International Journal of Advanced Mechanical Engineering.
ISSN 2250-3234 Volume 8, Number 1 (2018), pp. 63-70

http://www.ripublication.com

Review on Application of Minimum Quantity Lubrication (MQL) in Metal Turning Operations Using Conventional and Nano-Lubricants Based Cutting Fluids

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Abstract

In any metal machining operation, the cutting fluid acts a crucial role by cooling the surface of the work piece and the cutting tool, removing chips from the cutting zone and by lubricating the tool work piece interface. Although, misemployment of the cutting fluid and inaccurate methods of its disposal can influence human health and the environment badly. Also, it accounts for 16-20% of the total cost of manufacturing in the production industry. Amid various techniques available on application of the coolant, researchers, have been focusing on Near Dry Machining (NDM) or Minimum Quantity Lubrication (MQL) as it reduces the application of coolant by spraying the mixture of compressed air and cutting fluid in an optimized mode instead of flood cooling. The MQL technique has proved to be suitable because it complies with the requirements of 'green' machining. This paper presents a review of the important research papers published regarding the MQL-based application of mineral oils, vegetable oils and Nano-lubricants based cutting fluids for metal turning operations. This review paper explains the mechanism of the MQL technique. In a routine manner, the present work also discusses its effect on the performance parameters in turning operations. Many experimental studies have shown that application of MQL produces surface better than dry machining and similar to that as produced under wet machining. Its employment also reduces cutting forces, cutting zone temperature, tool wear, friction coefficient in comparison to dry and wet machining. Therefore, MQL technique has proved to be a viable alternative to the flood lubrication under similar performance parameters.

Keywords: *Minimum Quantity Lubrication, Nano-lubricants, cutting fluid.*

I. Introduction

Last decade witnessed rapid increase in development of advanced materials for high performance applications. While these materials solve a great deal of technological issue, they also pose considerable challenge in machining due to poor machinability characteristics. Since machining involves plastic deformation of the workpiece material and friction between tool-chip and tool-workpiece interfaces, lot of energy supplied is converted into heat. During the machining of low strength alloys, this heat generation is less but when ferrous and other high strength alloys are machined, lot of heat is generated which increases with a subsequent increase in the cutting speed. This heat generated, if not dissipated successfully, may affect the finished surface quality, reduce the tool life and hence overall performance of the process. Many techniques were evolved for the effective removal of heat from the vicinity of the machining area. One of those techniques is applying coolant in the form of fluid during the process. For many years, coolants, popularly known as metal working fluids (MWF) continued to be successfully employed for the heat removal until it was realized that these fluids are a serious damage to the environment and to the health of the operator working with it. The researchers of Klocke and Eisenblatter (1997) showed that they create a waste disposal problem and add to the cost of the manufacturing. These negative consequences of the flood cooling promoted the researchers to switch to those technologies which involve least usage of the cutting fluids. In recent years, among various techniques, the researchers have been largely working on MQL/NDM because of its eco-friendly qualities.

II. Minimum Quantity Lubrication

The main aim of minimum quantity lubrication (MQL) is to reap the benefits of cutting fluids without getting affected with the harmful effects of the cutting fluids. It involves the usage of minimal quantity of cutting fluid with a typical flow rate of 50-500 ml/h which is directly applied to the cutting zone thereby avoiding the need of fluid disposal as it happens in flood cooling. Since MQL involves significantly lesser amount of cutting fluid, this phenomenon is popularly referred to as 'near dry machining' or 'micro lubrication' or 'spatter lubrication'. This system consists of an atomizer, cutting fluid sump, discharge nozzle, etc. The atomizer works as an ejector in which high pressure air is used to atomize the coolant. Atomized coolant is then delivered to the machining zone by the air in a low-pressure distribution system. Due to the venturi effect in the mixing chamber, partial vacuum sucks the cutting fluid from the oil sump where it is maintained at a constant hydraulic load. The air passing through the mixing chamber atomizes the coolant stream into aerosol of micron-sized particles. When this aerosol is sprayed in the cutting zone as mist, it works as coolant as well as lubricant and penetrates deep into the tool-work piece interface.

There are two methods of mixing air and lubricant in MQL method: 1. Mixing inside the nozzle 2. Mixing outside the nozzle. In the first method, the lubricant and air is mixed just before reaching the nozzle in a mixing chamber. The oil-mist is then supplied through the nozzle at high pressure onto the cutting zone. The oil performs the lubricating function while highly pressurized compressed air performs the cooling action. In the second method, the mixing of oil and compressed air is done in a separate mixing chamber. The figure below illustrates the MQL techniques.

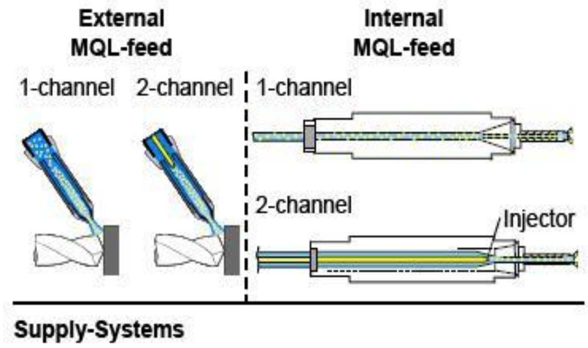

Fig.1 MQL Methods

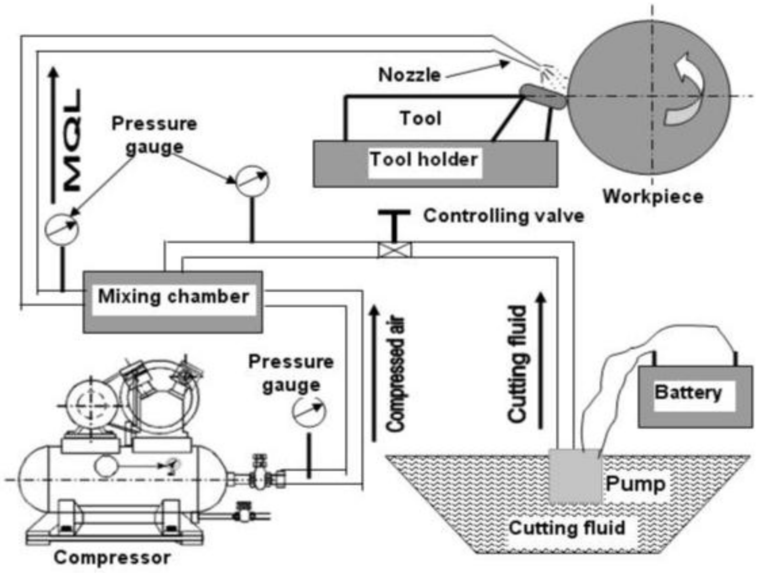

Fig.2 MQL setup

III. CUTTING FLUIDS

Cutting fluids are widely used in machining operations to serve the purpose of reducing thermal deformation by cooling the machining zone and improving the surface finish by providing good lubrication. The application of MQL in machining has emerged as an alternative for reducing the abundant flow of cutting fluids and achieving cleaner production. There are two broad categories into which cutting fluids may be classified (i.e.) Water miscible cutting fluid and Mineral-oil based cutting fluid. Water miscible cutting fluids are those cutting fluids which contain water as the main base fluid. Water is a fluid which has got excellent cooling property. This cutting fluids have good heat absorbing characteristics. In case of Mineral-oil based cutting fluid, oils do not get mixed with water. They can be used as mixtures of mineral or vegetable oils. Several additive compounds such as Sulphur, Phosphorous, Chlorine based components can be added to the base cutting fluids in order to improve their cooling and lubricating properties.

IV. DISCUSSION

By introducing Nano-Lubricants, it was observed that MQL could be used as an alternative to the dry and flood lubricating conditions only at mild cutting conditions. Under aggressive machining conditions such as high cutting speed, as soon as the small quantity of oil mist comes in contact with the machining zone, it vaporizes without effectively removing the heat. Thus, there arose a need to enhance the properties of the MQL fluid in such a way that it can prove to be beneficial in all the cutting conditions. One such solution provided was addition of small sized thermally conducting particles, having lubricating properties to the base fluid medium which can cool as well as lubricate the cutting zone. Nano-particles such as Molybdenum disulphide, Aluminium oxide, Carbon nanotubes and Graphite powder are widely used in MQL environment. The following discussions are based on the introduction of nano lubricant, conventional cutting oil, effect of minimum quantity lubrication on cutting force, temperature, tool-life, surface roughness & chip morphology.

[1] **Stephenson et al.** carried out machining of Inconel 750 which resulted in improved tool life and showed 40% increase in material removal rate.
[2**] Saini et al**. used mineral oil for machining AISI 4340 steel, which resulted in cutting forces upto 17.07% & tool tip temperature upto 6.77%.
[3] **Saravanakumar et al.** analyzed the dispersion of silver nanoparticle enriched cutting fluid and found that the cutting forces were reduced up to 8.8% and surface roughness up to 7.5% by the use of nanofluid with the MQL technique.
[4] **Sayuti et al.** investigated performance of SiO_2 nanofluid in turning of hardened steel AISI 4140 using MQL. They could achieve best surface quality with 0.5%wt SiO_2 concentration, 30° nozzle orientation angle and low air pressure. The minimum tool wear could be observed by 0.5%wt SiO_2 concentration, 60° nozzle orientation angle and 2 bar air pressure.
[5] **He et al.** carried out a comparative study of high speed turning of bearing steel GCr_{15} under different cooling environments of dry, external and internal MQL. It was observed that high speed spray could penetrate effectively into the cutting zone thereby reducing the cutting forces as compared to other cooling environment at high cutting speeds.
[6] **Sharma and Sidhu** investigated the effects of dry and minimum quantity lubrication technique during the machining of AISI D2 steel with tungsten carbide tool inserts. The lubrication was done using vegetable oil which is environmentally friendly as compared to other mineral and petroleum based metal working fluids. It was observed that a significant amount of temperature reduction occurred during minimum quantity lubrication as compared to dry machining at all the combinations of machining process parameters. It was also observed that machining under MQL technique produced better surface finish as compared to machining under dry condition. This causes formation of built up layer also which ultimately deteriorates the surface finish of the final workpiece.

[7] **Roy and Ghosh** observed that during high speed turning of AISI steel using nanofluid (1 vol% MWCNT and 3 vol% alumina) with twin jet small quantity lubrication (SQL) system, a significant reduction in specific energy and cutting force could be observed.
[8] **Amrita et al.** investigated and evaluated the performance of nano-graphite-based cutting fluid in turning and found that the use of MQL improved the cutting fluid's performance in comparison with conventional flood machining by reducing the surface roughness (30%), cutting forces (54%), cutting temperature (25%) and tool wear (71%). It also improved chip morphology.
[9] **Prasad and Srikant** observed an appreciable reduction in cutting forces and surface roughness with increase of nano-graphite concentration during AISI 1040 turning with MQL.
[10] **Itoigawa et al.** used rapeseed oil & synthetic ester for machining AISI 4140 steel, the experiment resulted in better lubricating effect in case of ester.
[11] **Hadad and Sadeghi** carried out a comparative study of the performances of dry, MQL and flood lubricating conditions during machining of AISI 4140 steel. It was observed that highest cutting forces were observed for machining under dry environmental conditions followed by machining under flood lubrication and least value of cutting forces were encountered during machining under MQL lubricating conditions. When the oil mist was supplied both on the flank and rake surfaces of the cutting tool, the temperature reduced by about 350 ºC than that in dry machining. When only rake surface was lubricated, the temperature reduced by 200ºC than dry machining. The temperature recorded under flood cooling was approximately 300 ºC lower than that in dry machining. Maximum surface roughness was observed for machining under dry environmental conditions whereas least amount of surface roughness was obtained for machining under MQL conditions, thus reducing the heat generation and maximum temperature of the chip tool interface, due to this temperature reduction, adhesive and diffusion wear of the tool was reduced which helped in contributing to the improved surface finish of the final product.
[12] **Khandekar et al**. carried out machining on AISI 4340 using Al_2O_3 nanoparticles and compared the output responses with that of machining under dry and MQL cutting conditions. The chip morphology showed that continuous helical chips were formed with dry and MQL cutting conditions while nanofluid resulted in the formation of segmented chips. Application of cutting fluid also helped in increasing the helix angle of the chips.
[13] **Rao and Satyanarayana** performed experiments to estimate the tool wear and cutting temperatures during the turning with CNT based nanofluid using MQL. An increase in CNT concentration reduced the nodal temperatures but appreciable reduction was limited only up to 2% of CNT inclusion.
[14] **Vasu and Reddy** carried out machining operation on Inconel 600 alloy by using minimum quantity lubrication with Al_2O_3 nanoparticles and compared the responses with machining under dry and MQL lubricating conditions. The study of chip morphology showed that light coloured chips were formed when machining was done

with nanofluid whereas brown coloured chips were formed with dry machining. Further, it was observed that using nanofluid helped in producing discontinuous chips.

[15] **Khan et al.** compared the performance of MQL with dry and wet lubricating conditions during the machining of AISI 9310 steel by using vegetable based cutting fluid. It was found that MQL machining was much superior than machining under dry and wet lubricating conditions. Significant reduction in cutting zone temperature (10%) was observed especially at high cutting speeds at which even wet cooling could not produce satisfactory results. It was observed that surface finish improved as a consequence of reduction in tool wear under MQL lubricating conditions as compared to dry and wet lubricating conditions. Significant reduction in the tool flank wear was observed for machining under MQL cutting conditions. Abrasion, adhesion and diffusion wear were reduced and tendency of formation of built up edge was also decreased which consequently resulted in an improvement in tool life. The study of chip morphology showed that chips formed under dry and flood lubricating conditions were of continuous ribbon type. Applying minimum quantity lubrication helped in chip reduction coefficient and under surface of chips appeared lighter and brighter**.**

[16] **Li and Liang** conducted an extensive study to analyze the performance of MQL machining with respect to the process parameters. It was found that application of MQL during machining reduced the tangential cutting forces upto a significant limit especially when machining is done at low cutting speeds. Temperature was found to get reduced significantly almost under all cutting speeds when machining is done at MQL environment.

[17] **Attanasio et al.** carried out to research works to determine whether the technique of minimum quantity lubrication (MQL), if applied during turning operation gives some advantages in terms of tool wear reduction. During machining of normalized 100Cr6 steel, it was visible that lubricating the rake surface of a tip by the MQL technique did not produce evident wear reduction as compared to when flank surface was lubricated by MQL. Lubrication on the rake surface gave similar tool life as that under dry cutting conditions whereas it was observed that flank surface lubrication by the MQL technique reduced the tool wear significantly and increased the tool life. The only disadvantage in this technique is the difficulty of lubricant in reaching the cutting surface during machining.

[18] **Dhar et al.** carried out turning experiments on AISI 1040 steel under dry and MQL lubricating conditions with uncoated cemented carbide inserts. It was found that both Fz (cutting force) and Fx (feed force) reduced significantly (5-15%) with increasing cutting velocity under the MQL lubricating environment. It was also found that MQL machining reduced the cutting temperatures in a range of 5-10 % depending upon the machining process parameters. The results also indicated significant reduction in the cutting temperature and tool wear. As a consequence of reduction in tool damage, the dimensional accuracy and surface finish also improved to a significant extent. Due to reduction in tool temperature, the damage of the tool cutting edges reduced thus improving the dimensional accuracy and product quality, better surface finish as compared to machining under dry environment. Experiments resulted in lesser auxiliary flank wear and hence an improved tool life. The study of chip morphology indicated

that more discontinuous and light coloured chips were produced with cutting under MQL conditions.

[19] **Kishawy et al.** performed high speed face milling tests on aluminium alloy Al356 at different cutting speeds upto 5225 m/min under different cutting environments of dry, flood and MQL. The highest cutting forces were observed for machining under dry conditions and lowest cutting forces were observed for machining under flood cooling. The cutting forces under MQL lubricating conditions were lower than that under dry machining but it was slightly higher that forces developed under flood cooling.

V. CONCLUSION

It is interesting to observe that most of the experimental studies showed that MQL machining can be a viable alternative to wet machining and can facilitate environment-friendly machining. Mostly research has been carried in the application of mineral oils, vegetable oils and nanofluid-based cutting fluids with the help of MQL technique during metal turning operations. Hence, nano-lubricant powder-mixed MQL would be highly recommended for the application where cooling is more stringent requirement compared to lubrication effect for example for machining materials with low thermal conductivity like stainless steel, titanium alloy or nickel-based super alloys. Further research and development can be done in MQL machining by introducing different cryogenic gas mixed with nano-lubricant powder.

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