Enhancement of Machining Performance with the Application of Nano Cutting Fluids Under Eco-Friendly MQL Technique: A Review

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Abstract

Nanofluid based lubricants have immense acceptability in sustainable and eco-friendly machining, this is due to their superior heat transfer ability. Extreme demands for sustainable manufacturing compelled the manufacturers to avail synergistic benefits with higher machinability and lower carbon footprint on the environment. Cooling and lubricating properties such as conduction, convection and lubricant stability at higher temperature are improvised by the addition nanoparticle into metal cutting fluids. Therefore, nanoparticle enhanced cutting fluids have recently attracted the attention of researchers. This paper presents a review of some important published research works on the application of nanoparticles enriched cutting fluids in different machining processes. Further, this review article discusses the influence of different types of nanofluids on machining performance in various machining processes. From literature review, it has been found that nanofluid MQL machining significantly reduces cutting forces, cutting zone temperature, tool wear and friction coefficient in comparison to dry and wet machining. Moreover, sufficient amount of nanoparticles could improve the anti-friction and nano-ball bearing capacities of the tribofilm layer formed in the machining zone. On the other hand, very low concentration of nanoparticles in the base oil will result in weakening of the tribofilm layer owing to insufficient lubrication effect. Therefore, MQL technique has proved to be a viable alternative to the flood lubrication under similar performance parameters.

Keywords: Machining; Nanofluids; Nanoparticles; Minimum quantity lubrication.

1. Introduction

Machining process is an important process in manufacturing of metal components [1]. In all machining processes, tool wear is a natural phenomenon and it leads to tool failure. The growing demands for high productivity of machining need use of high cutting velocity and feed rate [2]. When machining difficult-to-cut materials, the high temperature in the cutting area is one of the dominating phenomena affecting tool wear, process capability and product quality [3]. The coolant application in machining processes plays a very important role as many operations cannot be carried out efficiently without cooling [4]. The high temperature generated in the region of the tool cutting edge has a controlling influence on the wear rate of the cutting tool and on the friction between the chip and the tool during machining process [5]. The cutting fluids are very essential in machining for cooling the workpiece and tool, reduce friction and wash away the chips [6]. In addition, cutting fluids help to provide a uniform temperature field inside the workpiece and machine tool, and help to meet specified tolerances [7]. These advantages of using cutting fluids in machining are accompanied by a number of drawbacks. Cutting fluids may create several environmental problems such damaging the soil and polluting the water resources [1]. Other factors are worker's health and the increasing law demands [8].

In Conventional flood lubrication a large quantity of lubricant is applied continuously at the tool chip interface. Therefore, this system is becoming uneconomical for machining and unsuitable for environment [9]. There are number of alternative for large cutting fluids. Some are dry machining and near dry machining also known as minimum quantity lubrication [10]. Dry Machining is less effective when higher machining efficiency, better surface finish and severe cutting conditions are required. For these situations, minimum quantity lubrication (MQL) machining operations utilizing very small amounts of cutting fluids are expected to become a powerful tool [2]. However, in MQL secondary characteristics are important. These include their safety properties (environment pollution and human contact), biodegradability, oxidation and storage stability [11].

Many researchers have reported about a number of research works on effects of different cooling techniques using conventional cutting fluids in different machining

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processes. However, there is no comprehensive literature available on the effects of MQL using nano-particle-enhanced cutting fluids. The aim of the present work is to review the effect of MQL using different nano-cutting fluids in different machining operations.

2. Minimum Quantity Lubrication (MQL) Technique

Minimum quantity lubrication (MQL), as its name implies, uses the smallest amount of metal working fluid (MWF) to achieve lubrication during machining processes [12]. In MQL technique, a very small amount of lubricant/coolant is mixed with air to form aerosol, which is sprayed at a high pressure in the cutting zone with the help of a nozzle [13]. The typical fluid flow rate in MQL system is 50-500 ml/h, which is estimated to be 10,000 times less than the conventional flood cooling [1]. Industrial experiences have concluded the advantages of MQL in power consumption, environment (emission, waste), chips recycle value, safety and flexibility, as well as the major challenges including thermal issues (expansion, wear and firing), tool development (through spindle / tool) and chips removal. During MQL machining, the metal chips produced are nearly dry and virtually clean. The near-dry chips do not require drying and thus bring more net revenue to the plant [14].

The application of conventional cutting fluids creates several environmental issues, such as the pollution due to the chemical disassociation at high temperatures, water pollution, soil contamination during disposal, and biological problems to the operators [15, 16]. One problem is linked to the growth of bacteria and fungi. This lowers the service life (since the presence of bacteria could reduce the lubricity and change the pH of the cutting fluid) and may increase the health hazards [17].

In order to make machining process more ecological, the Minimal Quantity Lubrication has been accepted as a successful near dry applications because of its environmentally friendly characteristics [18]. The schematic view of the MQL setup is shown in Figure 1 [19].

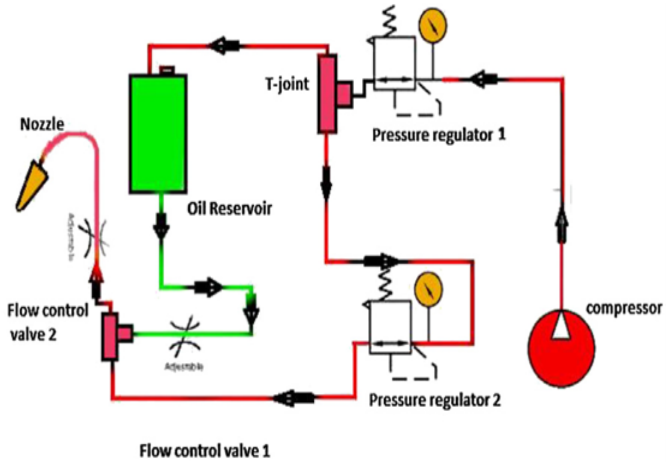

Figure 1: Schematic diagram of MQL unit

Kamata et al. (2007) experimentally investigated high speed turning of Inconel-718 with different coated tools using the MQL technique and made a comparison between dry, wet and MQL techniques with regard to tool life and surface finish as shown in Figure 2(a) and 2(b) [20]. The surface finish and tool life attained using MQL was found to be better than that in the wet and the dry machining for differently coated cutting tools. In another study, da Silva et al. (2007) studied the effect of surface integrity for minimum quantity lubricant (MQL) in grinding of ABNT 4340 steel [21]. It was observed that the performance of MQL technique was superior in the grinding process compared with the conventional cooling method in terms of surface integrity. The 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. The use of MQL did not effect the surface integrity.

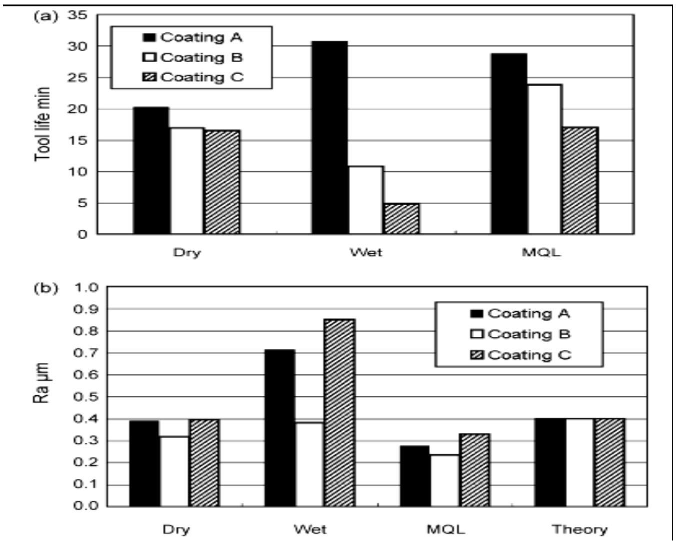

Figure 2: (a) Tool life and (b) surface roughness in dry, wet and MQL machining for three different coated tools

Moreover, Fratila et al. (2011) observed that MQL could be applied in place of conventional milling without much affecting the milling process results in the terms of cutting power and surface roughness [22]. Hassanpour et al. (2016) investigated surface roughness, micro hardness and white layer thickness in hard milling of AISI 4340 using MQL and found that increasing cutting speed has a significant influence in the reduction of surface defects [23]. Kang et al. (2008) also reported that MQL milling showed an excellent cutting performance under high speed end milling and recorded the lowest flank wear among all the three cooling conditions, namely, flood, dry, and MQL [24].

Furthermore, the technological and industrial sector has already recognized the feasibility of bio-lubricants as a substitute for synthetic lubricants, as reported by [25]. Minimum quantity vegetable oil offers excellent potential to machine hard materials. Actually, the presence of –COOH and –COOR polar groups in vegetable oil produces excellent lubricating environment during machining operation [26]. A few years ago, Belluco et al. (2004) performed a drilling operation using five vegetable oils as a lubricant [27]. The experimental study was performed on AISI 316L material. The outcome of this study revealed that vegetable oil could advance the tool life up to 177% as compared to dry machining. Ojolo et al. (2008) inspected the lubricity of some bio-oils during machining of copper, aluminum, and mild steel [28].

Although, many studies in the past validated the effectiveness of MQL technique, but still during the machining of hard materials there is a need to control the temperature of machining zone. Many researchers have confirmed that the addition of metal based nanoparticles in the base fluid enhanced the heat-carrying capacity of the fluid [29]. These nanoparticles based fluids are termed as nanofluids. Various research studies have reported and found that nanoparticles based-minimum quantity lubrication (MQL) technique is an alternative to disperse heat from the machining zone.

3. MQL Technique Using Nano-Cutting Fluids

In the recent years, nanoparticle based MQL cutting fluids are established in order to boost the lubrication stability and heat transfer efficiency during machining. Nanoparticles of average size ($<$ 100nm) dispersed into the metal cutting fluids are indicated as nano-cutting fluids. It has been observed that the nano-additives play a major role in altering thermal transport phenomena and physical stability of cutting fluids to a greater extent. Various nanoparticles have been added for enhancing the quality of metal working fluids, this includes, metal and ceramic based nano particles. These includes several nanoparticles such as Al_2O_3, diamond, SiO_2, graphene and MoS_2 are mainly used to upgrade the thermal properties and lubrication stability of cutting fluids. Nanoparticles possess enhanced thermo- physical properties owing to their large surface to volume ratio, which when dispersed in small proportions by volume in base fluids like biodegradable fluids (vegetable oils), result in formulations which imbibe the eco-friendly and user friendly aspects of the base fluid which are not harmful to the environment like conventional cutting fluids [30].

According to the fact that preparation of nanofluids is rather expensive, these new suspensions are not desirable for utilization in conventional wet machining. However, because MQL method needs a low fluid amount, application of nanofluids in this method is completely favourable.

3.1. Role of Nanoparticles in Nanofluid MQL Machining

Many researchers have reported a noticeable reduction in friction and an increment in load bearing capacity of friction parts by adding nanoparticles into conventional fluid. Sharma et al. (2015) found that nanofluid exhibited better tribological and thermo-physical properties relative to its base fluid and reduced the cutting forces, surface roughness, cutting zone temperature and tool wear [31]. Moreover, various researchers have reported several different mechanisms which enable nanoparticles to act as a powerful additive to improve the tribological performance of a lubricant. These include the rolling mechanism [32], self-repairing or mending mechanism [33], polishing mechanism [34, 35] and tribo-film formation [36]. These mechanisms are illustrated in Figure 3 [37].

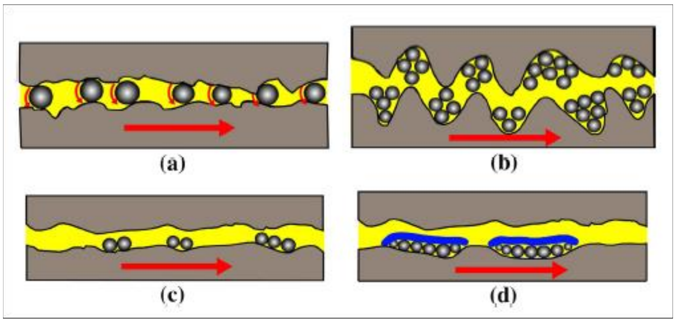

Figure 3: Schematic illustration of (a) rolling mechanism, (b) selfrepairing or mending mechanism, (c) polishing mechanism and (d) tribo-film formation

Amrita et al. (2014) 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%) [38]. It also improved chip morphology. The surface roughness and flank tool wear observed under different machining as shown in Figure 4.

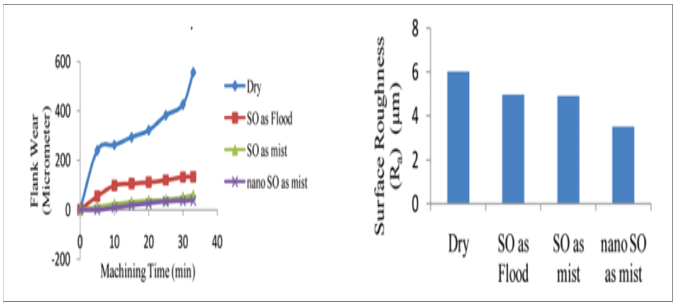

Figure 4: Variation in flank tool wear and surface roughness at different lubricating conditions

Zhang et al. (2015) examined the behaviour of nanofluid MQL using different types of vegetable based cutting fluid in grinding [39]. The observations revealed that the application of nanoparticles in base oil increases the viscosity of the oil and produce good lubrication effect by increasing the heat dissipation rate. In another study Setti et al. (2015) dispersed the Ag and ZnO nanoparticle into the deionized water to prepare the nanofluid to improve the grinding performances of the Inconel 718 superalloy [40]. The research results indicated that the ZnO nanofluid exhibited the best grinding performances and obtained better surface quality, minimum friction coefficient, and minimum grinding force. Manoj Kumar et al. (2016) added the multi-walled carbon nano-tube to the sunflower oil to improve the working and wetting performance during the grinding of the tool steel [41]. The research results showed that the cooling/lubricating performances in terms of the thermal conductivity and anti-friction performance were significantly improved. Meanwhile, the wetting performance was also significantly enhanced. Chatha et al. (2016) reported that owing to the ball-bearing effect of nano-particles and their superior cooling capabilities, the number of drilled holes increased significantly along with high quality of holes during drilling aluminium 6063 using nanofluid MQL technique [42]. Also, the drilling forces and drill wear significantly decreased in comparison to other cooling strategies when NFMQL condition was applied. The SEM micrographs of tool wear (at cutting edge) under 1.5% volumetric concentration Al_2O_3 nanofluid MQL drilling condition at the cutting speed of 30 m/min. and 53.7 m/min. are presented in Figure 5. In another study Singh et al. (2020) concluded that graphene-based MQL turning of Ti-6Al-4V had better results compared to dry machining due to high thermal conductivity and shearing behaviour of graphene [43]. Wang et al. (2016) concluded that the lubrication properties of the six kinds of nanofluids can be described in the following order: ZrO_2 < CNTs < ND < MoS_2 < SiO_2 < Al_2O_3. Among these compounds, Al_2O_3, MoS_2, and SiO_2 nanoparticles are more appropriate as additives for nanofluids [44].

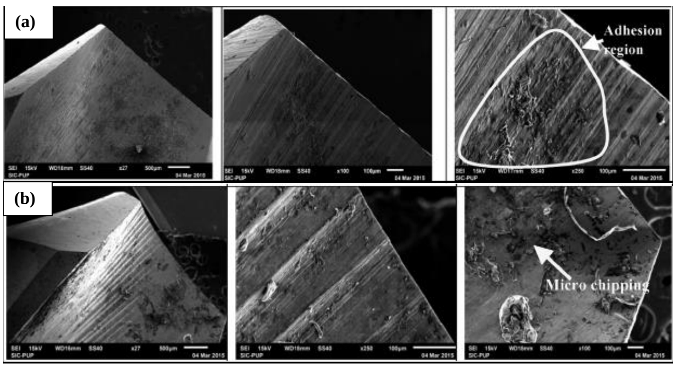

Figure 5: SEM micrographs of tool wear (at cutting edge) under 1.5% volumetric concentration Al_2O_3 nanofluid MQL drilling condition at the cutting speed of (a) 30 m/min. and (b) 53.7 m/min.

Jia et al. (2014) evaluated MQL grinding of AISI 1045 steel using ZrO2, diamond, and MoS2 nanoparticles [45]. It was reported that MoS2 nanoparticles achieved the optimum lubrication performance, followed by diamond nanoparticles. Nam et al. (2018) evaluated the performance of nano-diamond particles by using nano-lubrication system in micro-drilling operation of Ti-6Al-4V alloy [46]. Results revealed that higher nanofluid's weight concentration prominently reduces the drilling forces and edge radius at lower machining speed and feed rate. This is mainly because more nano-diamond particles could provide rolling and sliding effects. In another investigation, Sayuti et al. (2014) employed the nanofluid containing the SiO_2 nanoparticles for the cutting zone in a milling process [47]. The outcomes indicated that the increase of the nanoparticle concentration increases the development of thin protective film on the surfaces under machining owing to the rolling of many particles at the interface between chip and tool.

The development of the thin film on the surface enhanced the milling efficiency with decreasing the cutting force and temperature and increasing the surface quality. Figure 6 shows the elemental mapping of surface machined at weight fraction of 0.5%.

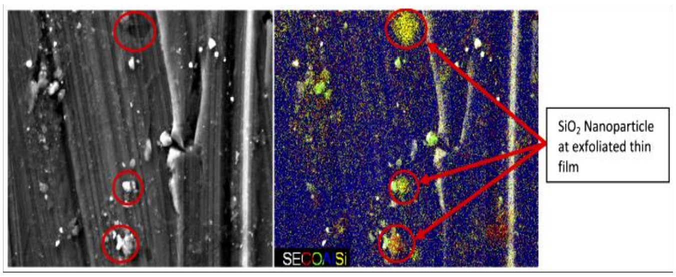

Figure 6: Elemental mapping of surface machined at nanoparticle concentration of 0.5 wt%

4. Conclusions

This paper has presented a review of important published researches in the application of nano-cutting fluids with the help of MQL technique during various machining processes. It has also presented a brief description and mechanism of the MQL technique, systematically discussing its effect on performance parameters in different machining processes. Most of the experimental studies showed that MQL machining can be a viable alternative to wet machining and can facilitate environment-friendly machining. The following conclusions may be drawn from the present literature review:

- MQL technique has emerged as a superior technique which minimized the ecological and biological problem caused by the rampant use of metal working fluids.

- MQL technique not only significantly reduced amount of metal cutting fluids (MCFs), but also enhanced the machining performance with respect to machining characteristics than conventional flood and dry cutting.

- Nano-particles show excellent performance in friction and wear reduction when combined with vegetable oil. The anti-wear mechanism is attributed to the deposition of nanoparticles in surface and physical film formation, which may reduce the friction and wear.

- Nanofluid MQL machining significantly improved the machining performance as compared to dry, flood and MQL machining. The lubrication film formed by nanoparticles reduced the tool wear, coefficient of friction, surface roughness and cutting forces. Additionally, the high thermal conductivity of nanoparticles effectively reduced the cutting temperature and hence improved the overall process performance. Overall, the application of the nanoparticles-dispersed vegetable-oil-based cutting fluid in the machining process is very meaningful and promising.

5. Future Directions

- In future work, the fundamental mechanisms of the effect of the nanoparticles-dispersed vegetable oil-based cutting fluid on the machining characteristics need to be further studied. More theoretical modeling is required for better understanding of these fundamental mechanisms.

- Meanwhile, the scholars have given higher attention to single nanofluids (i.e., ordinary nanofluids) as cutting fluids, whereas they can expand the studies on the preparation and use of hybrid nanoparticle suspensions to enhance efficiency of machining processes.

- In addition, tribological evaluations by SEM, DLS, XPS, TEM, and AFM are strongly needed to disclose the physical mechanisms between different nanoparticles and interfacial zones.

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