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To cite this article: J Kananathan *et al* 2018 *IOP Conf. Ser.: Mater. Sci. Eng.* **342** 012078

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Nanofluid as coolant for grinding process: An overview

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Abstract. This paper reviews the recent progress and applications of nanoparticles in lubricants as a coolant (cutting fluid) for grinding process. The role of grinding machining in manufacturing and the importance of lubrication fluids during material removal are discussed. In grinding process, coolants are used to improve the surface finish, wheel wear, flush the chips and to reduce the work-piece thermal deformation. The conventional cooling technique, i.e., flood cooling delivers a large amount of fluid and mist which hazardous to the environment and humans. Industries are actively looking for possible ways to reduce the volume of coolants used in metal removing operations due to the economical and ecological impacts. Thus as an alternative, an advanced cooling technique known as *Minimum Quantity Lubrication (MQL)* has been introduced to the enhance the surface finish, minimize the cost, to reduce the environmental impacts and to reduce the metal cutting fluid consumptions. Nanofluid is a new-fangled class of fluids engineered by dispersing nanometre-size solid particles into base fluids such as water, lubrication oils to further improve the properties of the lubricant or coolant. In addition to advanced cooling technique review, this paper also reviews the application of various nanoparticles and their performance in grinding operations. The performance of nanoparticles related to the cutting forces, surface finish, tool wear, and temperature at the cutting zone are briefly reviewed. The study reveals that the excellent properties of the nanofluid can be beneficial in cooling and lubricating application in the manufacturing process.

1. Background

In recent years, the increased requirement for product quality and precision has demanded the use of high-performance grinding technology, particularly in automotive and semiconductor industries. These have also necessitated an enhanced grinding process which capable of providing near optimal yield with respect to productivity, precision and cost. In general, the goal of manufacturing processes is to maximize the production rate to the specified product quality bounds and simultaneously reduce the production costs. In precision manufacturing industries, components that require precise tolerances and smooth finishes are typically manufactured by the grinding process. Figure 1 shows the representative of the grinding machine setup. Grinding process guarantees the final accuracy and surface quality of any produced parts [65,66]. However, the energy consumption for the removal of a unit volume of material



in grinding is typically higher than other machining processes. One of the major limiting factors in grinding production rates are the thermal damage [31]. The most severe damage that usually occurs on the grinded work-piece is the 'work-piece burn,' where discoloration and blemishes can be observed on the work-piece [37]. Also, during the grinding process the surface microstructure of the material expected to change due to the increase in the working temperature. These microstructure changes eventually vary the hardness of the material and subsequently results in detrimental internal stresses. This internal stress creates a higher tensile stress on the workpiece surface that leads to a reduced fatigue life [12]. As a result, it decreases the service life, reliability of the produced parts and the precision of the grinding wheels [66]. Also, while machining a high strength material, the working temperature rises with the speed and load of the cutting tool used, this decreases the tool strength leading to a quicker tool wear [11]. Besides, the dulling (removal of the worn grains to develop the new cutting points) drives the formation of scattering marks on the work-piece surface upon machining which later affects the surface quality of the workpiece. However, this damage can be reduced by the application of a coolant to aid in removing the heat created by the work piece-tool interaction. The primary objective of lubricators is to decrease the amount of friction between two sliding surfaces and to maintain the work piece surface property without any alteration or damages [31,47].

The suitability of using coolants in abundance to cool and lubricate machining processes become one of the most crucial subjects in the manufacturing industry. In metalworking operations, application of the coolants is involved in processes such as cutting (separation of the metal from the workpiece in the form of chips) and abrading (rubbing away the surface by friction). The coolants also used to protect the machined surface from corrosion. Usually, coolant is applied directly to the grinding zone to limit the heat generation. The fluid accomplishes this by reducing the amount of friction in the grinding zone through its lubrication properties which minimize the cutting forces thereby saving the energy [58]. These results in an increased of cutting tool life (grinding wheel) and capacity utilization. Thus the production is kept consistently at a high level in terms of quality and efficiency [3]. Thus, a proper selection of coolant is crucial to eliminate the heat effectively and efficiently [23]. In addition, the cutting fluid also helps to flush the produced chips from the grinding process [18]. Whereby improper chip removal could clog and damage the wheel. Also, the forces and energy input would substantially increase due to clogging and would result in heat input to the work-piece [22].

The conventional mechanism of applying the coolant is known as flood coolant system, where a large quantity of coolant continuously impinges on the rake face of the tool [28]. The conventional flood delivery method is as shown in Figure 2. This mechanism has several drawbacks such as high cost, high pumping power requirement, and limited practical usefulness. Due to the large fluid delivery, an extensive amount of hazardous mist is generated during grinding process which contributes to health and environmental hazards. However total elimination of this conventional coolant delivery is not recommended because for high depth machining it would shorten the tool life [16]. Another drawback that is associated with conventional flood coolant mechanism is that the hefty amount of fluid would bound its way to the machining surface owing to the chips and swarf obstruction [59].



Figure 1. Illustration of whole grinding machine set-up.



Figure 2. Conventional fluid delivery system (Flood Coolant system).

There are two alternatives available for flood coolant mechanism. One is known as dry grinding and another is near dry grinding (minimum quantity lubrication, MQL). Dry grinding utilizes no cutting fluid, as such, it is not recommended for machining hard materials due to the high heat generation. Since there is no coolant used, the transfer the heat from the contact zone is disrupted resulting in severe thermal damages on the ground surface of the material. These also increase the grinding energy and grinding forces, wear of the grinding wheel, low material removal rate (low depths of cut) and reduced surface integrity compared to conventional flood delivery mechanism [27].

Whereas, MQL is a technique of supplying a minute quantity of cooling lubricant to the zone or contact point so that the applied amount of coolant can be reduced immensely while retaining the cooling and lubrication effects that are absent in dry machining [56]. MQL helps in reducing the friction at the tool-workpiece interface. MQL technique produces the best surface finish, and improved tool life compared to dry grinding [36]. MQL with oil shown to produce better surface finish than MQL-water grinding [63].

As to date, many researches have reported on the effect of different cooling techniques using conventional cutting fluid in the different machining process. However, there is limited or no comprehensive review available on the effect of MQL using conventional and nanoparticle enhanced cutting fluid in grinding machining. Thus, this paper targets to provide a review focusing on the use of Nano fluids in grinding applications. Present work aims to review the effect of MQL using different Nano fluids and conventional cutting fluid on grinding machining operation.

2. Minimum Quantity Lubrication (MQL)

MQL technique implicates the application of a small quantity coolant dispensed to the tool-work piece interface by compressed air flow. MQL grinding refers to the delivery of a minute quantity of fluid following an aerosol mechanism to the grinding zone for cooling and lubricating the work piece. The MQL lubrication system is as shown in figure 3.



Figure 3. Minimum quantity lubrication (MQL) system.

In MQL system, a compressor is used to supply the air at high pressure. The fluid chamber is connected to a small diameter flexible tube. This tube is made to pass through a roller type flow controller which permits small amount of fluid to flow at high pressure and velocity. The compressed air entering into the inlet port produces pressure to cause the fluid to flow continuously to the mixing chamber through the controller at a constant rate. The air and the cutting fluid then mixed in the mixing chamber so that the mixture of cutting fluid and air impinged at a high velocity through the nozzle on the tool-work piece interface. The schematic and working mechanism of the MQL set-up is shown in figure 4. In MQL technique, the typical flow rate for the coolant is 10–100 ml/h [33] compared to flood machining which is 30000–60000 ml/h [17].

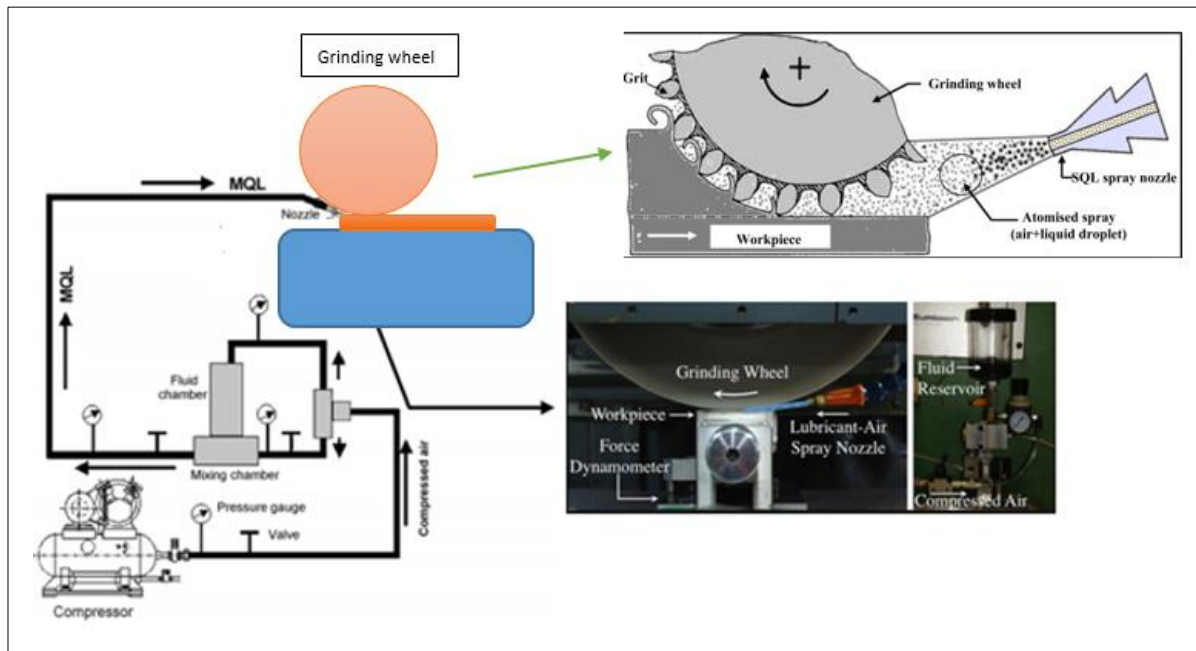


Figure 4. Schematic of MQL Set-Up in Grinding,

Numerous advantages have been reported for the MQL grinding compared to the conventional technique and dry grinding. The cooling and lubrication performance of the grinding fluid is the key to the success of MQL grinding process. As to date, numerous studies related to MQL have been carried out to investigate the effectiveness of this technique. Most of the investigators have indicated that minimum quantity lubrication (MQL) technique is the best alternative to flood cooling in machining. Moreover, the MQL technique also enhances the surface finish, reduces the cost, reduces the impact on the environment and the health of the operating persons. In grinding process, it was shown that MQL provides low friction with the development of thin-film layer lubrication between the tool and workpiece which significantly reduces the tool wear and cutting forces.

Da Silva et al. [13] have studied the effect of surface integrity for minimum quantity lubricant (MQL). This technique showed superior effect in the grinding process in terms of surface integrity (roughness, residual stress, microstructure and micro hardness). It was observed that surface roughness values substantially reduced with the use of the MQL technique, probably due to excellent properties of lubricity and also no significant clogging of the grinding wheel pores was found. Despite of high residual stress value obtained, MQL technique did not negatively affect the surface integrity after Grinding.

Tawakoli et al. [62] studied the role of MQL in grinding soft and hardened steel. It was observed surface roughness was higher in grinding the soft steel. Whereas improved surface roughness in grinding hardened steel. MQL technique shows reduction in the cutting force in both cases which has led to lesser wheel wear out, improved wheel life.

3. MQL Techniques Using Conventional Cutting Fluid

Application of MQL in machining has emerged as an alternative for reducing excessive use of cutting fluid and cost saving with in a more economical way. This section discusses use of conventional cutting fluid with MQL and its influence on machining parameters in grinding machining process based on available research works done. [63] have investigated an MQL grinding or near dry grinding (NDG) system. In this system, an air-oil mixture called an aerosol is fed into the wheel-work zone. Compared to dry grinding, MQL grinding substantially enhances cutting performance in terms of increasing wheel life and improving the quality of the ground part.

In general, the use of synthetic oil is used widely been used in researches done and gives better results than the vegetable oil [24]. [51] studies the effect of grinding 17CrNi6-6 steel.it seen that MQL shows better residual stress when CBN wheel is used. It was shown that MQL does not affect the surface integrity. Anand et al. [4], investigated grinding of Pre-Sintered zirconia using synthetic oil with water soluble oil. It was reported that, MQL showed reduced grinding force and lesser wheel wear out. However, the G-ratio was better in wet condition. Tawakoli et al. [61] found that MQL with oil produced better surface than the MQL-water grinding. Rodriguez, Hildebrandt and Lopes [45] in their study noticed that MQL using lower flow rate less than 120ml/h exhibit bad surfaces and higher wheel wear.

MQL reduces specific grinding energy thus also providing efficient lubrication in able to control the thermal deformation occurring on the work piece and able to give good surface quality then the flood grinding [8]. Belentani et al. [10] found out that MQL not only improves surface roughness but also helps in disrupting the air barrier formed around the rotating wheel thus lower grinding power obtained. Numerous advantages were found for MQL grinding compared with the conventional technique and dry grinding. The cutting fluid parameters along with the summary of MQL influence on cutting parameter performances is briefed in Table 1.

Table 1. Summary of cutting fluids, MQL and machining parameters, mode of lubrication for grinding and machining performance findings.

Authors	Cutting Fluid	Work-Piece material	Lubrication	MQL flow rate	MQL air/fluid pressure	Depth of Cut (μm)	Wheel speed (m/s)	Table speed (mm/min)	Findings
Guo, Li, Zhang, & Wang, 2017 [24]	Castor oil	nickel-based alloy named GH4169	Mode	50 ml/h	0.6 Mpa	10	30	3000	Use of Mixed base oils shows lesser Specific Grinding energy and better surface roughness compared to pure castor oil.
De Mello, de Silva, Machado, Gelamo, & Diniz, 2017[15]	Water soluble synthetic oil	Ti-6Al-4V alloy	MQL	240 ml/h	0.3 MPa	10, 20	32	6.8 m/min	MQL shows lesser surface roughness and better surface quality in lesser depth of cut. At higher depth of cut, flood outperformed MQL.
Anand, Arunachalam, & Vijayaraghavan, 2017[4]	Synthetic Oil and Water soluble oil of 5% concentration	Pre-Sintered zirconia	MQL and flood	250 ml/h	6 bar	10, 15, 20, 25 and 30	22, 26, 32, 36 and 42	2, 4, 6, 8 and 10 (m/min)	MQL showed reduced grinding force and lesser wheel wear out. The surface finish and G-ratio was better in wet condition.
Huang, Ren, Li, Zhou, & Zhang, 2017[30]	MB-103A coolant based on synthetic oil	AISI140 annealed steel	MQL and wet cooling	120, 240, 360, 480 ml/h	3, 4, 5, 6, 7 bar	100	45	0.5 m/min	MQL produced better surface quality with reduced hardened layer depth with increased fluid rate and pressure. MQL has higher cooling rate.
Rodriguez, Hildebrandt, & Lopes, 2017[45]	Vegetable Oil, Water miscible – Semi-synthetic vegetable oil	AISI 4340 steel	MQL	30, 60 and 120 ml/h	0.6 Mpa	1.2, 2.5, 3.7	30	0.5 m/min	MQL with lower flow rate than 120ml/h exhibited inferior performances in terms of bad surface roughness, higher wheel wear and more power consumption.
Sawicki, Kruzynski, & Wójcik, 2017[47]	Micro5000 oil and oil emulsion 5%	17CrNi6-6 steel	MQL and flood	25 ml/h	-	25	30	-	Flood cooling with oil emulsion produces better residual stress than MQL. MQL shows better residual stress when CBN wheel in use based on grinding condition. Use of MQL did not negatively affect the surface integrity
Saber, Rahimi, Parsa, & Ashrafiqou, 2016[46]	RS1642 Behran Oil, Water-miscible coolant lubricant at 5% concentration	CK45, 90 \pm 3 HRB (mild carbon steel)	MQL and flood	120 ml/h	0.7 Mpa	5, 10	20	4000	CAMQL shows reduction of power consumption than to dry grinding. Better surface Quality using MQL. CAMQL is used for fine grinding of soft steels.
Balan, Vijayaraghavan, & Krishnamurthy, 2016[5]	Cimtech D14 MQL oil	Inconel 751 super alloy	MQL and dry-grinding	60 ml/h	6 bar	10, 20, 30		0.4, 0.6, 0.9 m/min	MQL produces better performances than dry grinding. Thin flaked and elongated chips produced by MQL.
Wójcik & Wejman, 2016[67]	(MC) - Micro 3000, (EC) – Eco Cut micro 82, (BO) 3000	Titanium Alloy(Ti-6Al-4V and TIGER.5)	MQL and dry-grinding	50 ml/h	0.6 Mpa	5	22.5-26.5	0.2 - 0.5 m/s	MQL has contributed in reduced cutting force and thermal deformation at top layer of object minimised.

Rabiei, Rahimi, & Haddad, 2015[44]	RS1642 Behran oil	Mild carbon, bearing, & tool steels, raw HSS,	MQL and WET cooling	120 ml/h	4 bar	5, 20, 35, 50	30	3	MQL reduced the friction coefficient and reduced the tangential forces. MQL was more useful for grinding of hard steels
Haddad, 2015[25]	Syntilo XPS Castrol in a 5% concentration	hardened 100Cr6	MQL, DRY, FLOOD	20, 50, 100 ml/h	2, 3, 4, and 7 bar	20	30	1000	Surface Roughness improved better using MQL than in dry condition. Moreover MQL reduces grinding force which lowers heat generation in contact zone. The nozzle distance from the grinding zone plays an important role. The lesser the distance of MQL spray from grinding zone, the lubrication effect reduces
Batako & Tsiakoumis, 2015[9]	Castrol "Carecut ESI" oil	nickel alloy and BS-534A99 steel	MQL, DRY, FLOOD	30 ml/h	0.45 MPa	10-30	30	200	MQL also showed reduced grinding forces and better surface finish than dry grinding. The relative improvement in surface finish (lower roughness) is explained by the semi-lapping effect induced by the superimposed oscillations to the cutting process.
Emami, Sadeghi, & Sarhan, 2014[20]	Synthetic oil, hydrocracked oil, vegetable oil, and (conventional) mineral oil.	alumina (Al2O3) ceramic	MQL and Dry condition	150 ml/h	-	20	30	200	Use of MQL produce higher surface quality and preferred in finish grinding. Use of MQL retains its lubricity ability property at high temperature and wheel-work piece contact.
Barros, Silva, & Canarim, 2014[8]	Quimatic ME-I semi-synthetic soluble oil, with 2.5 % concentration	AISI 4340 steel rings	MQL	$2.7 \times 10^{-8} \text{ m}^3/\text{s}$	0.6 Mpa	-	30	0.25, 0.50, and 0.75 mm/min	Flood coolant produces better surface roughness. The high rate of flow if flood coolant is responsible for removing chips from the cutting zone. MQL reduces specific grinding energy thus also providing efficient lubrication in able to control the thermal deformation occurring on the work piece and able to give good surface quality.
Belentani, Funes Júnior, Canarim, & Hassui, 2014[10]	MQL with water, vegetable oil in the proportions of: 1:1, 1:3 and 1:5 parts of oil	SAE/AISI 4340	MQL and WET cooling	-	0.8 Mpa	-	30	0.25, 0.5 and 0.75 mm/min	MQL improves surface Roughness, with addition of water in decreases wheel wear than the conventional cooling lubrication. It helps in disrupting air barrier formed around the rotating wheel thus lower grinding power obtained.
Abdul Rahim, Ibrahim, Mohid, & Ahmad, 2014[2]	-	AISI 1020	MQL and Flood cooling	80 l/h	-	0.2 mm	-	400, 500, 600 mm/min	Use of MQL reduces surface temperature than to flood coolant. The grinding forces are reduced with increased cutting speed. MQL also helps in reduction of temperature which attributed to the capability of the tiny mist particles of MQL penetrating into the grinding zone, subsequently reduces the grinding friction.

Hadad & Hadi, 2013[26]	Vegetable oil and synthetic ester oil	Aluminium alloy 6061 & hardened steel	MQL and FLOOD cooling	4 ml/h	-	5, 15, 25	30	1.5	MQL reduced the surface roughness and grinding forces as compared to dry and wet grinding and provided better cooling than dry grinding though not better than conventional wet grinding.
Balan, Vijayaraghavan, & Krishnamurthi, 2013[6]	Cimtech D14 MQL oil	Inconel 751 super alloy	MQL, dry, flood	60, 80, 100 ml/h	2, 4, and 6 bar	30	2826 m/min	0.9	Minimum grinding force and surface roughness could be achieved by increasing the MQL oil flow rate and air pressure. MQL considerably reduced the grinding forces, temperature and surface roughness.
Emami, Sadeghi, & Sarhan, 2013[19]	Mineral oil	Al2O3 engineering ceramic	MQL	25-400 ml/h	-	18	30	10	Use of optimally designed MQL in grinding reduced the tangential as well as normal grinding force and surface roughness.
Li & Lin, 2012[36]	Vegetable oil (Bluebe lubricant LB-1)	SK3 steel (HRC 18)	MQL	1.88 and 0.63 ml/h	0.5 MPa	50	30000, 39000, 48000 RPM	-	-
Barczak, & Batako, 2012[7]	Synthetic oil Castrol Carecut ES1	Common steels EN8, M2 & EN31		33 ml/h	0.4 Mpa	5.15	25, 45	6.5, 15	Low grinding temperature and lower surface roughness values were recorded with MQL.
Morgan, Barczak, & Batako, 2012[40]	Castrol Carecut ES1 oil	Common steels EN8, M2 and EN31	MQL, dry, wet	33 ml/h	0.4 Mpa	5.15	25, 45	6.5, 15	More favourable for softer materials.
Tawakoli, Hadad, & Sadeghi, 2011[63]	Mineral oil, hydrocracked oil, synthetic oil, ester oil	Hardened steel (100Cr6)	MQL, dry, wet	100 ml/h	4 bar	30	30	3	Reduced the grinding forces and surface damages Among many oils, MQL produced best surface quality with mineral hydrocracked oil
Tawakoli, Hadad, & Sadeghi, 2010[61]	HAKUFORM 20c30 MQL oil	Hardened steel (100Cr6)	MQL, dry, flood,	20, 50, 100 ml/h	2, 3, 4, and 7 bar	20	30, 45	1, 2	MQL, dry, flood MQL nozzle, while set angular toward the wheels, produced lowest surface roughness and tangential grinding and normal forces. Increase of nozzle distance improved the surface quality.

4. Role of Nanoparticles in Nano-fluid Machining

Recently, the inclusive of nanoparticles in conventional lubricants has shown remarkable improvement in thermo-physical, heat transfer capabilities, reduction in the coefficient of friction, wear effect to enhance the efficiency, and reliability of machined part [47,48]. The friction force at the tool chip interface normally increases due to tool wear which leads to increment in the cutting force and friction force. It is noted that by adopting to the Nano lubricants at the tool chip interface, the coefficient of friction can be reduced. It is believed that nanoparticles deposits on the friction surface and compensate for loss of mass, which called 'mending effect'. Due to porous nature of spherical nanoparticle, it could impart high elasticity and enhances the gap at tool to work-piece interface. Some particles have rolling effects and some are sheared due to high pressure at the cutting zone. The shape of particles changes due to high compression. With increasing the concentration of nanoparticles the degree of shaping and shearing increases. For this reason, Nano lubricants are able to reduce the cutting force with less power consumption [49,50]. Nanoparticles in the mineral oil impart their effect by combined effect of rolling and sliding at the tool-chip interface. This effect reduces the coefficient of friction. The lubrication mechanism is shown in figure 5.

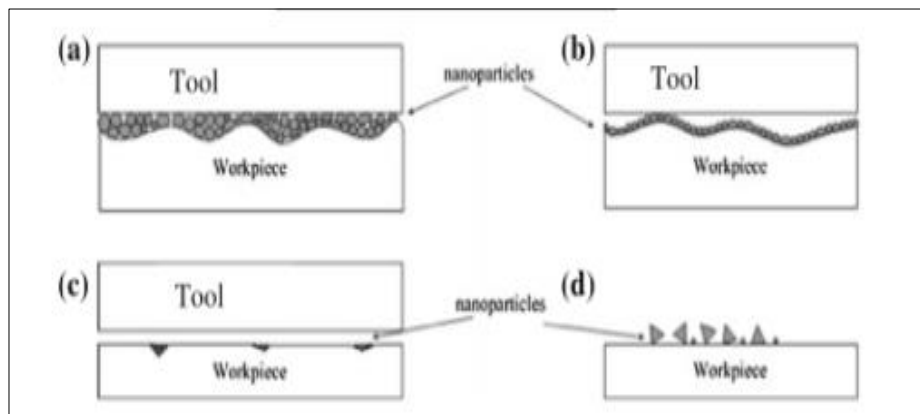


Figure 5. (a). Rolling effect. (b) Protective film (c) Mending effect (d) Polishing effect [34].

Nano-fluid is a new class of fluids engineered by dispersing nanometer size solid particles into base fluids such as water, lubrication oils. Nanoparticles have much higher and stronger temperature dependent thermal conductivity, and enhanced heat transfer coefficients at very low particle concentration. These are the key parameters for their enhanced performance in many of the machining applications. Their ball bearing effect lubrication at the cutting zone through formation of film layer which reduces friction between the contact surfaces thereby reducing cutting force, temperature and tool wear [41,49]. Also, the addition of nanoparticles into base fluid can enhance their convective heat transfer coefficient, lubricating properties, and wettability apart from their tribology, and wear characteristics. The excellent properties of the Nano-fluids makes them very attractive in cooling and lubricating application in manufacturing. The application of various nanoparticles and its performances in metal cutting operations with respect to the cutting forces, surface finish, tool wear and temperature at the cutting zone are evaluated and highlighted.

5. MQL Using Nano-fluid in Grinding Process

In the MQL lubrication process, the coolant or lubrication medium used is posed certain restrictions especially at very high cutting speeds where the lubricating oil tends to evaporates as it strikes the already heated cutting tool at elevated temperature. Desire to compensate for the shortcomings of the lubricating medium in the MQL technique led to the introduction of nanoparticles in the cutting fluids for use in the MQL lubrication process. Nano-fluids has emerged as a promising solution to this problem.

Friction, and wear result in the increase of energy consumption, and reduction in the life of mechanical parts [54,50]. Friction is a principal cause of wear and energy dissipation. Moreover high temperature generations at cutting zone affects the work-piece dimensional accuracy and surface quality [72,73]. It has been reported in various studies that nanoparticles introduction in cutting fluids led to excellent machining performance in reduction of cutting forces, reduced tool wear, reduced cutting temperature and improved surface finish of the work piece thereby increasing productivity and reduction of hazards to the health of personnel and the environment better than the pure or conventional MQL process [57]. Nano lubricant confers rolling action of billions of nanoparticles at the tool chip interface thereby reducing friction and thermal deformation of the work piece in addition to less consumption of lubricating oil. Hisakado et al. [29] added copper and nickel nanoparticle into paraffin and to investigate its frictional properties. It showed that coefficient of friction reduced by 18%. This finding shows that nanoparticle improves the anti-wear and friction reducing performance of lubrication oil. Nanoparticle size and concentration are two important parameters that affect grinding performance.

Lee et al. [34] studied micro grinding of a tool steel under four lubrication media (Nano-diamond of 2 level concentration, Nano- Al_2O_3 of 2-level concentration, dry air and pure MQL of the paraffin based oil. Nanoparticle concentration considered are 2% vol. and 4% vol. while particle size of 30nm and 150nm selected for both Nano-diamond and Nano- Al_2O_3 , shows that the smaller particle size surface roughness enhanced producing smoother surface than the larger particle. Optimizing the nanoparticles concentration leads to better surface roughness and reduced grinding force. [52] studied grinding of titanium alloy using silicon carbide wheel with different lubrication media and with water based Al_2O_3 nano-fluid of 1% and 4% concentration. It was reported that grinding forces reduced using Nano cutting fluid with lower nanoparticle concentration. However, the surface finish was improved with increased nanoparticles concentration. [64] compared the performance of MQL with vegetable oil with MQL+Vegetable oil+ Al_2O_3 nanoparticle in machining Inconel 600alloy. The experiment resulted temperature, surface roughness and tool wear were reduced under the MQL with 6% vol. of Al_2O_3 particle). Mao, Huang, Zhou, Gan and Zhang [38] investigated study of Nano-fluid (Al_2O_3 /water) in grinding of hardened AISI 52100 steel. It was found that addition of Al_2O_3 nanoparticle into deionized water helps in reducing grinding force. Setti et al. [53] continued the research comparing the performance of two different Nano-fluid (Al_2O_3 /water, and CuO /water) in grinding of Ti-6Al-4V using MQL system. It showed that Al_2O_3 /water reduction in friction coefficient due to its ability to form and prevent tribo films on the work-piece surface. The lotus effect of titanium and Al_2O_3 lead to effective flushing of debris thus improved the grind ability by reduction friction, temperature from grinding zone.

Kalita et al. [32] studied that surface-grinding test were performed on ductile iron work pieces using an aluminum oxide wheel and impingement of advanced Nano lubricants, consisting of organic molecules with phosphide intercalated-MoS₂ Nano particles (<100nm), was observed the effectiveness of Nano lubricants measuring reduction of 45-50% in the grinding force and 48-55% in the reduction in the abrasive wheel wear than MQL with paraffin lubricant. Zhang et al. [69] evaluated MoS₂ nanoparticles in three different oils (soybean, palm and rapeseed oil) as base fluid. It showed that the optimal concentration range of MoS₂ nanoparticle is 6% which showed excellent lubricating property which have reduce specific grinding energy and lower coefficient of friction. Zhang et al. [68] extended the research by investigating surface quality under MQL grinding of Ni-based alloy with MoS₂, CNT and Mix (MoS₂+CNT). It showed that Mix MQL showed the best surface quality followed by MoS₂, and CNT. It is also observed increase of Nano concentration lowers grinding force ratio (G) which improves the lubrication and surface quality.

Prabu and Vinayagam [43] carried out experimental studies to evaluate the impact of using Nano lubricants containing MWCNT and SAE20W40 oil with MQL technique during grinding process on work piece (AISI D2 tool steel) for surface smoothness. It was observed specimen sparked using MWCNTs have better surface finish, reduced micro cracks and better surface morphology [70]. The surface smoothness was evaluated using surface roughness meter and atomic force microscope (AFM). The MWCNT and SAE20W40 oil improved its surface quality to Nano level from micro level. [42] extended the study on surface characteristic of AISI D2 tool steel in grinding process but using SWCNTs

in SAE20W40 oil base fluid as the Nano lubricant. The fractal dimension and surface roughness were measured. It was found that under the fractal dimension and the roughness are decreased when without using Nano fluid. However, under presence of Nano fluid with optimum speed of the grinding wheel, the surface was even and smooth. CNTs increases the heat carrying capacity and thermal conductivity of the lubricating oil and thus prevents any damage to the work piece. [53] studied the effect of CuO, and Al₂O₃ Nano-fluids with different concentration in MQL grinding of Ti-6Al-4V on grinding force, surface roughness and wheel morphology. It is observed that Al₂O₃ offered significant reduction in the coefficient of friction due to its ability to form and prevent tribo film in ground surface. Al₂O₃ Nano-fluid improved the grindability of Ti-6Al-4V with conventional abrasive wheel by reducing friction, temperature, favoring effectively grain fracturing, ideal chip formation and effective flushing out of debris from grinding zone.

[39] studied the effects of Nano-fluid MQL combined with ultrasonic vibration on surface grinding. Seen that the lubricants with MoS₂ additives show significant improvement in grinding performance by lowering the grinding forces and the force ratio. Normal force is reduced by around 25% and tangential force is reduced by around 50% compared to dry grinding, and it also produces smaller forces than flood cooling. The reduction can be attributed to penetration MoS₂ NP into the grinding interface. It is found that using UAG with MoS₂ Nano-fluid MQL lead to significant improvement in the surface roughness. Improvement in surface is due to the fact that the grit motion with low friction in horizontal vibration creates a higher chance of cutting the peaks of the surface. [60,70] investigated grinding of Inconel 718 of two different Nano particle (Ag/water and ZnO/water) under SQL mode. It is observed that addition of NPS in DI water have further improved in further convection in the higher grinding zone temperature. The thermal load on the abrasive grits is improved by the high heat carrying capacity and improved lubricity of the Ag and ZnO Nano-fluids. Low grinding forces, smaller friction coefficient, minimal sticking of debris over alumina grits, and better ground surface have been observed in the case of grinding with ZnO Nano-fluids. This is due to the spreading nature of the ZnO. The wheel wear is almost invisible when ZnO Nano-fluid is used. This is due to better wettability of the ZnO NF. [35] investigated heat transfer performance of MQL grinding of Ni-based alloy GH4169 with different Nano-fluid (MoS₂, SiO, PCD, CNT, Al₂O₃ and ZrO₂,) which palm oil as MQL base fluid. Nano-fluid with high thermal conductivity is believed to have good heat transfer performance. CNT have stated the highest thermal conductivity when added with to base fluid. It is observed that SiO have the lowest grinding force followed by MoS₂ and PCD Nano-fluids.

However, CNT have the lowest grinding temperature, thus CNT has the best heat transfer performance compared to other Nano-fluids analyzed. [66,71] further investigated the lubricating property of different Nano-fluid (MoS₂, SiO₂, ND, CNTs, α -Al₂O₃, and ZrO₂) in MQL grinding of 440C steel ball. It showed that Al₂O₃ Nano-fluid has the best antifriction property contributing the best surface morphology. Based on the frictional test and grinding experiment the Diamond, ND nanoparticle can cause grinding and polishing effect on the work piece surface during plane grinding. The Al₂O₃, MoS₂ and SiO₂ nanoparticles however are suitable as friendly additive's of base oil. Wang et al. [65] studied on the effect of using different concentration of Al₂O₃ on surface quality specific energy and wheel morphology in MQL grinding Ni-based alloy GH4169. Different volume concentrations (0.5%, 1.0%, 1.5%, 2.0%, 2.5%, 3.0%, 3.5%, and 4.0%) of Al₂O₃ nanoparticles were added into palm oil. Al₂O₃ nanoparticles can form thin protective oil films on the grinding wheel and work piece surface. These films improve the tribological performance of grinding wheel/work piece interfaces significantly. It is observed that as Nano-fluid concentration in base oil increases, the force ratio and specific grinding energy decrease first and then increase, reaching the minimum at 1.5% vol. At 2.5% vol., the wearing loss of the grinding wheel is the lowest. Best tribological performance is gained when the Nano-fluid concentration is 2% vol. However further increase of vol. % than 2%, could have possibly increase the thickness of lubricating film but it will not reduce the friction and wearing loss. At 2% vol. is where the largest wetting area and lubricating effect occurs.

6. Conclusion

This paper has presented a review of research activities carried in the application different types of cutting fluid and Nano-fluid based cutting fluid with the help of the MQL lubrication technique. This paper reviews MQL lubrication technique in the grinding machining process. A brief description and mechanism of the MQL technique and systematically discussing its effect on performance in the grinding process are also presented. There is enough literature which clearly reveals that MQL system provides better performance than dry machining. So MQL is found to be promising alternative for flooded and dry machining due to their environmental friendly characteristics. Researcher have done inclusive review on the application of Nano-fluid in grinding process. Different type of nanoparticles which benefits in grinding were reviewed. The nano fluid has gained significant attention due to its capability to enhance the heat transfer and lubrication performance. Nano fluid MQL was proven to reduce the coefficient of friction and wear effect by enhancing the efficiency and reliability of machine tools. MQL gave the best performance in terms of the surface roughness, feed forces, tool wears and surface quality. Very few records can be seen in the literature indicating more experimental research that is needed to ensure maximum performance of using nano fluids as a coolant in grinding process.

Acknowledgement

Universiti Malaysia Pahang fully supports the facilities and resources for this research. The authors would like to acknowledge the support from the Universiti Malaysia Pahang internal grant RDU1703150, RDU170320, and Ministry of Higher Education, Malaysia (FRGS Grant) RDU160119.

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