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Experimental investigation on the application of vegetable oil based nanofluids in machining

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ABSTRACT

The need for eco friendly alternatives to conventional cutting fluids arises because usage of conventional cutting fluids poses threat to ecology and health of workers. The present work focuses on performance of nano solid lubricant suspensions in vegetable oils in turning of AISI1040 steel in minimum quantity lubrication(MQL). Soyabean, canola and coconut oils are taken as base lubricants with suspensions of 100nm sized boric acid particles. These particles are characterized by X-Ray Diffraction (XRD) and particle size analyzer to confirm their purity and particle size. Variation of basic properties like thermal conductivity, specific heat and heat transfer coefficient are evaluated from empirical relations, to check the viability of nano lubricants in machining. Variation of cutting tool temperatures, average tool flank wear and surface roughness of the machined surface with cutting speed and feed are studied with the prepared nano lubricants. Results are encouraging and coconut oil seems to be more advantageous compared to other vegetable oils.

1.Introduction

During machining, friction between the tool and work piece gives rise to high temperatures. Dimensional accuracy and surface quality of the work piece are highly influenced by these temperatures. In this context, cutting fluids play the dual role of lubricants and coolants by reducing the friction between tool-work piece, tool-chip interface through effective lubrication and by controlling the machining temperatures respectively. Environmental pollution, dermatitis to operators, soil contamination during disposal and water pollution are the adverse effects of application of conventional cutting fluids [1, 2]. Despite their widespread use, they pose significant health and environmental hazards throughout their life cycle. It is reported that about 80% of all occupational diseases of operators in manufacturing industry were due to skin contact with cutting fluids [3–7]. In USA alone about 700,000 to one million workers were exposed to cutting fluids [8]. As cutting fluids are complex in their composition, they may be irritant or allergic. Even microbial toxins are generated by bacteria and fungi present, particularly in water-soluble cutting fluids [9], which are more harmful to the operators. Further, the cutting fluids also incur a major portion of the total manufacturing cost. All these factors prompted investigations into the use of biodegradable coolants or coolant free machining.

To overcome these challenges, various alternatives to petroleum-based cutting fluids are currently being explored by scientists and tribologists. Such alternatives include dry machining, coated tools, cryogenic cooling, minimum quantity lubrication (MQL), synthetic lubricants, solid lubricants and vegetable oil based lubricants. Solid lubricants are highly attractive substitutes for petroleum-based oils because they are environmental friendly, less toxic and readily biodegradable. Many investigations are in progress to develop new solid lubricant based lubricant systems around the world. By their higher biodegradability and lower environmental impact the use of vegetable oil in metalworking applications may alleviate problems faced by workers, such as skin cancer and inhalation of toxic mist in the work environments.

2. Literature Review

Many researchers have been working to achieve eco-friendly sustainable manufacturing. Solid lubricants like boric acid, MoS_2, graphite, etc. were used in machining applications as alternative to cutting fluids. Shaji and Radhakrishnan [10-12] investigated the effect of graphite, CaF_2, BaF_2 and MoS_2 in grinding at various cutting conditions. The tangential force and surface roughness were lower and normal force was higher compared to those in the conventional grinding. But, wheel clogging is major hindrance in obtaining more desirable results. Then investigations on solid lubricant moulded grinding wheels by including lubricant in the wheel structure during the moulding stage were tried [13]. Normal force and tangential force obtained were lower due to the frictional effects. Reduction in cutting forces is more in case of CaF_2 resin bonded wheels compared graphite wheels. Specific energy is reduced at lower feeds, where as it converges to more or less the same value at higher feeds. Wheel wear is lower in CaF_2 moulded wheels; surface roughness is not improved with resin bonded wheels because of increased wear of the resin bonding. Reddy and Rao [14] reported that graphite and MoS_2 assisted end milling process showed considerable improvement compared to machining with a cutting fluid in terms of cutting forces, surface quality and specific energy. In another work, graphite was used as a solid lubricant to reduce the heat generated at the milling

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zone [15]. The remarkable reduction of cutting force, specific energy and surface roughness is observed.

Jianhua et al [16] studied the friction coefficient at the tool-chip interface in dry cutting of hardened steel and cast iron with an Al_2O_3/TiC/CaF_2 ceramic tool and reported reduction in friction coefficient with the addition of CaF_2 solid lubricant. Rao and Singh [17] studied the use of solid lubricants during hard turning while machining bearing steel with mixed ceramic inserts at different cutting conditions and tool geometry. Results showed 8 to 15% improvement in the surface finish with the use of solid lubricants. Suresh et al [18] investigated the applicability of solid lubricant in turning AISI 1040 steel using coated carbide inserts. Surface roughness and chip thickness ratio were reduced in solid lubricant assisted machining process compared to wet machining in all the test conditions. Krishna and Rao [19-21] used boric acid during turning of AISI1040 steel using HSS and carbide cutting tools. Boric Acid improved the process performance by reducing the cutting forces and tool wear, surface finish was also improved. Machining performance was improved with reduced particle size while using dry solid lubricants. They also reported improvement in machining performance with boric acid suspension in SAE-40 oil.

Jianxin et al [22] made micro-holes and filled MoS_2 on the rake and flank face of the cemented carbide (WC/Co) tools to form self- lubricated tools. It was observed that the cutting forces were reduced. Self-lubricated tool with one micro-hole in its rake face possessed lower friction coefficient at the tool-chip interface; while tool with one micro-hole in its flank face revealed more flank wear resistance. Wenlong et al. [23] investigated with solid lubricant coated cemented carbide tool in machining hardened steel. The cutting forces of coated tool were decreased by 25-30%, and flank wear resistance was improved by 30-35%. Electrostatic solid lubrication system was developed to supply constant and defined amount of solid lubricant mixture to the drilling zone [24]. SAE 40 oil was chosen as the mixing medium with graphite solid lubricant and observed improvement in thrust force, tool wear, chip thickness, hole diameter and surface finish of machined work piece in drilling of AISI 4340 steel.

Ioan et al [25] presented the first experimental results on lubricating capacity of rapeseed oil. Belluco and De Chiffre [26] made an investigation on the effect of new formulations of vegetable oils on surface integrity and part accuracy in reaming and tapping operations with AISI 316L stainless steel. Cutting fluids based on vegetable oils showed better performance than mineral oils in tool life, tool wear, cutting forces and chip formation. Skerlos and Hayes [27] studied canola, soybean and rapeseed vegetable oil as cutting fluids. They demonstrated that in certain machining operations, the performance of vegetable based cutting fluids is comparable or better than that of traditional petroleum based metal working fluids. Jayadas and Prabhakaran [28] compared the cooling behavior, thermal and oxidative stabilities of coconut oil with sesame oil, sunflower oil and a mineral oil (Grade 2T oil). The thermal and oxidative stabilities were determined from the onset temperature of decomposition. Onset temperature of thermal degradation of coconut oil is lower compared to sunflower oil and sesame oil whereas the onset temperatures of oxidative degradation are comparable. It was concluded that coconut oil shows better oxidative stability in comparison to other vegetable oils that contain high percentage of unsaturated fatty acid content. Coconut oil showed comparatively lesser weight gain under oxidative environment among the vegetable oils considered. Coconut oil has very high pour point (23-25^{0}C) because of the predominantly saturated nature of its fatty acid constituents precluding its use as base oil for lubricant in temperate and cold climatic conditions.

Nano fluids have emerged as promising coolants and lubricants in many industries because of their specific properties [29]. Putra et al [30] reported that the heat transfer rates depend on the inclusion level of the nano particles in the fluids. The heat transfer characteristics of the fluids were significantly different and enhanced as compared with the conventional fluids. Wong and Leon [31] have reviewed a number of applications of nano fluids ranging from coolants in automobiles to medical devices. Krishna et al [32] investigated the affect of nano solid lubricants in turning. Boric acid particles of 50 nm particle size were used as suspensions in SAE-40 and coconut oil. Influence of solid lubricant to oil proportion on cutting temperatures, tool flank wear, and surface roughness was studied with respect to cutting conditions. Cutting temperatures, tool flank wear and surface roughness were decreased significantly. Srikant et al [33] studied the application of nano cutting fluids using CuO particle suspensions in water miscible fluids and found substantial improvement in terms of cutting temperatures. However, the work was just a simulation and lacked experimental verification of the results.

Kulkarni et al [34] investigated the properties of nanocoolants in another application than machining. Different properties of nanofluids like specific heat and thermal conductivity are calculated as given below:

$$k_{nf} = k_f \left[\frac{k_p + (n-1)k_f - (n-1)\phi(k_f - k_p)}{k_p + (n-1)k_f + \phi(k_f - k_p)} \right] \quad \text{--------} \quad (1)$$

where k_{nf} is the nanofluid thermal conductivity, k_f is the base fluid thermal conductivity, k_p is the bulk solid particle thermal conductivity, φ is the particle volume fraction, and n is an empirical scaling factor that takes into account how different particle shapes affect thermal conductivity. The effective density of nanofluids is given by:

$$\rho_{nf} = (1-\phi)\rho_f + \phi\rho_s \quad \text{--------} \quad (2)$$

where ρ_{nf} is the nanofluid density and ρ_s and ρ_f are the densities of the solid particles and base fluid, respectively. The specific heat of nanofluids, C_{pnf}, can be calculated using the standard equation based on the volume fraction.

$$C_{pnf} = \phi C_{ps} + (1-\phi)C_{pf} \quad \text{---------} \quad (3)$$

where C_{ps} is specific heat of solid particles and C_{pf} is specific heat of base fluid. With the calculated properties of nanofluids, the heat transfer coefficients were obtained. It was concluded that nanofluids have high thermal conductivities and heat transfer rates compared to the conventional fluids.

Based on the available literature, it can be concluded that suspensions of boric acid particles in vegetable or other lubricating oils, provide better lubrication compared to the conventional fluids. Further, reduced particle size provides better lubricating action. However, earlier work is limited to micro particle size or nano particle suspensions in coconut oil and SAE oil; the impact of nano particles in other vegetable oils is not studied, though nanofluids are known to be more effective coolants compared to any other suspensions or fluids. An attempt is made in the present work to investigate the affect of nano solid lubricants in turning. Boric acid particles of 100 nm particle size are used as suspensions in soyabean oil, canola oil and coconut oil and machining was carried out with varying proportions of solid lubricant suspensions i.e. 0.25%, 0.5%, and 1% by weight. Influence of solid lubricant to oil proportion on cutting temperatures, tool flank wear, and surface roughness was studied with respect to cutting conditions.

3. Experimentation

Boric acid particles of 100 nm particle size were obtained through mechanical milling with high energy ball mill. A planetary ball mill (40-400 rpm table speed) was used to produce particles in the nano scale size range. XRD analysis was done to assess the purity of the sample taken and particle size of nano boric acid particles is confirmed through particle size analyzer. Solid lubricant particles of 100 nm size were manually mixed in vegetable oils in different weight proportions at room temperature, followed by mixing with a sonicator for 1hour. In addition to these suspensions, pure vegetable oils were also used as lubricants. Experiments were conducted to evaluate the performance of nano boric acid suspensions in vegetable oils during turning. All the experiments were conducted three times and average value is taken as response value. All the cutting tests were performed on PSG-124 lathe with cemented carbide tool (SNMG 120408) and heat treated AISI 1040 steel of 30±2 HRC work piece material. Experimental details are presented in Table 1. The temperature is sensed by the embedded thermocouple. A thermocouple is placed at the bottom of the tool insert in the tool holder as shown in fig 1.

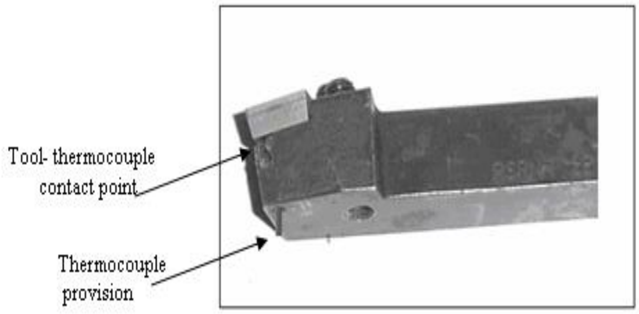

Figure 1. Tool holder with provision for thermocouple

The temperature measured by the thermocouple is only a representative figure for comparison purpose as this does not measure the cutting zone temperature. Calibration of the thermocouple is carried out in a water bath with a thermometer and a maximum of 2^0C difference is noted over a range from 40^0C to 95^0C. Cutting tool was analysed under an optical projector to measure tool flank wear. The obtained tool profiles were compared with the virgin tool profile and flank wear was determined. Talysurf with stylus radius 0.0025 mm and cut-off length 0.8 mm was employed for measuring average surface roughness (R_a). An average of three measurements was taken as a response value. The experimental setup was developed for liquid lubricant supply at the machining zone (Fig. 2). Lubricant oil with solid lubricant suspensions was stored in tank and placed above the axis of machining. Lubricant storage tank was open to atmosphere; hence flow of lubricant is due to its self weight and atmospheric pressure. Flow rate of lubricant mixture was controlled by a regulating valve. Initially lubricant mixture was collected in a vessel at different positions of the valve and flow rate is calibrated by measuring the volume of the lubricant collected in certain amount of time. In the trial tests we observed 10 ml/min flow rate is sufficient for selected cutting conditions and tool- work piece combination. Hence it is taken and flow rate is kept constant. After ensuring the flow rate of 10 ml/min, experiments were conducted.

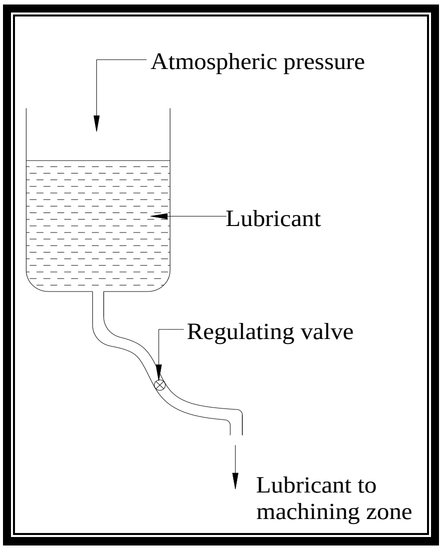

Figure 2. Lubricant supply system for supply of nano cutting fluid

4. Results and Discussion

4.1 XRD and particle size. In the present work nano boric acid particles are investigated and characterized by X-Ray diffraction technique which reveals the purity of material. XRD analysis confirms the purity of the nanoboric acid. Presence of single peak in XRD pattern symbolizes the purity of the sample as shown in fig 3. Multiple peaks in XRD graph indicate the presence of other materials in the sample considered. The purity of the sample is thus confirmed through XRD analysis. Particle size analyzer is used to determine the domain size of nano engineered boric acid particles. The particle size distribution is shown in fig 4. The average size of nano boric acid particles was found to be 100.

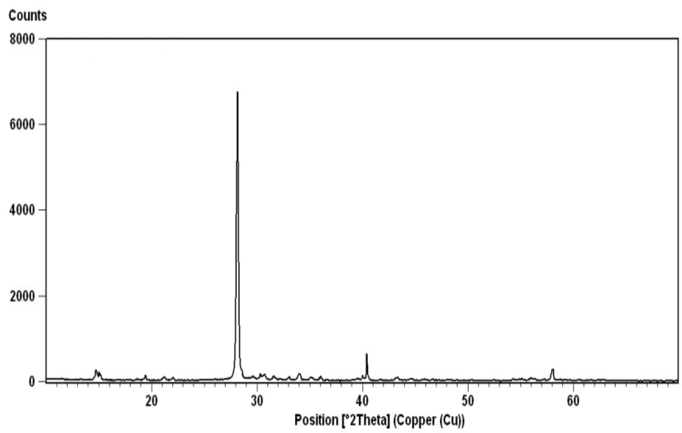

Figure 3. XRD pattern of nanoboric acid particles

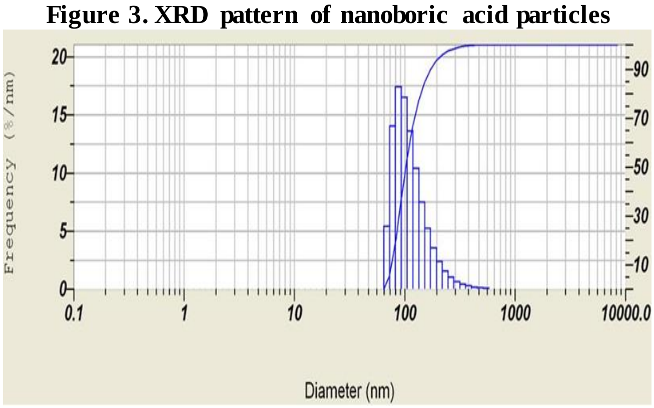

Figure 4. Average particle size of ball milled boric acid particles

4.2 Basic properties. Basic properties of nano lubricants were calculated from equations 1-3 and presented in Table 2 to understand their performance. 'n' in equation 1, was taken as 3, a value typical for spherical nano particles [34]. For calculation of heat transfer coefficient, Nusselt number, Nu, was obtained from the Hilpert equation for flow over cylinders, due to its analogy with turning process.

$$Nu= h*D/k_{nf} = C.Re^{m}Pr^{1/3} \quad \text{--------} \quad (4)$$

where, Re and Pr are Reynold's number and Prandtl number respectively, h is the heat transfer coefficient, D is the diameter of the workpiece and C & m are constants that depend on the value of Re [35].

Thermal conductivity and specific heat of nanolubricants increased slightly with percentage increase of nanoparticles compared to base oil. This is because of the high specific heat and thermal conductivity of boric acid compared to canola oil and soyabean oil. Heat transfer coefficient is also increased slightly with percentage increase of nanoparticles in base oil at specific cutting speed. However, significant improvement is observed in heat transfer coefficient with increase in cutting speed at particular quantity of nanoparticle suspensions.

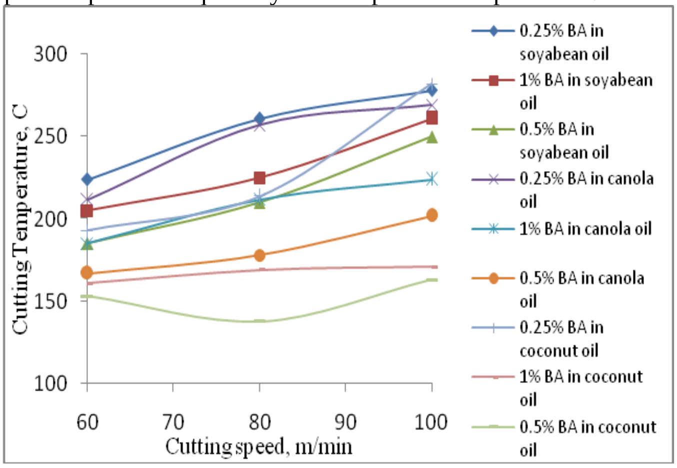

Figure 5. Variation of cutting temperatures with cutting speed

(feed= 0.2 mm/rev, d.o.c= 1 mm, time= 5 min)

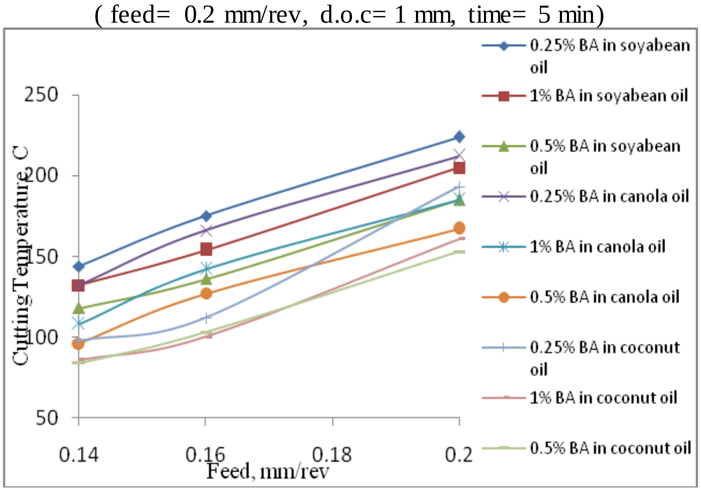

Figure 6. Variation of cutting temperatures with feed

(speed= 60 m/min, d.o.c= 1 mm, time= 5 min)

4.3 Cutting temperatures. Variation of cutting temperatures with cutting speed is presented in fig. 5. Cutting temperatures increased with cutting speed irrespective of the lubricant and cutting temperatures are less with coconut oil compared to other vegetable oils. Cutting temperatures increased with increase in feed rate at all the lubricating conditions (fig. 6). Lubricity of vegetable oils arises from the oiliness property of its constituents; and its properties are the result of long, heavy and dipolar molecules. The polar heads of the molecules have great chemical affinity for metal surfaces and attach themselves to the metal like magnets. The result is a dense, homogenous alignment of vegetable oil molecules, perpendicular along the metal surface that creates a thick, strong and durable film layer of lubricant. It can be seen from results that coconut oil suspensions are consistently better than the canola and soyabean oil suspensions. This is because of the high heat transfer coefficient of coconut oil based lubricants than the canola oil and soyabean oil based lubricants. The high lubricating property of coconut oil is due to by the fundamental composition of the molecules as well as the chemical structure of oil itself. Also, at elevated temperatures solid lubricant softens and forms a film, more over in nano level these solid lubricant particles increases the heat transfer capacity of the lubricating oil. This combined effect of coconut oil and nano solid lubricant particles is reason for reducing the cutting tool temperatures. It can be seen that though the heat transfer coefficients are not very high for either of suspensions, compared to the respective base oils, cutting temperatures reduced significantly. This may be due to reduced friction by the use of nano boric acid suspensions compared to the base oils. Among the coconut oil, lubricating oil with 0.5% nano boric acid particle suspensions performed well and same nature is exhibited by canola oil and soyabean oil with nano boric acid particles. This may be because, 0.25% boric acid cannot provide the adequate lubricating effect compared to 0.5%; 1% inclusions may reduces the flowability of the lubricant and prevents it from entering the cutting zone, thus decreasing its effectiveness.

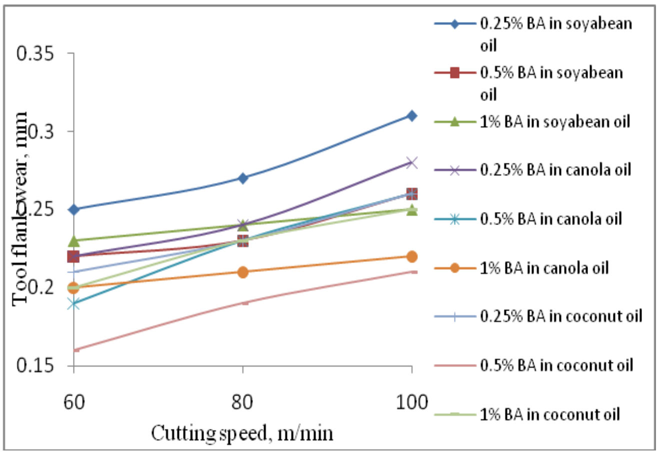

Figure 7. Variation of tool flank wear with cutting speed

(feed= 0.2 mm/rev, d.o.c=1 mm, time=5 min)

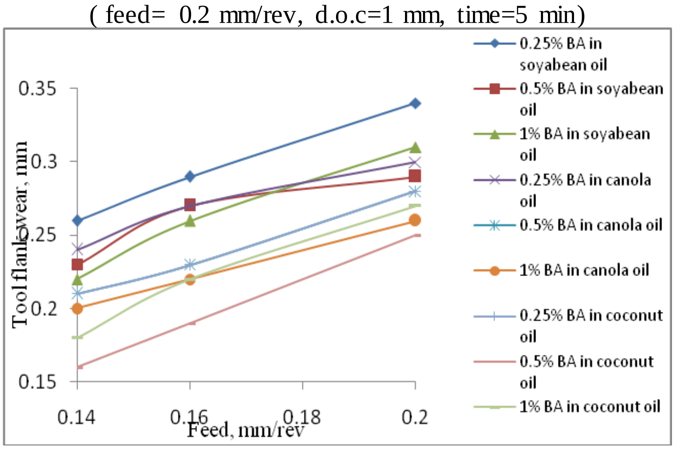

Figure 8. Variation of tool flank wear with feed

(speed= 60 m/min, d.o.c= 1 mm, time=5 min)

Table 1: Experimental conditions

Work specimen	
Material:	AISI 1040 steel (C = 0.36-0.45%, Mn= 0.6-1%, Si= 0.2-0.3%, S= 0.025%, P=0.015%)
Size (mm):	Ø70×400 mm
Hardness:	30±2 HRC, heat treated
Process parameters	
Cutting velocity,	V= 60, 80, 100 m/min
Feed rate,	S= 0.14, 0.16, 0.2 mm/rev
Depth of cut,	t= 1.0 mm
Lubricating oil:	soyabean oil, canola oil, coconut oil
Solid lubricant particle size:	100 nm
Flow rate of lubricant oil:	10 ml/min
Machine tool	
Lathe Machine:	PSG Company, INDIA
Motor capacity:	10 hp
Cutting tool (insert):	Carbide, SNMG 120408 (H-13A, ISO specification),
Tool holder:	PSRNR 12125F09 (ISO specification)
Working tool geometry	
Inclination angle:	-6^0
Orthogonal rake angle:	-6^0
Orthogonal clearance angle:	6^0
Auxiliary cutting edge angle:	15^0
Principle cutting edge angle:	75^0
Nose radius:	0.8 mm
Planetary Ball Mill	
Make:	INSMART
Number of Sample Holders:	4 Nos. on Rotating Table.
Number of Bowls:	4 Nos.
Table Speed:	40-400 R.P.M Continuously Variable
Sonicator	
Maximum Power Output:	600 W
Operating Frequency:	20 kHz
Input:	110 VAC @ 10 Amps
Programmable Timer:	1 sec to 1hr
Thermocouple	
Designation:	K type, Shielded Thermocouple.
Element outside diameter, d:	2 mm.
Element Length, L:	120 mm.
Element Type:	Duplex.
Sheath material:	Recrystalised Alumina.
Temperature Range:	-250 ^{0}C- 1260 ^{0}C.
Tolerance:	± 2.2 ^{0} C or ± 0.75% (Whichever is greater between 0 ^{0}C -1250 ^{0}C).
Talysurf	
Stylus material:	Diamond
Stylus radius:	0.0025 mm
Cut-off length:	0.08 – 2.5 mm
Accuracy:	± 3% of reading

Table 2: Properties of Lubricants with nano boric acid suspensions

(a) Thermal conductivity in kW/m-K

Percentage of nano boric acid suspensions	0	0.25	0.5	1	2	3	4	5
Soyabean oil	0.17	0.1704	0.1709	0.1718	0.1737	0.17548	0.17733	0.1792
canola oil	0.179	0.17945	0.1799	0.1808	0.1826	0.1844	0.186	0.188
Coconut oil	0.35	0.3502	0.3504	0.3509	0.3518	0.3527	0.3536	0.355

(b) Specific heat J/kg-K

Percentage of nano boric acid suspensions	0	0.25	0.5	1	2	3	4	5
Soyabean oil	2230	2233.12	2236.24	2242.48	2254.96	2267.439	227.919	2292.3999
Canola oil	1910	1913.92	1917.84	1925.68	1941.36	1957.04	1972.72	1988.4
Coconut oil	2100	2103.44	2106.9	2113.78	2127.56	2141.34	2155.12	2168.9

(c) Heat transfer coefficient W/m^2-K

Percentage of nano boric acid suspensions		0	0.25	0.5	1	2	3	4	5
Soya bean oil	60 m/min	455.171	456.014	456.86	458.56	461.99	465.459	468.97	472.52
	80 m/min	519.864	520.83	521.79	523.733	527.65	531.614	535.624	539.679
	100 m/min	576.43	577.496	578.57	580.72	585.06	589.457	593.9	598.4
Canola oil	60 m/min	450.137	451.032	450.1376	453.7311	457.365	461.039	464.75	468.5
	80 m/min	514.115	515.136	516.16	518.219	522.37	526.566	530.8	535.091
	100 m/min	570.053	571.186	572.322	574.6	579.6	583.85	588.56	593.313
Coconut oil	60 m/min	730.74	731.175	731.60	732.48	734.266	736.75	737.934	739.832
	80 m/min	834.61	835.096	835.59	836.58	838.61	840.69	842.81	844.98
	100 m/min	925.417	925.96	926.61	927.61	929.86	932.16	934.52	936.922

4.4 Tool flank wear. Tool flank wear measured at different lubricating conditions with cutting speed is shown in fig. 7. Flank wear increased gradually with increase in speed. During machining, heat is generated at the primary deformation zone and secondary deformation zone, and induces high cutting temperatures. Under such high cutting temperatures, the solid lubricant creates a thin lubricating film on the workpiece and tool. The particles of solid lubricant flow at the interface with the oil and decrease the plastic contacts, leading to reduction of flank wear. Low coefficient of friction, sliding action and low shear resistance within the contact interface reduce flank wear. From the results it is observed that flank wear with 0.5% nano boric acid particles suspensions in coconut oil is less compared to 0.25% and 1% conditions. But in case of canola oil, 1% nano boric acid suspensions showed better performance compared other conditions. Again, boric acid particle suspensions exhibited same trend in soyabean oil. This indicates that type of vegetable oil influences the optimum percentage of nano boric acid suspensions for lubricity. It is also observed that increase in tool flank wear with cutting speed in case of 0.5% nano boric acid in coconut oil is more than the 1% nano boric acid in canola oil. Variation of tool flank wear with feed rate at all lubricating conditions is presented in fig 8. Tool flank wear is increased with increase in feed rate and same trend is observed as discussed above.

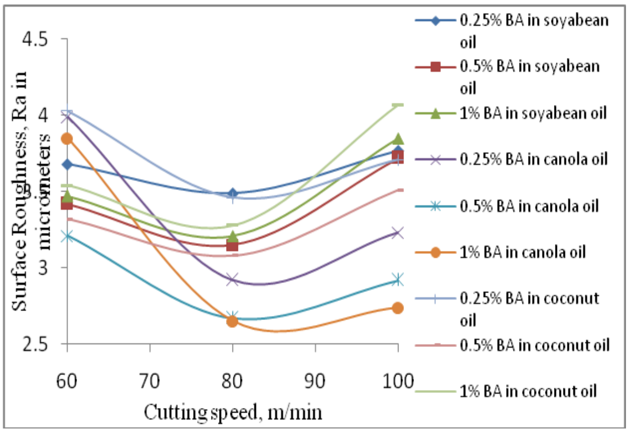

Figure 9. Variation of surface roughness with cutting speed
(feed= 0.2 mm/rev, d.o.c.= 1 mm, time= 5min)

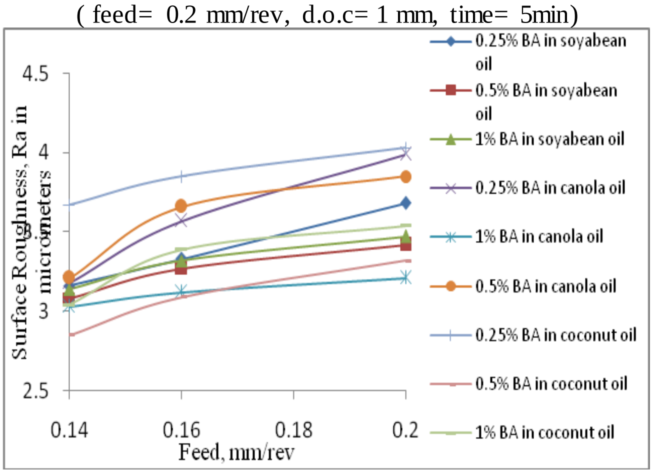

Figure 10. Variation of surface roughness with feed
(speed= 60 m/min, d.o.c=1 mm, time=5 min)

4.5 Surface roughness. Surface roughness initially reduced and then increased with increase in cutting speed at all the lubricating conditions (fig. 9). At lower cutting speed 0.5% nano boric acid suspensions shown lower surface roughness, but at high cutting speeds 1% boric acid suspensions in canola oil shown lower surface roughness. This may be attributed due to at high cutting speeds high temperatures are developed, at this high temperatures film formation and smearing action of 1% nano boric acid suspensions in canola oil is suitable compared to other conditions. Variation of surface roughness with feed rate is plotted in fig. 10, and it is observed that surface roughness increased with increase in feed rate. Same trend is observed among the selected lubricating conditions, surface roughness is less with 0.5% nano boric acid suspensions in coconut oil compared to other conditions at lower feed rate. But at higher feed rate, 1% nano boric acid suspensions in canola oil performed well in reducing the surface roughness compared to other lubricants. This is because of the lubricating action of the solid lubricant and vegetable oils at different temperatures and load conditions. The reduction in surface roughness in case of nano boric acid suspensions in vegetable oils may be attributed to its better lubricating action, which reduced the frictional forces between the tool and workpiece there by reducing the temperatures developed and ultimately preventing tool wear, thus prolonging tool life, resulting in surface quality improvement.

5. Conclusion

XRD pattern of nano engineered boric acid particles reveals the nanostructure of the sample taken, particle size analyzer reflects the presence of nano sized particles. Nanolubricants prepared with nano boric acid suspensions in vegetable oils are tested for basic properties and in machining. Thermal conductivity and specific heat increased with nano boric acid suspensions in all vegetable oils. Heat transfer coefficient increased slightly with increase in percentage of nano boric acid in base oil and cutting speed. Cutting temperatures and tool flank wear were decreased significantly with 0.5% nano boric acid suspensions in vegetable oils. In all the cases, coconut oil based nano particle suspensions showed better performance compared to other vegetable based lubricant. But in case of surface roughness, at lower speed and feed 0.5% boric acid suspensions in coconut oil performed well and at higher speed and feed 1% boric acid suspensions in canola oil performed well compared to other lubricating conditions.

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