Machining Performance and Sustainability of Vegetable Oil based Nano Cutting Fluids in Turning

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Abstract

Metal cutting industries use cutting fluids to reduce temperatures and forces in machining. However, the application of cutting fluids has been always debatable due to their impact on workers' health. With the increase in awareness on sustainable practices, several alternatives have like Minimum Quantity Lubrication (MQL) are replacing the conventional form of cutting fluid application. The present work investigates the efficacy of nanofluids in MQL, in terms of both machining performance and sustainability. Nanofluid was prepared by dispersing 100 nm size boric acid nano particles in vegetable oil. Various machining parameters like cutting forces, temperatures, tool wear and surface roughness were monitored at constant cutting conditions. Upon observing improved machining performance, the sustainability of the formulated fluids was assessed through carbon foot print calculations and the results were compared with conventional cutting fluid.

Keywords: Cutting fluids, machining, nanofluids, sustainability

1. INTRODUCTION

Machining is a major stakeholder in the manufacturing industry and significantly contributes to the product cost and quality. Due to the interaction of cutting tool with workpiece, high temperatures and cutting forces are produced in machining. This leads to premature failure of the cutting tool and affects the product quality. Hence, in order to control the temperatures and forces, cutting fluids are applied in machining. Currently a wide variety of cutting fluids are available in the market, amongst which water based emulsions are most popular. Water based emulsions have a confluence of the beneficial properties of both water and oil. However, these fluids are highly susceptible to microbial contamination and can cause various health issues to the operators. Further, the fluids are not biodegradable and need treatment before disposal. This increases the maintenance and disposal cost of the fluids. In this scenario, different alternatives are being investigated. Minimum Quantity Lubrication (MQL) is one such alternative that is gaining attention recently. In MQL, very little cutting fluid is supplied, typically, about 10 ml/min. Since the supplied fluid evaporates during machining, the disposal problems do not arise. In order to obtain high performance, nanofluids are being lately used in MQL[1].

The choice of base fluid and nanoparticles decide the properties of the nanofluid. Since the basic function of the cutting fluids is to cool and lubricate the machining zone, the selected nanoparticles and base fluid must contribute in this direction. Hence, popular solid lubricants such as MoS_2, H_3BO_3 and graphite can be used in their nano form [2, 3]. Solid lubricants usually have a layered structure, wherein, the layers can slide over each other. This reduces the sliding friction, which is dominant in machining. Apart from using nano inclusions to improve the performance of the lubricants, the base oils, which are usually petroleum based, are replaced by vegetable oils. The vegetable oils have higher viscosities and smoke points, besides being non-toxic. Kumar et al. [4] investigated the efficacy of coconut oil with EP additives in MQL. It was reported that cutting forces, temperatures, wear and surface roughness were reduced with the application of coconut oil compared to the conventional lubricant. Padmini et al. [5] dispersed nano boric acid in varying concentrations in coconut oil, canola oil, sesame oil. The formulated fluids were used in machining AISI 1040 steel under MQL conditions. It was reported that cutting temperatures and tool flank wear have decreased significantly with 0.5% nanoboric acid suspensions in all vegetable oils. Among the considered oils, coconut oil based nanofluids showed better performance compared to other vegetable-based lubricant.

Though the application of nano cutting fluids is receiving attention in recent times, not many works report the environmental and sustainability aspects of these cutting fluids. Amrita et al. [6] studied the biodegradability aspects of the nano cutting fluids. However, the base fluid was regular water miscible cutting fluid, not vegetable based. In addition, quantitative analysis of sustainability and environmental effect is not discussed. Rajemi et al. [7] tried to optimize the cutting conditions for sustainable machining. Power consumption was taken into account, but complete cradle to grave analysis of materials was not done. Some works study the sustainability aspects using quantitative methods [8, 9]. However, the works do not consider nanofluids. Bell et al. [8] quantified the environmental effects of cutting fluids by studying temperature rise due to evaporation and spin/flash of the fluid. Though the work tries to quantify the effects, it does not consider the carbon footprint of production and use of the materials. Li et al. [9] calculated the carbon footprint of dry machining and machining with cutting fluids. Production of materials and processes were considered in the study. However, nanofluids were not considered. With the promising results obtained by using nano fluids and the increasing interest in nanofluids, it is the need of the hour to study the sustainability of these fluids in MQL Since, the production of nanofluids is an energy intensive process, it is important to know the carbon footprint of using the fluids in order to justify their application. The present work experimentally tests the applicability of the vegetable oil based nanofluids in machining of AISI 1040 steel under MQL and evaluates the carbon footprint of the process to study the sustainability of the fluids. The highlight of the work lies in doing a comprehensive carbon footprint calculation of machining using vegetable oil based nano cutting fluids, which is not found in literature.

ISBN: 978-93-80689-28-9

2. MATERIALS & METHODS

Machining was carried out on a precision lathe by turning AISI 1040 steel under different lubricating environments. The details of machining are presented in Table 1

Table 1: Experimental conditions

Machine tool	Precision Lathe, Magnum make, 3Hp
Workpiece material	AISI 1040 steel (Ø40 mm, 458 mm)
Hardness of workpiece	30±2 HRC, cold rolled)
Tool holder	PCLNR 2525M12
Cutting tool	CNMG120408NC6110 uncoated carbide
Cutting conditions	
Cutting speed	80 m/min
Feed rate	0.161 mm/rev
Depth of cut	1mm
Lubrication environment	Dry, flood cooling, MQL (nano fluid)
MQL flow rate	10mL/min
Flood cooling flow rate	24L/hr
Base fluid	Water+ coconut oil
Surfactant	Triton x100
Duration of machining	5min
Nanoparticle	Boric acid
Concentration of nanoparticle inclusion	0.25%
Measurements	Force, temperature, tool wear, surface roughness

In the present work, the base fluid was prepared with 10% of coconut oil, 0.1% of Triton X100 and remaining water. Boric acid nanoparticles with average size of 90nm were procured from the market. The nanoparticles were dispersed in the base fluid by sonicating for 1 hour. The concentration of the particles was maintained at 0.25%. The prepared fluids were tested for stability using the sedimentation test and were then applied in machining.

3. RESULTS & DISCUSSIONS

Machining was carried out at constant cutting conditions as shown in Table 1. Machining was done under MQL using the nanofluids, flood cooling and dry machining. In order to assess the performance of the formulated fluids, cutting forces, temperatures, surface roughness and tool wear were monitored. Flood lubrication and dry machining were also carried out for comparison. The results are presented in table 2.

3.1 Cutting Forces

Cutting forces are influenced by the friction in the tool-chip interface. Hence, monitoring the cutting forces gives information about the lubricating properties of the cutting fluid. In the present work, cutting forces were measured using piezoelectric dynamometer (Make: Kistler, Model: 9272). It can be seen that dry machining has the highest forces, followed by the flood lubrication. MQL gives rise to the least force. It is because of the better ability of the pressurized cutting fluid jet to reach the chip/tool interface. In flood lubrication, the chances for the fluid to reach the zone are limited. The cutting fluid will be able to reach the chip/tool zone if the pressure of the jet overcomes the opposing force of the chip [10]. As MQL is supplied with high pressure, the fluid can penetrate into the zone. This increases the shear plane angle and makes it easier for the chip to get separated from the tool, thus reducing the cutting forces. With the addition of nano boric acid, the lubricity of the fluid increased. Boric acid has a layered structure. The layers are held by weak Vander Waal's forces that allow easy sliding of the layers, thus reducing friction. Further, the saturated fatty acids of coconut oil help in forming a consistent and stable lubricating layer [11]. Among all the considered lubricating environments, application of nano cutting fluid reduced the force by 14..28 % and 6.38% compared to dry machining and flood cooling respectively.

Table 2: Machining results

Type of lubrication	Main cutting force, N	Cutting temperature, ^{o}C	Tool wear, mm	Surface Roughness, μm
Dry	499	225	0.16	2.79
Conventional cutting fluid	457	179	0.15	2.45
Nano cutting fluid	427	190	0.14	2.1

3.2 Cutting temperatures

Cutting temperatures are typically obtained due to the friction between the tool and chip at the secondary shear zone. Hence, it is important to know the cutting temperatures in order to assess the performance of a cutting fluid. In the present work, cutting temperatures were measured using an infrared thermometer (Fluke Ti200). Since it is difficult to precisely measure the temperatures at the cutting zone, due to the flow of the chip, a nodal point was considered. The highest temperatures measured at this point were used for comparison. Due to the absence of any cooling mechanism, cutting temperatures are very high in dry machining. This is followed by MQL and flood cooling. It is interesting to note that while nano cutting fluids outperformed the flood lubrication in terms of cutting forces, it is the other way in terms of cutting temperatures. Usually, the generated heat in machining is carried away by the cutting fluid mainly due to conduction. However, as explained above, MQL has better chances to reach the tool/chip zone due to the high pressures of the jet. Nevertheless, the temperatures obtained in the primary shear zone are not effectively conducted by the small amount of the lubricant in MQL. Further, the nano particle added in the present work is boric acid, which does not have very high thermal conductivity like the metallic oxide or graphite nano particles. However, it can be noted that the temperatures in MQL are about 5% higher than the flood lubrication temperatures.

3.3 Tool flank wear

In order to study the performance of the cutting fluids, tool wear was studied under an optical microscope (Olympus, Model: GX1) after each turning operation. It can be seen from the results that tool wear was high in dry machining, followed by flood lubrication and least for MQL. Since dry machining does not have any lubricating or cooling aid, the tool is worn out quickly. In case of flood lubrication, though the temperatures are lower than MQL, the cooling is mainly due to conduction and does not reduce the temperature produced in the shear zones, which has a serious effect on the life of cutting tool. On the other hand, the MQL helps in forming a lubricating film at the secondary shear zone, which significantly reduces adhesion and diffusion forms of tool wear. Solid lubricant particles reach the tool/chip interface and decrease the plastic contacts, reducing tool wear. In the present work, MQL reduced the tool wear by about 13.5% and 6% compared to dry machining and flood lubrication.

3.4 Surface roughness

The quality of the product is characterized by the surface finish. In the present work, surface roughness of the machined part was measured using a surface roughness tester (Make: Mahr, Model: MahrsurfM400). Similar to tool wear, highest surface roughness was obtained for dry machining followed by flood cooling and least roughness was obtained for MQL. Better lubrication in MQL helps to reduce the friction and hence, the surface roughness. Compared to dry machining and flood cooling, surface roughness reduced by 24.74% and 14.28% respectively in case of MQL.

It may be observed that MQL with nano cutting fluids gave satisfactory performance in machining and is superior to flood cooling or dry machining. However, the sustainability of the coolants, especially in MQL, is not explored in literature. Hence, the carbon footprint for all the three forms of machining is computed in the present work.

4. CARBON FOOTPRINT CALCULATIONS

Sustainability of a product/process is estimated by its carbon footprint. This involves the cradle to grave analysis of the product/process and the impact at each stage on the environment is expressed as carbon emission. In this section, total carbon emission generated by the machining process is presented for each lubricating condition. The basic equations are taken from the literature [9] and are adapted to suit the present work Carbon emission due to the machining process is expressed as:

$$CE_{cms} = CE_{elec} + CE_{coolant} + CE_m + CE_{tool} + CE_{chip} \qquad (1)$$

CE_{cms} = Generated carbon emission in the conventional machining system
CE_{elec} = Generated carbon emission by generating the electricity while processing the machining operation
$CE_{coolant}$ = carbon emission by usage of coolant
CE_m = carbon emission due to raw material
CE_{tool} = carbon emission due to production of tool
CE_{chip} = carbon emission by generation of chips in machining
Carbon emission occurred due to electricity used by lathe is:

$$CE_{elec} = CEF_{elec} \times EC_{machine} \qquad (2)$$

Where CEF_{elec} is the carbon emission factor of the generating electricity, taken from Li et al,(2015) as 0.6747 kg CO_2 /KWh.

$EC_{machine}$, energy consumption of the lathe during dry machining is given by:

$$EC_{machine} = P_u (t_{idle} + t_c) + P_c \times t_c + P_a \times t_c$$
$$= P_u (t_{idle} + t_c) + P_c \times t_c \qquad (3)$$

Error! Reference source not found.$CE_{tool} = t_c \times (CEF_{tool} \times M_{tool}) / T_{tool}$ (4)

Where t_c is the cutting time of tool in seconds, T_{tool} is the life of the cutting tool in seconds taken as 1214s, 1320s, 1504s in the present work for Dry, flood coolant, nanocutting fluid by MQL. CEF_{tool} is the tool carbon emission factor in Kg.CO_2/Kg; M_{tool} is the mass of the cutting tool.

$$CE_m = CEF_m M_{chip} \qquad (5)$$

Where CEF_m **Error! Reference source not found.**is the carbon emission factor of raw material scrap in Kg CO_2/Kg.

M_{chip} is the mass of the removed material in kg. CEF_m **Error! Reference source not found.** chosen in this study is 2.69 Kg CO_2/Kg (Li et al., 2015) The mass of removed material during cutting time can be calculated as follows

$$M_{chip} = (Q \times t_c \times \rho) / 10^6 = (v \times f \times d \times t_c) / 1000$$

$$Q = 1000 \times v \times f \times d$$

Where v, f, d are the cutting speed m/min, feed rate mm/rev, depth of cut in mm.

$$CE_{chip} = CEF_{chip} \times M_{chip} \qquad (6)$$

CE_{chip} is the chip carbon emission factor taken from Li et al. (2015). $EC_{machine}$, energy consumption of the lathe during machining by using conventional cutting fluid is given by:

$$EC_{machine} = P_u (t_{idle} + t_c) + P_c \times t_c + P_p \times t_c \qquad (7)$$

Where P_c, P_p is the power of cutting and power of fluid pump for supply conventional cutting fluid.**Error! Reference source not found.**

$$CE_{coolant} = (T/T_{coolant}) \times (CE_{oil} + CE_{wc}) \qquad (8)$$

Where $T = t_c + t_{idle}$

$$CE_{oil} = CEF_{oil} \times (S+K)$$

$$CE_{wc} = CEF_{wc} \times ((S+K) / C)$$

CE_{oil}, CE_{wc} the carbon emission of oil, cutting fluid waste, CEF_{oil}, CEF_{wc} are the carbon emission factor of the oil and disposal of the cutting fluid. S, K is the initial and remaining amount of the cutting fluid in replacement cycle. C is the concentration of oil in water. In the present work CEF_{oil} and CEF_{wc} value was taken from Li et al 2015. i.e. 2.85 Kg.CO_2/L and 2.85 Kg, CO_2/L respectively.

In the present work **Error! Reference source not found.**and**Error! Reference source not found.** values were taken from Li et al 2015. i.e. 2.85 kgCO_2/L, 0.2Kg CO_2/L respectively. For nanocutting fluid energy consumption can be expressed as:

Energy consumption = $P_u (t_{idle} + t_c) + P_c \times t_c + + P_s \times t_1$ (9)

Where P_s was the power consumption of sonication for nano coolant and t_1 be the sonication time of nano coolant

Error! Reference source not found.$CE_{nano\ coolant} = (T/T_{nano\ coolant}) \times \{(CEF_{bf} \times (S+K)) + (CEF_{np} \times M_{np})\}$ (10)

Where, $CEF_{bf} = CEF_{w+} CEF_{cc\ oil}$
$T_{nano\ coolant}$ is the life of the nano coolant, **Error! Reference source not found.**is the carbon emission factor of water, coconut oil. i.e.0.04 Kg.CO_2/litre,1.9Kg.CO_2/kg. **Error! Reference source not found.Error! Reference source not found.**$_{np}$ is carbon emission factor of nano particle, 0.72 Kg.CO_2/ Kg, M_{np} is the weight of nanoparticle (Boric acid) (kg). Values of P_u, P_c Dry, P_c for conventional cutting fluid, P_c nanocutting fluid, P_s, P_p in (KW) are 1.84, 0.663, 0.607, .0.568, 0.1, 0.5. The carbon emissions for different lubrication environment are shown in table 3.

The carbon emission caused by electricity is higher for nanocutting fluids due to the power required for ball milling of nano particles. The carbon emission generated by the chip, workpiece material is constant for all lubrication environments. However, since tool life is highest with nanocutting fluids, carbon emission due to tools is less. The total carbon emission generated is least for nanocutting fluid while it was highest for conventional cutting fluid.

Table3: Carbon emissions for different lubricating environment

Lubrication environment	CE_{elec}	$CE_{coolant}$	CE_{tool}	$CE_{material}$	CE_{chip}	Total
Dry	0.161	0	0.0575	1.226	0.1650	1.60
Conventional Cutting fluid	0.19	0.0067	0.0529	1.226	0.165	1.64
Nano cutting fluid	0.18	0.0006	0.049	1.226	0.165	1.62

5. CONCLUSIONS

The following conclusions may be drawn from the present work.

Significant reduction in main cutting force, surface roughness, tool flank wear was observed with the application of nanocutting fluids. Cutting force reduced by 14.28% compared to dry machining and 6.38% compared to conventional cutting fluid. While surface roughness reduced by 24.74% & 14.28% and tool wear by 3.5% & 6% respectively.

Cutting tool temperature obtained in dry machining was very high because of absence of the cutting fluids then followed by nanocutting fluid and conventional cutting fluid. It is observed that highest amount of carbon emissions occur in flood lubrication, followed by nanocutting fluids. Least emissions were obtained for dry machining.

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