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Overview of Nanofluid Application through Minimum Quantity Lubrication (MQL) in Metal Cutting Process

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Abstract. Pollution related activities in addition to handling cost of conventional cutting fluid application in metal cutting industry has generated a lot of concern over time. The desire for a green machining environment which will preserve the environment through reduction or elimination of machining related pollution, reduction in oil consumption and safety of the machine operators without compromising an efficient machining process led to search for alternatives to conventional cutting fluid. Amongst the alternatives of dry machining, cryogenic cooling, high pressure cooling, near dry or minimum quantity lubrication (MQL), MQL have shown remarkable performance in terms of cost, machining output, safety of environment and machine operators. However, the MQL under aggressive machining or very high speed machining pose certain restriction as the lubrication media cannot perform efficiently at elevated temperature. In compensating for the shortcomings of MQL technique, high thermal conductivity nanoparticles are introduced in cutting fluids for use in the MQL lubrication process. They have indicated enhanced performance of machining process and significant reduction of loads on the environment. The present work is aimed at evaluating the application and performance of nanofluid in metal cutting process through MQL lubrication technique highlighting their impacts and prospects as lubrication strategy in metal cutting process for sustainable green manufacturing. Enhanced performance of vegetable oil based nanofluids over mineral oil-based nanofluids have been reported and thus highlighted.

INTRODUCTION

Nanofluids are new class of fluids engineered by dispersing nanometerized materials (nanoparticles, nanofibers, nanotubes, nanorods etc.) usually of particle size of 1-100 nm in base fluids which could be deionized water, esters or vegetable oils based coolant [1-4]. The discovery in 1993 by Matsuda [5] that dispersion of Al_2O_3 improved the thermal conductivity of water by 30%, propelled further studies to investigate thermal conductivity enhancement by nanoparticles materials at different volume concentration, particle size and types of base fluids in which they are dispersed. Nanofluid introduced by Choi in 1995 [6] has proven to provide efficient heat transfer compared to conventional fluids due to the enhancement of thermal properties of base fluids. Several researchers have consensus agreement that thermal conductivity and convective heat transfer coefficient are enhanced by suspended nanoparticles [7-10]. For CuO water based nanofluid at 2% volume concentration, the overall heat transfer coefficient and pumping power was observed to be more than that of the base fluid [11]. The heat transfer enhancement of about 40% with Al_2O_3 nanofluid can be obtained when compared to the base fluids [12]. It has been

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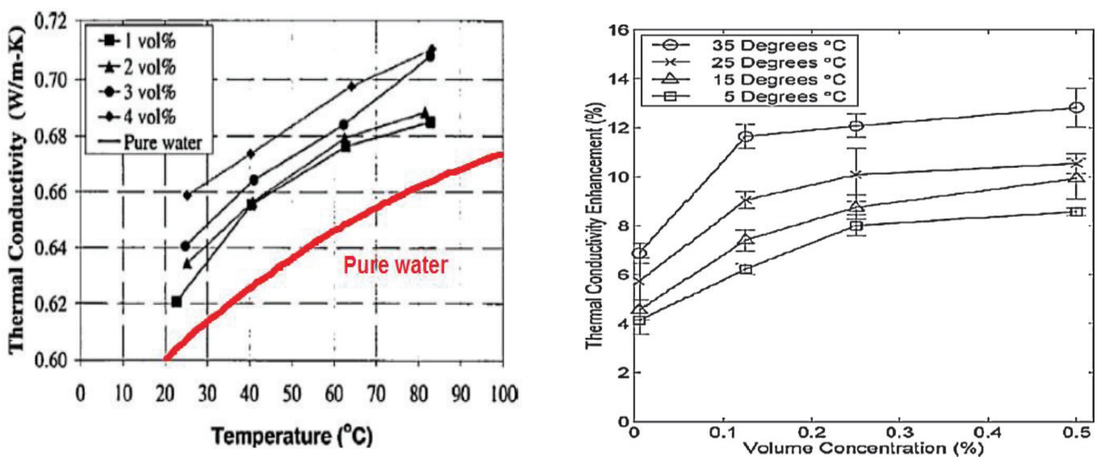
found that nanoparticles in cutting fluids have much higher and stronger temperature-dependent thermal conductivity at very low particle concentration, which is a key parameter for enhanced performance for many of the applications [13] as shown in Figure 1. Nanofluids have shown efficient performance in engine cooling, solar water heating, industrial cooling, microelectronics, cooling of transformer oil, nuclear power generation, improving diesel generator efficiency, cooling of heat exchanging devices, improving heat transfer efficiency of chillers, domestic refrigerator, freezers, in nuclear reactor and defence and space applications [1,2,13-14].

Kole and Dey [15] reported that internal combustion engine performance improved by 5 - 10% by using nanoparticles suspended commercial engine coolant. Bhogare and Kothawale [16] reported that nanofluids has the ability of improving the engine cooling of automobile and heavy duty vehicles through enhanced efficiency and reduction of weight and complexity of thermal management. M'hamed et al [17] reported that thermal performance of vehicle radiator was improved with 0.5% concentration of water/ethylene glycol MWCNT nanofluid. Heat exchanging devices with the introduction of nanofluids as heat transfer fluids, have been able to reduce heat transfer time and efficient energy utilisation improvement [18-19]. In industrial application, nanofluid are known for improvement of friction-reducing, anti-wear properties and load carrying capacity of base oil [20-21]. In metal cutting processes, nanofluids have been applied recently with remarkable reduction of grinding/cutting forces shown excellent performance in cutting force reduction, temperature reduction, surface roughness improvement etc [22-23]. The desire for sustainable and green machining environment with improvement of machining responses has seen the evolution of cooling and cooling strategies from dry machining, high pressure cooling, cryogenic, MQL/NDM and recently nanofluids in metal cutting process to reduce environmental pollution, improve operator’s safety and improved quality of products output. In view of fast adaptation of nanofluid application in metal cutting processes, the present work is to evaluate the various cooling strategies and the application of nanofluid in metal cutting process through MQL lubrication technique, highlighting their impacts and prospects as lubrication strategy in metal cutting process for sustainable green machining.



(a) (b)

FIGURE 1. (a) Temperature-dependent Thermal Conductivity (b) Volume concentration-dependent Thermal Conductivity Enhancement [13]

COOLANT AND COOLANT STRATEGIES IN MACHINING

Metal cutting process is accompanied with quantum of heat generation due to the excessive friction between the contacting surfaces with adverse effect on the tool life of cutting tool and corresponding poor surface quality of the workpiece. Lawal et al [24] stated that the development of coolant and coolant strategies became more complex due to severity of machining processes over time in comparison with early stage of cooling and lubrication in machining. Cutting fluids have been the conventional choice to address challenges [25] and it plays an important role for efficient operation [26]. Application of cutting fluid helps to cool and lubricate the machining process, thus reducing tool wear, increased tool life and improving surface finish of the machined surface [27]. Removal of heat from the cutting zone by cutting fluids as reported by Silliman and Perich [28] aid in elongation of tool life by preventing the cutting tool from exceeding its critical temperature range beyond which it softens and wear rapidly [29-30]. Cutting flood application was further enhanced with the introduction of high pressure cooling (HPC) with the aim of delivering high pressure fluid onto the cutting zone. HPC application was first published by Ojmertz and Oskarson [31] in machining of Inconel material. In 2005, Ezugwu and Bonney [32] reported that HPC has capacity of reducing tool chip contact length, offer more efficient cooling characteristics thereby reducing tool wear [33-34] as the coolant delivery pressure eliminates chips away from the tool rake face. Courbon et al [35] observed that HPC ensures better chips breakability and reduction of cutting forces and therefore is a potential alternative lubrication technique over conventional flood cooling. Palanisamy et al [36] stated that tool life improved by almost 3 times in the turning of titanium alloy under HPC cooling technique.

Despite their seeming benefits, there are also negative impacts of cutting fluids such as carrying problems, disposal problems, the toxic nature of fluid, and the environmental pollution such as soil pollution, water pollution, and air pollution which constitute serious threat to its continuous usage [37-38]. It was reported that larger percentage of all occupational diseases of operators in metal cutting industry resulted from their skin contact with metal working fluids [39-40]. It has been observed [41] that usage of mineral based oils caused adverse effect on the environment such as surface and ground water contamination, soil pollution and consequently agricultural product, and air pollution. From their findings, Klocke and Eisenblaetter [42] estimated that cost of cutting fluids accounts for 17% of the total cost of machining and when hard-to-cut materials are involved, it can be as high as 20-30% of the total cost [43]. In addressing these seeming challenges led researchers in the industry to explore alternatives that enhance machining processes, reduction of hazards and loads on the operators and the environment respectively.

Dry Machining

Dry machining was the first alternative considered as replacement for conventional cutting fluid. But several researchers have reported that dry machining has adverse effect on the cutting tool and the surface roughness of the machined component. Cantero et al [44] concluded that dry cutting is not suitable for machining of titanium alloys due to combustion of the generated chips thereby destroying the coating of the cutting tool. At higher cutting speed with dry cutting condition, excessive temperature is generated that causes changes in material properties and phases [45-46] and the generated temperature could be double when feed rate is increased [47]. Sugihara et al [48] reported strong adhesion of aluminium chips to cutting tool surface which has adverse effect on cutting performance under dry machining condition. It was concluded that dry machining can only be suitable alternative to coolant in machining when cost implication for the use cutting fluids (which accounts for 17-20%) and pollution of the environment in machining processes are the only constraint.

Cryogenic Cooling

Cryogenic cooling technique is known for temperature reduction in machining operation. Liquid nitrogen (LN_2) at -196°C is the most used cryogen gas and it has significantly improved machinability through alteration of material properties of workpiece and/or cutting tool and reducing temperature [49]. It's an environmental friendly [50] and it enhance tool life and surface finish with reduction of tool wear as the cutting zone temperature are controlled [26]. Cryogenic cooling with LN2 as coolant is considered viable alternative to flood cooling due to its ability to absorb the heat generated from cutting process and evaporates into the air with no harmful residue to the environment [51]. Dhananchezian and Kumar [52] reported that cryogenic machining when compared to flood/wet machining in turning of titanium alloy could reduce the cutting temperature, cutting force, flank wear and improvement of surface roughness by over 60%, 35-42%, 27-39% and maximum of 36% respectively. In comparison with dry and wet machining, cryogenic cooling lowers the cutting forces, cutting temperature, tool wear and surface roughness in the milling of hardened steel [53]. Lower thrust forces and improved surface roughness was observed in the drilling of Ti-6Al-4V under cryogenic cooling due to less friction and better chips breakage [54]. The cryogenic cooling improves the surface integrity better than dry machining which enhance product life and performance [55]. Extreme cooling by cryogenic cooling causes work hardening and result in damage of work surface [56]. Preheating of workpiece is necessary in most cases to reduce the hardening effects of cryogenics on the workpiece thereby reducing the cutting force [57].

Minimum Quantity Lubrication

Minimum quantity lubrication (MQL) otherwise known as near dry machining (NDM) involves the use of minute quantity of cutting fluids usually one-thousandth of the quantity of cutting fluid used in flood/wet machining [58]. In 2005, Kishawy et al [59] evaluated the effect of coolant strategy on tool performance, chip morphology and surface quality during HSM of A365 aluminium alloy and concluded that MQL technique can be regarded as a viable alternative to flood cooling. Sharif et al [60] reported that MQL can be regarded as an alternative to flood cooling in terms of cost, safety of operators and environment and tool performance. MQL lubrication was reported to produce the best surface quality when compared with wet and dry cutting conditions in the turning of AISI 4140 steel [61]. Performance of MQL was observed to be better than dry machine as it reduces cutting forces and cutting temperature by 17.7% and 6.72% respectively [62]. Sharma et al [63] concluded that under same cutting conditions, the MQL lubrication technique has proven to be a viable alternative to flood lubrication as its application reduces cutting forces, cutting zone temperature, tool wear and friction coefficient in comparison with dry and wet machining. The excellent performance of the MQL lubrication in addition to minimised cost, minimise coolant usage and improved protection of the environment has made a choice to beat amongst the alternatives to flood/wet machining.

However, the coolant or lubricating media used in MQL technique posed certain restrictions especially at very high cutting speeds where the coolant becomes less effective. In 2014, Tai et al [64], reported that due to low cooling challenge of MQL systems such as in grinding and machining of materials with low machinability, the Ford Motor Company was restricted in implementing the MQL systems in several of their CNC machines. In their investigation, Rao and Srikant, 2015 [65] observed that the low quantity of cutting fluid used in MQL system can play major role of lubrication than cooling effect. These limitations of the MQL system especially at high speed machining generated further interest in development of newer blends of lubricants for use in MQL for sustainable machining.

NANOFLUID WITH MINIMUM QUANTITY LUBRICATION (MQL) TECHNIQUE.

The efficient cooling and lubricating properties of nanofluids endeared it to operators of metal cutting industry. Since its application about a decade ago, several authors have reported excellent performance of nanofluids over conventional coolant strategies. Figure 2 indicates published papers from experimental application of nanofluid.

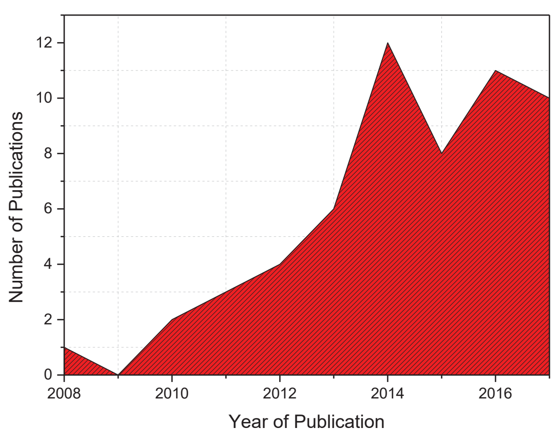


FIGURE 2. Number of published papers on experimental application of nanofluid in Machining operations

In 2010, the effects of cutting fluid with nanoparticles inclusion was evaluated by Liao et al [66] during the grinding of titanium alloy. They reported that use of nanocutting fluid caused less loading of the wheel and improve ground surface as the "lotus effect" of the nanocutting fluid lower grinding forces and coefficient of friction. Amrita et al [67] in 2013 evaluated the performance of mist application of nanographite-soluble oil in comparison with dry cutting, flood lubrication and mist application of pure soluble oil in the turning of AISI 1040 steel. Their effect on the cutting tools in comparison with dry and flood cutting conditions were evaluated. With cemented carbide tool, decrease of tool wear was found to be 94.4% and 75.24% and cutting force was found to be 76.25% and 56.98% in comparison with dry and flood cutting conditions. Similarly, the HSS tool had tool wear reduction of 71.9% in comparison with dry cutting while cutting force was reduced by 84.02% and 77.76% in comparison of dry and flood cutting conditions. Yigit et al [68] observed that there was improvement of surface roughness under all cutting speed during the milling of Aluminium 7075 using Al_2O_3 nanocoolant to reduced adhesion of material onto the machined workpiece surface.

Application of vegetable oil based nanofluid have shown excellent performance over other base nanofluids and pure base oil under MQL cutting conditions. Krishna et al. [69] evaluated the influence of nanoboric acid suspensions in SAE-40 and coconut oil during turning of AISI 1040 steel with cemented carbide tool (SNMG 120408). They investigated variation of cutting tool temperatures, tool flank wear and the surface roughness of the machined workpiece with cutting speed and feed rate using nanoboric acid particle suspensions in lubricating oil. The experiments were conducted under the following conditions; cutting speed (60, 80 and 100 m/min); feed rate (0.14, 0.16 and 0.2 mm/rev); depth of cut (1.0 mm). Nanoboric acid with particle size of 50 nm mixed with lubricating oil SAE-40 and coconut oil at 0.25, 0.5 and 1.0% concentrations in each case and flow rate of 10 ml/min were used for lubrication. They reported that cutting temperature, tool wear and surface roughness reduced significantly under coconut oil-based nanofluid in comparison with SAE-40 oil which could be attributed to the better lubricating properties of the coconut oil base fluid.

Su et al. [70] investigated the effect of nanographite dispersed in vegetable-based oil and ester oil as base fluid during cylindrical turning of AISI 1045 medium carbon steel with two cutting inserts of uncoated carbide (CNMG 120408-QM5015) employed for the cutting force tests and YT15 cemented carbide (type in ISO) employed for cutting temperature tests. The variation of cutting force and cutting temperature with cutting speed were studied using nanosolid graphite suspension in lubricating oil. The experiments were conducted under the following conditions: cutting speed (55, 96 m/min), feed rate of 0.1 mm/rev and depth of cut of 1.0 mm. The graphite oil-based nanofluid MQL showed reduced cutting force compared with pure base oil MQL lubrication. The graphite- LB2000 nanofluid MQL yielded lower cutting force than graphite-PriEco6000 nanofluid MQL, especially at a higher cutting speed, because of its better penetration and wettability. Maximum reduction of main cutting force using graphite-PriEco6000 nanofluid and graphite- LB2000 nanofluid at cutting speeds of 55 and 96 m/min was 11% and 26% respectively when compared to dry cutting at 0.5% mass fraction of graphite nanoparticles inclusion. The temperature was significantly reduced by 11.9% and 21% at cutting speeds of 55 and 96 m/min respectively in comparison with dry cutting.

Hadi and Atefi [71] studied the effect of dissipation of vegetable oil gamma-Al_2O_3 nanofluid suspension with MQL technique on surface roughness of AISI D3 steel using MQL lubrication technique during milling operation at different speed-feed-depths of cuts combination by HSS TiN coated end mill tool (ISO 1641-1-78) of 8mm diameter. It was observed that the gamma-Al_2O_3 vegetable oil-based nanofluids gave better surface roughness. Point to point evaluation of the graph indicated that the surface roughness improved by 15% for 1% volume fraction and about 25% for 2% volume fraction when compared with pure MQL. This result indicates good performance of gamma-Al_2O_3 nanoparticles.

CONCLUSION

The paper presents review of various coolant and coolant strategies that have been prior to the interest of metal cutting industry operators in nanofluid lubrication. The drawbacks associated with the various strategies were highlighted. Nanofluid MQL has shown superior performance in metal cutting processes in comparison with pure MQL base fluid, wet and dry machining. The excellent performance of nanofluid could be attributed to the enhanced thermal conductivity and convective heat transfer coefficient of the base fluid. Vegetable oil-based nanofluids indicated superior performance over mineral or petroleum oil-based nanofluid. This is attributed to the excellent lubricating properties of vegetable oil and its combination with nanoparticles in MQL resulted in superior performance. However, challenges of agglomeration of particles at higher concentration needs to be addressed for maximum benefit of nanofluid applications in metal cutting processes.

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