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Performance Investigation of Eco-Friendly Nano Cutting Fluids in Turning Operation of Stainless Steel Billet.

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ABSTRACT

Mineral oil based coolants have been used as a cutting fluid in metal cutting operations for over generations. However, its lack of biodegradability and the potential to affect the operator's health instigated the need for alternative cutting fluids and several studies have already investigated the performance of vegetable oil based cutting fluids in metal cutting operations. In the present study, the influence of different nano-cutting fluids on the machining parameters during turning operation of stainless steel billet was investigated. An improved quality of work piece and reduced cutting temperature was resulted by application of vegetable oil based nano-cutting fluids, compared to that obtained by application of plain vegetable oil cutting fluids.

Keywords: Metal Cutting Operations, Nano-Cutting fluids, Vegetable oil, Cutting Temperature, Surface Roughness

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INTRODUCTION

Metal cutting operation involves, high temperature zone at shear plane by virtue of friction between the tool-work and tool-chip interface. This temperature rise is undesirable and may cause failure of cutting tools and formation of micro-cracks. To overcome this, cutting fluids are used in metal cutting operations. Cooling and lubrication are the important functions of cutting fluids. Mineral oil based cutting fluids are most commonly used in metal cutting operations in different forms as straight oil, synthetic oil and semi-synthetic oil. However, these classes of cutting fluids are non-biodegradable and pose threats to the environment either during use or after use during their disposal. In addition to this, long term exposure to these cutting fluids may lead to respiratory diseases, cancer and skin diseases [1,2]. To overcome these problems and taking the renewability factor into consideration, vegetable oil emerged as an alternate to mineral oil based cutting fluids. These are also biodegradable and therefore do not pose any threat both to the environment and the operator working with that machine. The chemical composition of vegetable oil is constituted by the combination of fatty acids with glycerol. The long chain fatty acids present in the vegetable oil are responsible for its better lubricating properties compared to mineral oil based cutting fluids, which in turn is responsible for the reduced wear and friction between the tool and the work piece [3]. Various studies have already investigated the effect of different vegetable oils such as rapeseed oil, canola oil, coconut oil, mustard, palm oil, ground nut oil in metal cutting operations and have reported positive results. Antony et al.,[4] stated that application of coconut oil during turning of AISI 304 stainless steel produced an improved surface finish and a reduced tool wear when compared to the same while application of mineral oil. Belluco et al.,[5] reported 177% increase in tool life and 7% reduction in thrust force was resulted by using vegetable oil as cutting fluid when compared to the values obtained by usage of plain mineral oil during drilling operation. Scientists like Huseyin et al.,[6], Rohit et al., [7], Ujjwal et al., [8] have also investigated the performance of different vegetable oil based cutting fluids in machining processes and have compared it with that of mineral oil based cutting fluids. However due to the poor thermal stability and oxidative stability of Vegetable Oil based cutting fluids, there arose a need for anti-wear and extreme pressure additives to cope with the complexity of modern machining processes [9]. Due to the replacement of 'Minimum Quality Lubrication' by flood type lubrication it is necessary that the cutting fluid possesses improved operational characteristics [10].Recently nanomaterials have emerged aspotential additives in improving the lubricating and heat transfer properties of conventional lubricant. Nanofluids are stable dispersions of nanoparticles into a base fluid. The commonly used base fluids are water, oil and ethylene glycol. Various studies have already been carried out by dispersion of different nanoparticles into different cutting fluids including mineral oils and vegetable oils in different forms. Vamsi et al.,[11] and Prasad et al.,[12] studied the effect of inclusion of nanoboric acid suspensions and nanographitein coconut oil and water soluble mineral oil respectively during turning of AISI 1040 steel. Shrikant et al., [13] stated that dispersion of nano alumina powder in vegetable oil produced an improved surface roughness and a reduced cutting temperature during turning of EN353 steel when compared to the surface roughness and cutting temperature produced by application of plain vegetable oil. The present study involves preparation of vegetable oil based nano-cutting fluids prepared by dispersing 0.01 vol% of nano TiO_2 and a mixture of 0.01 vol% of alumina nano powders of average (particle size 50nm, 0.01 vol% of ZnOnano powder in the groundnut oil and the coconut oil. The desirable functional properties of the prepared nano-cutting fluids such as the thermal conductivity, viscosity, density, kinematic viscosity were evaluated and were compared with those of the plain oil samples. In addition to this, inorder to experimentally investigate the effect of dispersion of nanoparticles into the vegetable oil, a turning operation was carried out by the application of the nano-cutting fluids, by varying the process parameters and the characteristics of the workpiece such as the surface roughness, the cutting temperature and the tool wear were noted. The results show that, better quality of the workpiece is resulted by the application of vegetable oil based nano-cutting fluids compared to the quality of the workpiece resulted by the application of plain oil samples. In addition to the improvement obtained in the lubrication properties, the usage of nano cutting fluids allows the execution of machining processes in Minimum quantity lubrication (MQL).

Drawbacks of Previous Studies and Suitable Remedies

The major problems were the high cost of nanomaterials and the loss of stability of the prepared nanolubricant along its service. Though surfactants were used to solve the problem of coagulation, the usage of surfactants resulted in the formation of lathers. This in turn affects the heat transfer properties of the nanofluids at higher temperatures, as stated by Xiang et al [14]. In the present study, an attempt was made to overcome this problem by using a very small volume fraction of nanomaterials. This makes the process cost effective. Also coconut oil and ground nut oil naturally exhibits excellent solvency for additives [3], and so the coagulation could be avoided without the usage of surfactants.

METHODS AND MATERIALS

Materials

Nanomaterials

The nanomaterials chosen were Alumina nanopowder, Zinc oxide nanopowder and Titanium dioxide nanopowder and were purchased from Sigma Aldrich and Siscon laboratories, the properties of whose are detailed in Table 1.Based on the results of previous studies, it is evidential that alumina nanomaterials possess good heat transfer properties, Zinc oxide nanomaterials and Titanium dioxide nanomaterials possess good lubricating properties.[15,16,17]

Table 1: Properties of various Nano-materials

Nanomaterial	Properties
Aluminium oxide (Al_2O_3) (α-type)	Appearance - Ivory powder Assay > 98% *APS < 50nm
Zinc Oxide (ZnO)	Appearance - White Powder Assay > 98% *APS < 100 nm
Titanium dioxide (TiO_2)	Appearance - Powder Assay > 98% *APS - 30 to 50 nm

***APS – Average Particle Size**

Tool and Work Piece

Stainless Steel - AISI 304 rod was the material chosen to be machined. Each work-piece was of 25mm diameter & 110mm length. The cutting tool used for turning the workpiece was single point Tungsten-Carbide tip tool where in tip is brazed to the tool shank. The hardness values of the workpiece and the tool, the tool signature are detailed in Table 2.

Table 2: Hardness values of work-piece and tool used

Materials	Hardness
Tool – Tungsten Carbide tip tool	92 HRB
Workpiece – AISI 304	940 HV

Tool signature is 0-7-6-8-15-16-0.8

Preparation of Nano-Cutting Fluids

Straight Coconut oil and Ground nut oil sample was the base cutting fluids in the present investigation. As of now, both coconut oil and ground nut oil are available in abundance (natural). Nano-cutting fluids were prepared by the two step preparation process. The first step involved addition of nanomaterials to a basefluid and the second step involved stirring for a suitable amount of time followed by ultrasonification using an ultrasonic agitator. The composition of each sample of prepared nanolubricant is mentioned in Table 3.

Table 3: Amount of nano-particle used across the various samples prepared

Sample	Base oil	Nanoparticle Composition

Sample 1	Coconut oil	0.01 vol. % Al_2O_3 + 0.01% vol. % ZnO
Sample 2	Groundnut oil	0.01 vol. % Al_2O_3 + 0.01% vol. % ZnO
Sample 3	Coconut oil	0.01 vol. % TiO_2
Sample 4	Groundnut oil	0.01 vol. % TiO_2

Measurement of Thermal Conductivity

Thermal conductivity of plain Vegetable oils, the nano-cutting fluids were measured using an instrument called KD 2 Pro at the National Institute of Technology, Trichy. KD 2 Pro works on the principle of transient line heat source method. The instrument has three sensors among which the TR-1 sensor is used for measuring thermal conductivity. The instrument consists of a platinum coated needle probe that is dipped into the samples to determine their thermal conductivity.

Measurement of Viscosityand Flash Point

The cutting fluid should exhibit such properties that makes it retains its viscosity without much loss throughout its operating period and with increasing temperature. The viscosity of the lubricant must be in an optimum range because usage of a high viscosity lubricant may lead to power loss and usage of a low viscosity lubricant reduces the lubricating effect of the cutting fluid causing excessive tool wear. Kinematic viscosity of the plain vegetable oil and the nano-cutting fluids were measured using redwood viscometer at the temperatures 30°C and 100°C.The flash point of the nano-cutting fluid and plain vegetable oil was measured by using Pensky Martens closed cup apparatus.

Machining

General purpose lathe was preferred for carrying out turning operation because it offers manual control over machining parameters. Prior to machining, tool was grinded using a green Silicon Carbide wheel running at 1400 rpm to sharpen the rake face, side cutting edge, and flank side. All the plain and nano-cutting oil samples were filled in a dripper setup. The flow rate was set at 10ml/min. by using the control slider adjusted by closing/opening the tube. End of tube was located 6cm above the Head stock of lathe such that the drop falls precisely on tool, chip, workpiece contact point all the time during machining and the end tube was moved gradually as the carriage wheel moved towards headstock while giving feed.This was done automatically by engaging the half-nut with rotating spindle rod in Carriage wheel side during turning the workpiece for 4.5 cm measured from end face towards spindle. Spindle speed was set to 407 rpm and 625rpm by adjusting the lever on Head stock side. A constant feed of 0.01 mm/rev was chosen. 0.25 mm, 0.5 mm, 0.75 mm were chosen to be the depth of cut for all the six experiments as shown in Table 4.

Table 4: Experimental parameters (Machining parameters) for each cutting fluid

Speed (rpm)	Depth of cut (mm)	Experiment
407	0.25	1
	0.5	2
	0.75	3
625	0.25	4
	0.5	5
	0.75	6

For each spindle speed, three depths of cut were to be machined. Temperature of workpiece was measured using a non-contact infrared thermometer. An infrared thermometer is a thermometer which infers temperature from a portion of the thermal radiation emitted by the object being measured. After completion of the operation, the Surface roughness was measured by using “Mitutoyo” Surface roughness tester. This entire process was repeated for all the six oil samples. While moving on to next oil Sample care was taken to clean the dripper setup completely to avoid mixing of nano particles from previously used sample. The tool was also re-grinded to eliminate the error which could be potentially caused by tool wear.

RESULTS AND DISCUSSION

Thermal Conductivity

Mechanisms such as Brownian movement, thermophoresis and diffusiophoresis, are responsible for increase in thermal conductivity of a solvent when a solute is added to it [17]. When nanoparticles are dispersed in a solvent, the unique surface properties of the nanoparticles further accelerates the Brownian movement in the dispersion resulting in excellent heat transfer properties of the resultant dispersion. From Table 5 it can be inferred that, dispersion of alumina nanopowder and ZnOnano powder produced the highest enhancement in the thermal conductivity of the base oils, by increasing the value by 27.3% in the case of coconut oil and 34.3% in the case of ground nut oil. The excellent heat transfer properties of nano-alumina accounts for such significant enhancement in the thermal conductivity. Dispersion of Titanium dioxide nanopowder produced a thermal conductivity enhancement of about 13.66% in coconut oil and about 13.55% in groundnut oil.

Table 5: Thermal Conductivity value measured for various samples,along with base oil

Samples	Thermal Conductivity (W/mK)
Plain Coconut oil	0.161
Plain Groundnut oil	0.172
Sample 1	0.205
Sample 2	0.231
Sample 3	0.183
Sample 4	0.199

Kinematic Viscosity

Based on the observations from Figure 1, the following can be concluded. Plain Ground nut oil exhibited a higher kinematic viscosity compared to plain coconut oil. Dispersion of Titanium dioxide nanoadditives produced the maximum enhancement in the Kinematic viscosities of the base oils. Sample 3 exhibited a kinematic viscosity of 12.3 cSt at 100^{o}C which is about 81.9% higher than the kinematic viscosity of plain coconut oil at 100^{o}C. Similarly, Sample 4 exhibited a kinematic viscosity of 16.6 cSt at 100^{o}Cwhich is about 87% higher than the kinematic viscosity of plain ground nut oil at 100^{o}C. Increased values viscosity are responsible for the increased lubricating properties which in turn will result in better quality of work and improved lifetime of the tool.

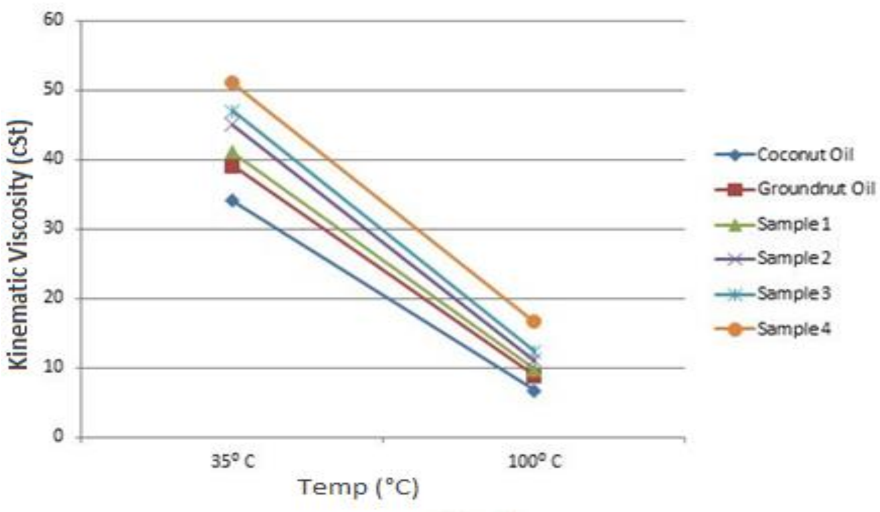

Figure 1: Graph depicting Kinematic viscosity of lubricants at 35^{o}C and 100^{o}C

Flash Point

From Figure 2, it can be concluded that plain ground nut oil exhibits a higher flash point compared to plain coconut oil, dispersion of Alumina and Zinc oxide nanopowder produces substantial improvement in the flash point of the oil samples compared to the improvement produced by dispersing Titanium dioxide nanopowder. Though the flash point of ground nut oil based samples are higher than the flash point of coconut oil based samples, the ground nut oil based samples exhibit a lower smoke point compared to that of coconut oil based samples. Lower smoke point paves way for production of smoke at lower temperature compared to coconut oil based samples.

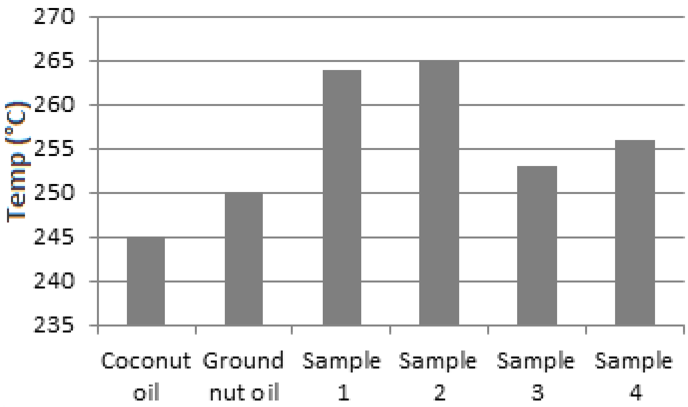

Figure 2: Flash point determination of prepared samples and base oil

Machining

Effect on Cutting Temperature

In accordance to the results of thermal conductivity analysis discussed in Section 3.1, application of plain ground nut oil in the machining of stainless steel results in a lesser cutting temperature compared to the same produced by application of plain coconut oil.

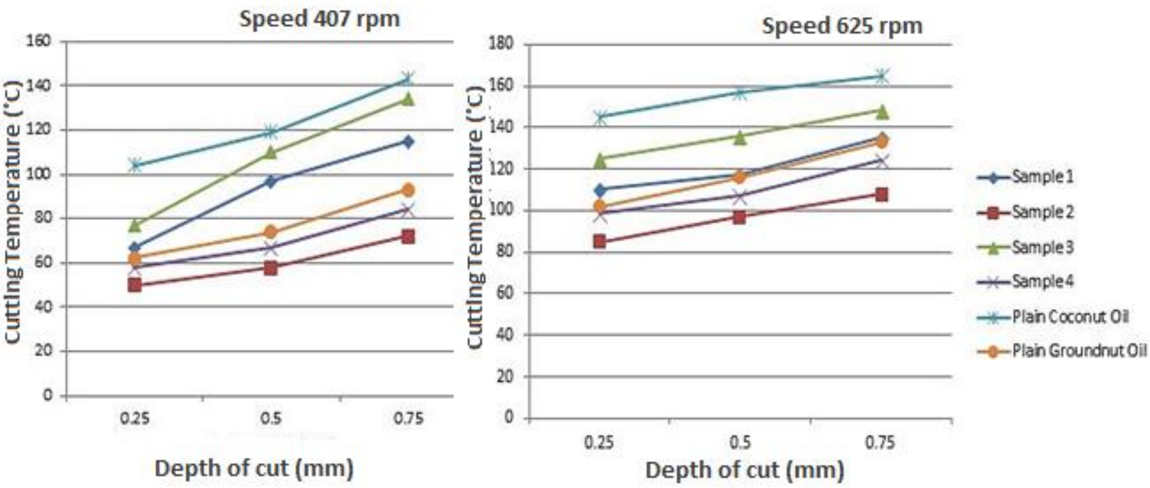

Figure 3: Cutting temperature at various depth of cuts

From Figure 3 it can be inferred that, of all the nanocutting fluid samples, Sample 3 produced the least cutting temperature. In addition to this, application of Sample 1 i.e., coconut oil containing a mixture of Alumina and Zinc oxide nanopowders yielded a lower cutting temperature compared to that produced by application of Sample 3 i.e., coconut oil containing Titanium dioxide nanopowder. Similarly, application of

Sample 2 i.e., groundnut oil containing a mixture of Alumina and Zinc oxide nanopowders yielded a lower cutting temperature compared to that produced by application of Sample 4 i.e., ground nut oil containing Titanium dioxide nanopowder for all the speed and depth of cut of machining. Lesser cutting temperature in machining lessens the frequency of formation of microcracks and failure of cutting tool.

Effect on Surface Roughness

In accordance to the results of kinematic viscosity discussed in Section 3.2, application of plain ground nut oil produced a lower value of surface roughness of the work when compared to the surface roughness obtained by application of plain coconut oil during machining. As expected, Sample 4 i.e., groundnut oil containing titanium dioxide nanoadditives yielded a better surface finish compared to the same yielded by application of Sample 2 i.e., ground nut oil containing mixture of alumina and Zinc oxide nanopowder. Sample 3 i.e., coconut oil containing titanium dioxide nanoadditives yielded a better surface finish compared to the same yielded by application of Sample 1 i.e., coconut nut oil containing mixture of alumina and Zinc oxide nanopowder. (Figure 4)

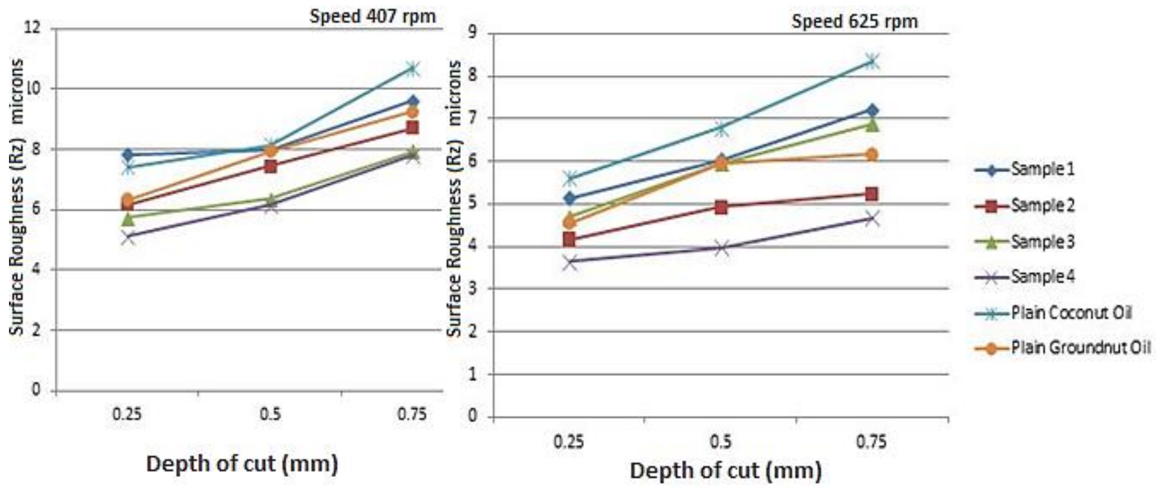

Figure 4: Surface roughness analysis of machined surface, plotted for set parameters on lathe

CONCLUSIONS

The experimental study investigated the performance of different vegetable oil based nano-cutting fluids and their influence on the machining parameters in the turning operation of AISI 3040 stainless steel. Based the observations, following can be concluded:

1. Plain Ground nut served both as a better coolant and lubricant when compared to coconut oil based cutting fluid samples
2. Dispersion of a mixture of 0.01 vol % of alumina and 0.01% Zinc oxide nanopowder produced a substantial improvement in the thermal conductivityupto34.83% increase for sample 2 to that of the base oil and therefore oil containing these nanopowders can serve as good coolants
3. Dispersion of 0.01 vol% of titanium dioxide nanopowder produced a substantial improvement in the kinematic viscosity of the base oil and therefore oil containing titanium dioxide nanopowders can serve as good lubricants

Thus the study recommends the usage of vegetable oil based nano-cutting fluids as an effective replacement to plain vegetable oil samples to cope up with the severity and complexity of modern machining processes.

But in present situations harnessing edible oils as cutting fluids restricts the use due to increased demands catering the growing population worldwide and local availability. Non-edible vegetable oils and other tree borne seeds can prove to be an effective alternative for edible vegetable oil especially in a tropical country like India and more further studies are to be carried out in-order to investigate the performance of nonedible vegetable oil based cutting fluids for application in machining operations.

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