klocke *et al* 1997)

Lubricant change - Before a new lubricant is used, the system should be completely drained and flushed. The flushing process should be performed with the new lubricant.

Corrosion protection - A check should be made as to whether the thin MQL residual film on the workpiece after machining offers corrosion protection that meets the requirements or whether additional corrosion protection is necessary.

4. MQL Coolant Systems

The main task of the MQL systems is the targeted supply of an appropriate lubricant to the contact point of the tool . A number of different systems are available for this purpose. The classification of this systems are shown in the figure 3.

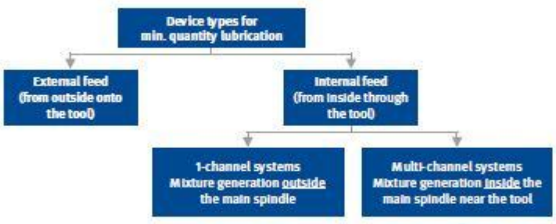

Figure 3 Different types of Coolant Systems of MQL

4.1 External Feed System

In external feed, the lubricant is applied by means of spray nozzles around the circumference of the tool. This system is especially suitable for entrance-level implementation for standard processes (turning, milling, drilling). Low cost, simple retrofitting and the option of deploying conventional tools are the key advantages of these systems.

The important two technologies that are widely used in external feed system are devices with metering pumps, devices with pressure tank & Targeted bombardment with oil droplets.

4.1.1. Devices with metering pumps

In this device the lubricant is transported by a pneumatic micro-pump. Lubricant dosage is regulated by means of the stroke and frequency of the pump plunger. The key advantages of the micro-pump system are the exact dosage volume settings and modular design, which, in addition to the decentral assembly of the pump elements, makes it possible to install nearly any number of pump elements.

Figure 4 Device with metering pump

4.1.2 Devices with pressure tank

In this device the lubricant tank is pressurized. Lubricant is forced out of the tank with pressure. Metering is done with supply pressure settings and with throttle elements in the pipework for air and oil atomization. To guarantee optimum use of these systems, it should be possible to adjust tank pressure, atomization air, and oil quantity separately.

Figure 5 Device with pressure tank

4.1.3 Targeted bombardment with oil droplets

This type device shoots single droplets of lubricant at the machining contact point via a high-speed valve. There can be a distance of up to 800 mm between valve and tool without air mixing in or atomization taking place. This metering principle makes it to break through the boundary-layer air that builds up during the turning movement.

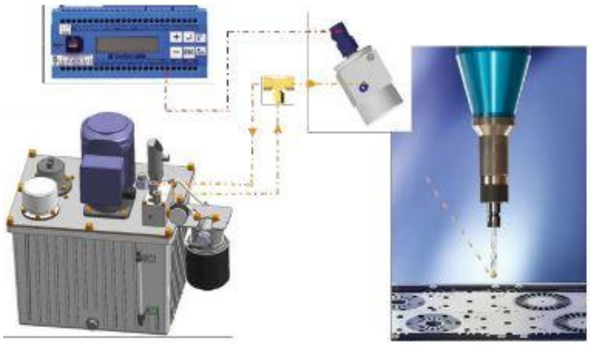

Figure 6 Targeted bombardment type system

4.1.4. Advantages and disadvantages of External Feed System

Advantages

- Simple adaptation
- Low investment costs
- Little work required to retrofit conventional machine tools
- Rapid response characteristics
- No special tools required

Disadvantages

- Limited adjustment options for the nozzles due to
- different tool lengths and diameters
- Possible shadowing effects of the spray jet when
- machining
- Possible shadowing effects of the spray jet when
- machining

4.2 Internal Feed Systems

Internal feed devices enable direct supply of the lubricant to the cutting zone. The lubricant must be transported through the spindle, tool revolver and through the inner cooling channels of the tool. In contrast to devices for external feed, no adjustment of the feed nozzles is necessary and there is very little loss due to dispersion. The settings for oil and air amounts can be performed with the machine control system. Depending on where the vapour is generated, there are two common types of internal feed systems namely, 1-Channel devices and 2-Channel devices (Figure 7).

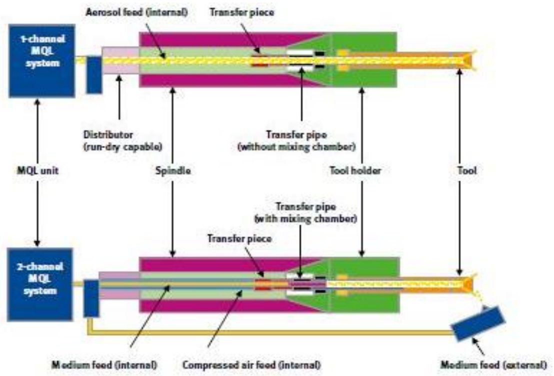

Figure 7 Comparison of 1-Channel & 2- Channel-Systems

4.2.1 1-Channel Systems

In 1-channel systems the aerosol is generated in the tank, before entering the spindle. The lubricant aerosol in these systems is usually created with the aid of compressed air.

Investigations of different MQL systems clearly show that in 1-channel systems, atomization using the venturi principle is the most effective and offers process-reliable operation. Designed on this principle, a higher quality aerosol (approx. 0.5 μm to 2 μm)(A.Ahanasio *et al 2006)* is generated and reaches the cutting point with nearly no loss. Further supplies to the cutting point are via components of the machine tool. Systems for flexible production systems are connected by a field bus interface to the machine control system. Settings for process parameters are controlled directly from the NC program.

A functionally reliable device contains different components for adjustment and monitoring. Simple devices (Figure 8) use manual adjustments for air and oil, a flow rate gauge and pressure gauge for visual inspection as well as pressure switches and fill level switches for monitoring purposes. Comprehensive accessories consisting of ball valves, external spray nozzles and replenishing units complete the equipment.

Figure 8 1-Channel system

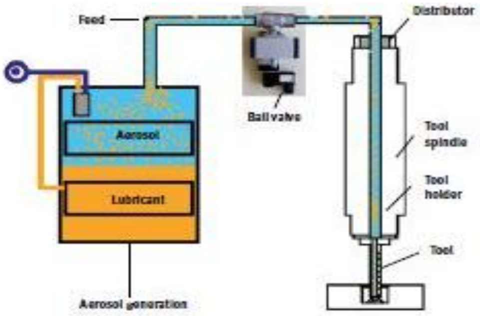

Figure 9 Different devices in 1-Channel System

4.2.2 2-Channel Systems

In 2-channel systems, lubricant and air are transported separately through two channels through the tool spindle to the tool holder, where the required mixture is created in a pipe nozzle. The separate supply of the two media in the spindle is by means of a lance located in the centre of the tool spindle. The MQL unit transports the lubricant to the high-speed valve, which precisely meters the process-dependent optimum lubricant quantity and conveys it to the 2-channel rotary chuck. The lubricant is transported through the internal channel of the lance while the air is supplied via the external ring channel between lance and spindle.

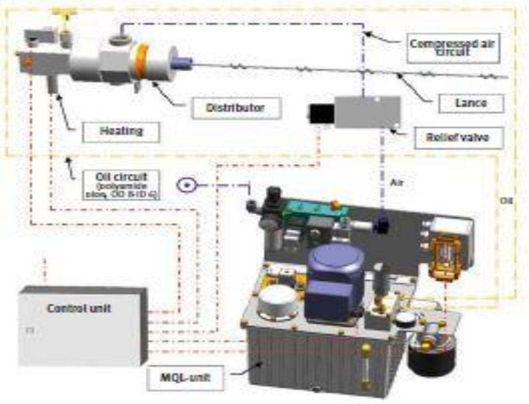

Figure 10 Structure of a 2-Channel system

4.2.3 Advantages and disadvantages of Internal Feed System

Advantages

- Optimal lubrication at the cutting point (for each tool, even for inaccessible points)
- No scattering or spray losses
- Optimised lubricant quantity for each tool

Disadvantages

- Special tools required
- High investment costs
- Suitability of the machine is required

5. MQL Applied to Drilling, Milling and Turning Operations

In May 2007, an article was published by Tech Solve, based on a comparison between flood and MQL (MaClure, *et al*, 2007). The lubricant used was experimental vegetable oil based soluble oil (10%). The flow rates used for flood and mist conditions were 1.7 gpm and 0.0029 gpm, respectively. Experiments were conducted for drilling and milling operations. The drilling operation used AISI 4340 Steel (32-34 HRC). Speed, feed rate and depth of cut were 55 sfpm, 0.007 ipr and 0.006 inch respectively. The drill used was 0.5 inch oxide coated HSS with a 135° split point. (R.P Zeilman *et al* 2006)Sixty holes were drilled using flood coolant and 61 were drilled utilizing MQL. Analysis showed no significant differences in tool life (number of holes to reach end of life criteria) between MQL and flood cooling. Average thrust forces were 570 lbs and 447 lbs for flood and MQL cooling respectively. The milling operation used AISI 4140 Steel (24-26 RC). Speed, feed rate and depth of cut were 400 sfpm, 0.005 ipr and 0.5 inch respectively. The cutter insert was grade SM-30 uncoated carbide. Analysis showed little differences in tool life between flood and MQL cooling. Sixty-six holes were milled for the flood tests and 80 were milled for the MQL tests. The average resultant forces observed were 46 lbs for flood and 36 lbs for MQL cooling (MaClure, *et al* , 2007). Yan et al in 2009 investigated the cutting performance of MQL and compared it to dry and wet cutting using cemented carbide tools in Milling High strength steel. The results indicated that MQL reduced tool wear and surface roughness as compared to dry and wet cutting. Similarly, Sharif et al in 2009, evaluated the performance of vegetable oil as an alternative cutting lubricant when end milling stainless steel using TiAlN coated carbide tools. The results indicated that vegetable oil using MQL outperformed dry cutting and flood cooling when tool life and surface roughness are the response variables. E.O Bennett et al. in 1985 reported on the advances in the ecological machining of magnesium and magnesium based hybrid parts . A study involving the intermittent turning of aluminum alloy on a CNC lathe was undertaken by Itoigawa, *et al* in 2006. There were two test conditions. The first had a cutting speed of 200 m/min, feed rate of 0.05 mm/rev and axial travelling length of 3 mm.

The second condition had a cutting speed of 800 m/min, feed rate of 0.2 mm/rev and axial travelling length of 10 mm. In both, the MQL oil supply rate was fixed at 30 ml/h and air flow rate at 70 l/min. (M.H.Sadeghi *et al* 2010)(S Woods *et al* 2005)For MQL with water droplets, tap water was used at a rate of 3000 ml/h. Rapeseed oil and synthetic esters (mono carboxylic acid with polyalcohol) were employed as lubricants. Cutting tests using emulsion type coolant and dry machining, were performed in the same conditions. Two tools were used; a sintered diamond tool with 0° rake angle and a K10 grade carbide tool with 5° rake angle. MQL with rapeseed oil has a small lubricating effect in light loaded machining conditions. The boundary film developed with rapeseed on a tool surface is not strong enough to sustain low friction and avoid chip welding. Results showed MQL with water droplets, specifically an oil film on a water droplet, provided good lubrication performance if an appropriate lubricant, such as synthetic ester, was used. When MQL with synthetic ester but without water was used, it showed a lubrication effect. However, tool damage was evident as was chip welding (Itoigawa, *et al* 2006) MQL performance using coated and uncoated HSS and Cobalt HSS drills, in a high aspect ratio operation, was examined by Heinemann, et al in 2006.The workpiece material was AISI 1045. The workpiece was mounted on top of a two component dynamometer which measured thrust force and torque. The twist drills tested had a diameter of 1.5 mm and an included angle of 130°. Drills were of uncoated HSS, uncoated Cobalt HSS, and Cobalt HSS with various coatings. A cutting speed of 26 m/min and a feed rate of 0.26 mm/rev were used. (R.Heinemann *et al* 2006) and three series of tests were performed. MQL-supply in the first series of tests was stopped once the drill reached a depth of 5 mm. In the second series of tests, two other lubricants were used; one with the same chemical composition as the lubricant used in the first series but without alcohol, and one composed of an oil-free synthetic lubricant with a water content of 40%. In the third test series, drilling was carried out under dry conditions. In the first series of tests, it was observed that the interruption of the MQL-supply caused a dramatic drop of 98% in tool life for the uncoated cobalt HSS drills. In the case of the TiN- and TiAlN coated twist drills, the tool life also decreased, but by 42% and 27%, respectively. The second series of tests, carried out with three different types of MQL, had the lubricant being supplied continuously at a rate of 18 ml/h. All tests were performed with uncoated HSS drills. (Dosbaeva *et al* 2008) The alcohol-free lubricant resulted in an increase of 23% in tool life over that achieved with the alcohol-blended lubricant. When using the oil-free synthetic lubricant plus 40% water, the tool life increased by a 100%. A continuous MQL supply is beneficial in terms of tool life, whereas interrupting the MQL supply leads to a substantial drop in tool life, especially in the case of heat-sensitive drills. With respect to the type of MQL lubricant, a low viscous type with high cooling capability gives rise to a notably prolonged tool life

6. Advantages of MQL System

Financial advantages

- Due to the omission of supply and disposal of coolant, high savings are possible.
- After optimization of processes, a higher tool life can be expected.
- Optimized processes reduce the machine cycle time up to 30 %.
- Purchase, warehousing and transportation costs as well as disposal costs of the coolant will be reduced considerably.
- There will be no expenditures for control and care of coolant.
- Depending on the application, extensive follow-up processes for cleaning/washing of the workpieces will be reduced or can be completely eliminated.
- Compared to wet metal chips, which are treated like hazardous waste, dry metal chips can be sold as recycling material.

Ecological advantages

- No used emulsions will accumulate.
- Accidents due to large quantities of leaking coolant are avoided.
- Due to a dry machine, the risk of accidents at work are reduced.
- Airway or skin diseases caused by coolants can be avoided.

Conclusion

The results obtained in several researches prove that MQL does generate a significant amount of mist compared to flood cooling. With these technologies in place however, machining is safe for both operators and the environment, particularly when vegetable based lubricants are used. On the other hand, the processes of lubrication and cooling in MQL are yet to be well understood. The use of MQL also decreases the production cost by reducing the coolant costs. It can be concluded that adaption of MQL coolant system over conventional coolant system yields significant advantages like reduction in costs, providing good environmental working conditions etc.

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