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Critical review of Nanofluid Minimum Quantity Lubrication for Grinding application

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Abstract

In recent years, the environment has become one of the most important subject. Emulsion-based cooling fluids are used in grinding for a variety of reasons such as improving surface finish, wheel life, flushing away chips, reducing workpiece thermal deformation. Due to large fluid delivery an extensive amount of mist is generated during grinding process. The workers who breathe in this hazardous mist is having health hazard. There are two alternative for large cutting fluids. One is dry grinding and another is near dry grinding also known as minimum quantity lubrication. MQL grinding refers to the delivery of minute quantity of fluid via an aerosol to the grinding zone. The typical flow rate of grinding fluid for MQL fluid consumption is generally 20-100 ml/hour. Although numerous advantages were found for MQL grinding compared with the conventional technique and dry grinding. The cooling and lubrication performance of the grinding fluid is the key technical area for the success application of MQL grinding process. Nanofluid has emerged as a promising solution to this problem. Nanofluid is a new class of fluids engineered by dispersing nanometer-size solid particles into base fluids such as water, lubrication oils. The excellent properties of the nanofluid makes very attractive in cooling and lubricating application in manufacturing. . This study provides a review of research in this field with focus on use of nanofluids in grinding applications.

Keywords: Nanofluids, MQL grinding, enhanced heat transfer, effective thermal conductivity, G ratio.

Introduction

In recent years, the environment has become one of the most important subjects within the context of modern life. Special attention is on energy consumption, air pollution and industrial waste by the government authorities. All the components requiring fine tolerances and smooth finishes are manufactured by the Grinding process. Emulsion-based cooling fluids are used in grinding for a variety of reasons such as improving surface finish, wheel life, flushing away chips, reducing workpiece thermal deformation. Due to large fluid delivery an extensive amount of mist is generated during grinding process. The workers who breathe in this hazardous mist is having health hazard. The cost of disposal or recycling of the grinding fluid is very high and considered in total machining cost. The increasing need for environmental friendly production technique, government regulation, public awareness, and the need for cost-reduction all have promoted the development of new environmentally conscious machining processes.

There are two alternative for large cutting fluids. One is dry grinding and another is near dry grinding also known as minimum quantity lubrication. Mao et al. tested grinding parameters with no grinding

fluid and small quantity of solid lubricant in dry grinding. He concluded that grinding heat cannot be transformed from the grinding zone effectively. He also reported that the energy generated in the machining process and dissipated as heat causes increase in grinding forces, wear of the wheel, elevated temperatures, thermal damage, poor surface integrity and dimensional inaccuracies. Cutting fluid plays important role in transportation of chips from cutting zone. Complete elimination of grinding fluid make it difficult to keep grinding wheels porous clean, favoring the tendency for clogging. Although dry machining is possible in some situations, there are still lots of issues regarding lubricity, tool life, thermal damage of workpiece, etc. Therefore Minimum Quantity Lubrication (MQL) was proposed.

MQL grinding refers to the delivery of minute quantity of fluid via an aerosol to the grinding zone so that the applied amount of grinding fluid can be reduced tremendously while maintaining the cooling and lubrication effects that are lost in dry grinding. The typical flow rate of grinding fluid for MQL fluid consumption is generally 20-100 ml/hour which is about three to four orders of magnitude lower

than the amount commonly used in wet grinding condition. In MQL technology, the lubricating function is provided by the oil mist and the cooling function is ensured mainly by the compressed air. MQL is widely applied in the cutting process such as turning, drilling and milling, but research reports on MQL in grinding are only now emerging. Previous research found that the MQL grinding provides efficient lubrication, reduces the grinding power and the specific energy to a level of performance comparable or superior to that obtained from conventional 5% soluble oil. At the same time it significantly reduces grinding wheel wear and provides slightly lower surface roughness, but presents insufficient cooling. Although numerous advantages were found for MQL grinding compared with the conventional technique and dry grinding. Cooling and lubrication performance of the grinding fluid is the key technical area for the success application of MQL grinding process. Since high cooling and lubricant effect is needed during MQL grinding. Nanofluid has emerged as a promising solution to this problem.

Preparation of nano fluids

A liquid suspended with particles of nanometer dimension is termed a nanofluid. The nanoparticles were used to produce nanofluids in the reviewed literature are: aluminum oxide (Al₂O₃), copper (Cu), copper oxide (CuO), gold (Au), silver (Ag), silica nanoparticles and carbon nanotube. The base fluids used were water, oil, acetone, decene and ethylene glycol. Nanoparticles can be produced from several processes such as gas condensation, mechanical attrition or chemical precipitation techniques. Gas condensation processing has an advantage over other techniques. This is because the particles can be produced under cleaner conditions and its surface can be avoided from the undesirable coatings. However, the particles produced by this technique occur with some agglomeration, which can be broken up into smaller clusters by supplying a small amount of energy. The preparation of a nanofluid begins by direct mixing of the base fluid with nanoparticles. Xuan and Li suggested methods used for stabilizing the suspensions: (1) changing the pH value of suspension, (2) using surface activators and/or dispersants, (3) using ultrasonic vibration.

These methods can change the surface properties of the suspended particles and can be used to suppress the formation of particle clusters in order to obtain stable suspensions. The use of these techniques depends on the required application of the nanofluid. Selection of suitable activators and dispersants depends mainly upon the properties of the

Nanofluid is a new class of fluids engineered by dispersing nanometer-size solid particles into base fluids such as water, lubrication oils, etc. Previous researches have shown that the convection heat transfer coefficient and the thermal conductivity can be largely increased. Wu et al. found that lubricating oils with nanoparticles exhibit improved heat carrying capacity, antiwear and friction reduction properties. These excellent properties make the nanofluid very attractive in cooling and lubricating application in manufacturing, transportation and electronics. Shen et al. proposed MQL grinding using nanofluid, and they found that grinding forces and tool wear were significantly reduced with nanofluid machining technique. Sridharan and Malkin studied the characteristics of nanofluid MQL grinding process using MoS₂ and carbon nanotube (CNT) nanoparticles. They found that nanofluid can be effective to improve surface roughness and to reduce specific grinding energy. However, the cooling and lubricating mechanism for nanofluid MQL grinding is not analyzed in detail for the previous researches.

solutions and particles. Particles can fracture or agglomerate after mixing into liquid. Transmission electron microscopy (TEM) is widely used to observe the characteristics of particles before and after dispersion in liquid. Some researchers used ultrasonic vibration techniques to disperse the particles in the base liquid. However, the ultrasonic vibration can break the agglomerates as indicated in experiments of Das et al. While Xuan and Li selected laurate salt and oleic acid as the dispersant to enhance the stability of the suspension, some researchers did not use any dispersants to stabilize the suspension. The reasons for this were that the addition of the dispersant could influence the thermal conductivity of the base fluid itself, and thus, the real enhancement by using nanoparticles could be over shadowed.

Experimental setup

The grinding experiments were conducted on an instrumented surface grinding machine. The setup of the grinding experiment is shown in Fig. 1. An MQL fluid delivery system is used to supply lubricant. In this system, a biaxial hose is used to independently transport liquid and air to the point of use and then the liquid is surrounded with air (coaxial) and propelled onto the tool or workpiece by air pulse at different flow rates (5, 15, and 30 mL/min).



1-Grinding Wheel, 2-Workpiece, 3-Dynamometer
 (a) Grinding machine setup



1-Controller, 2-Fluid reservoir, 3-FRL unit
 (b) MQL fluid delivery Device.

Fig. 1-Experimental setup: (a) Grinding machine setup,
 (b) MQL fluid delivery System.

Grinding wheel of average abrasive size is used. The size of the grinding wheel varies from 125 to 175 mm in diameter and width from 10 to 14 mm. The work material is prepared from iron bar. The width and length of the workpiece surface for grinding are 6 mm and 60 mm, respectively. The surface speed of the wheel and the down feed were set to be 30 m/s and 10 μm , respectively. The grinding was conducted by traversing the wheel across the workpiece at 2400 mm/min table speed in one direction. The normal and tangential grinding forces were measured using a dynamometer. The grinding temperatures were measured by the embedded thermocouple. After each grinding pass, the workpiece was allowed to cool to the initial temperature before the next pass was taken. Each G-ratio grinding test had to wear out at least 6 μm of the wheel to ensure the accuracy of the G-ratio. The profilometer was used to measure the surface roughness of the ground surfaces. Three measurement traces parallel and perpendicular to the grinding direction were measured. The average of the three arithmetic average surface roughness (R_a)

measurements along and across the grinding direction was used to represent the roughness.

4.Mechanics of chip formation during Grinding-

For grinding of a workpiece surface, ideal cutting can be obtained by many process combinations like ploughing due to lateral displacement, workpiece movement, grinding wheel movement, elasticity of the workpiece and vibration. Many parameters have effects on grinding process. Some of these parameters can be controlled while the others not. Non-deformed chip shape, tool path length of the abrasive grain (lk), maximum non deformed depth of cut (hm) and chip geometry are shown schematically in Fig.2. Chip formation in grinding process can be divided into three successive stages: friction, ploughing and cutting. In up-cut grinding, grinding wheel grains rub on the workpiece surface rather than cutting due to the elastic deformation of the system. This is called friction stage. And then, plastic deformation takes place as the elastic limit is exceeded between the abrasive grain and workpiece. This is called ploughing stage. Workpiece material flows plastically through forward and sideward ahead of the abrasive grain and forms a groove. When the workpiece material cannot resist the flow stress, chip is formed. The chip formation is called cutting stage. In this chip formation stage, energy is used most efficiently.

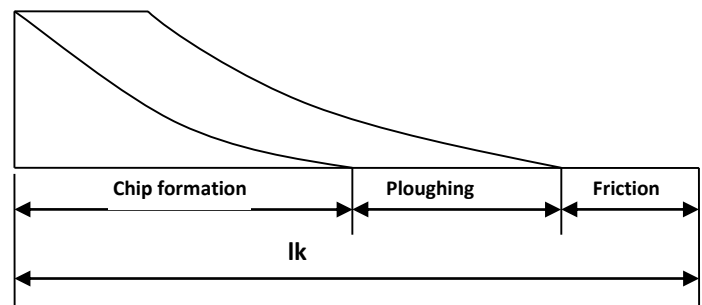


Fig.2 Chip formation in Grinding

Grinding forces not only affect chip formation mechanics, grain wear and temperature distribution but also efficiency of the grinding operation. Therefore, grinding forces are among the most important factors affecting grinding quality.

Experimental investigations

Grinding force

Nanoparticles are known to possess exceptional tribological properties. Bin Shen et al. has evaluated the tribological behavior and performance of MoS_2 nanoparticles based grinding fluids in minimum quantity lubrication (MQL) grinding of cast

iron. The results showed that lubricants with novel MoS₂ nanoparticles significantly reduces the tangential grinding force and friction between the wear flats and the workpiece. MQL system was able to penetrate into the region of contact between the grinding wheel and the workpiece more effectively than flood cooling. The force ratio is 0.23 for flood cooling with Cimtech 500, 0.20 for MQL with both CANMIST and paraffin oil, and 0.16 for MQL with soybean oil.

According to Malkin *et al.* the forces generated in grinding are directly proportional to the grinding energy, which depends on chip formation, plowing effect and sliding of grains over the surface of workpiece.

Cong Mao *et al.* has investigated the grinding characteristics of hardened AISI 52100 steel and compared with those of wet, dry and pure water MQL. He concluded that dry grinding without lubrication generates the highest specific tangential force and wet grinding has the lowest grinding force. He also found that MQL grinding has a lower grinding force in comparison with dry grinding. This clearly demonstrates that MQL system is able to penetrate into the contact zone between the workpiece and the wheel to lubricate contact zone.

Grinding Ratio (G-Ratio)

Wheel life in grinding process is expressed in terms of grinding ratio or G-ratio and is defined as the volume of material removed per unit volume of grinding wheel wear. Wheels with a high G-ratio last longer than those with lower G ratios (Krueger *et al.*). All the MQL grinding operations with pure oil based fluids have much higher G-ratio (ranging from 28 to 42) than flood cooling with water-based Cimtech 500 synthetic grinding fluid. It is important to note that G-ratio is higher for high concentration of nMoS₂ additive conditions for all the base oils, including soybean oil. He believed that this can be explained by the reduction in grinding forces with nMoS₂ additives, thereby, ensuring the retention of grit sharpness due to less wear and lower plastic deformation at reduced temperature.

The tests were carried out by Silva *et al.* using 15mm of the total width of the grinding wheel. The values obtained after 3 stages and 30 cycles, each cycle of 100µm, added up to a total removal of 9mm from the part's diameter. They reported that the application of MQL produced a superior result when compared with the use of conventional cutting fluid, possibly due to the excellent lubricating capacity in the region of contact between the grinding wheel and the work piece.

Higher fluid lubricating power reduces the wear on the grinding wheel by decreasing grain-part friction and chip-binder friction, allowing the abrasive grains to remain bound to the binder for longer periods and leading to lower wear of the tool. He found that the use of MQL under all the lubrication and cooling conditions led to a superior performance than conventional cooling.

Surface Roughness

Cong Mao *et al.* found that the surface finish can significantly affect the mechanical strength of components when they are subjected to fatigue cycles. The surface roughness used in this study is Ra, which is an arithmetic average roughness parameter defined by the mean value of the average deviation of the surface profile from the mean line in each sampling length. The surface roughness along and across the grinding direction for the ground work pieces are tested. It is obvious that wet grinding has the lowest surface roughness, which means the best surface finish is obtained during wet grinding. The surface roughness for dry grinding is the highest, which is expected. Similar to the case of grinding forces and surface morphology, the surface roughness of ground workpiece under the condition of nanofluid MQL is much lower than the case of dry grinding. Pure water MQL case also produced smoother surface than that of dry grinding, but the amount of surface quality improvement in the nanofluid MQL grinding is much higher.

Bin Shen *et al.* reported that flood cooling has the best surface finish (lowest surface roughness). In general, MQL grinding using nanofluids has a better surface finish than pure water but less than the flood cooling and MQL grinding using Cimtech 500 synthetic grinding fluid provides good lubrication, while pure water has a poor lubricating capability. The flood cooling also provides efficient chip flushing. The fact that the nanofluids outperform the pure water can be partly due to the reduction in grinding forces and friction. Dry grinding has the worst surface finish, which is expected.

Grinding Temperature

Bin Sen *et al.* has compared wet, dry, and MQL grinding temperature at the workpiece surface. He found that flood cooling has the lowest temperature and dry grinding has the highest, which is expected. All the MQL grinding experiments have the same flow rate (5 mL/min). By applying MQL, the peak temperature is about 100–150°C lower than that in dry grinding. This is due to both the cooling and the lubrication effects of the fluids provided by MQL, as

lubrication reduces the cutting forces and cutting energy, while convection heat transfer carries away some of the heat. There is no significant difference in grinding temperature among the experiments using different types of fluids for MQL grinding. Further investigation was conducted on the flow rate effects. Larger MQL flow rate leads to the lower grinding temperature. Increasing the flow rate from 5 to 30 mL/min, the peak grinding temperature was reduced by about 100°C, which is 250°C lower than that in completely dry grinding. This also indicates that the flow rate setting is a very critical factor in MQL grinding. By increasing the MQL flow rate, it is possible to achieve the desired cooling effects.

Cong Mao et al have measured five grinding temperature and grinding force for the same grinding condition, and the average values are used to study. He found that the dry grinding has the highest grinding temperature and the flood cooling has the lowest, which is expected. The average peak temperatures for wet and dry grinding are 192⁰ C and 51⁰C respectively. The peak temperature of MQL grinding is about 90-130⁰ C lower than that of dry grinding, which is a positive aspect. The peak temperature in the contact zone of the nanofluid MQL grinding is about 40⁰C lower than that of the pure water MQL grinding. The temperature in dry grinding is considerably higher than that in MQL grinding. This is due to the lack of lubrication and cooling for dry grinding

Conclusion

The following conclusions can be drawn from present work on Minimum Quantity Lubrication for Grinding application.

1- Nano particles mixed in fluid increases the thermal conductivity and heat transfer coefficient of base fluid. Nanofluid exhibit improved heat carrying capacity, antiwear and friction reduction properties. These excellent properties make the nanofluid very attractive in cooling and lubricating application in manufacturing.

2- The results showed that lubricants with novel different nanoparticles significantly reduce the tangential grinding force and friction between the wear flats and the workpiece. Dry grinding without lubrication generates the highest specific tangential force and wet grinding has the lowest grinding force. MQL grinding has a lower grinding force in comparison with dry grinding. This clearly demonstrates that MQL system is able to penetrate into the contact zone between the workpiece and the wheel to lubricate contact zone

3- All the MQL grinding operations with nanoparticle based fluids have much higher G-ratio (ranging from 28 to 42) than flood cooling with water-based Cimtech 500 synthetic grinding fluid

4- Wet grinding has the lowest surface roughness, which means the best surface finish is obtained during wet grinding. The surface roughness for dry grinding is the highest. Similar to the case of grinding forces the surface roughness of ground workpiece under the condition of nanofluid MQL is much lower than the case of dry grinding. Pure water MQL case also produced smoother surface than that of dry grinding, but the amount of surface quality improvement in the nanofluid MQL grinding is much higher.

5- Dry grinding has the highest grinding temperature and the flood cooling has the lowest. The average peak temperatures for wet and dry grinding are nearly 192⁰ C and 561⁰C respectively. The peak temperature of MQL grinding is nearly about 90-130⁰ C lower than that of dry grinding, which is a positive aspect. The peak temperature in the contact zone of the nanofluid MQL grinding is about 40⁰C lower than that of the pure water MQL grinding. The temperature in dry grinding is considerably higher than that in MQL grinding. This is due to the lack of lubrication and cooling for dry grinding

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