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Experimental evaluation of the basic properties and performance of nanolubricant in machining

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ABSTRACT

Machining is one of the most fundamental and indispensable processes in manufacturing industry. The heat generated in the cutting zone during machining is critical in deciding the workpiece quality. Though cutting fluids are widely employed to carry away the heat in machining, their usage poses threat to ecology and the health of workers. Hence, there arises a need to identify eco-friendly and user-friendly alternatives to conventional cutting fluids. The present work features a specific study on the application of nano solid lubricant suspensions in lubricating oil in turning of AISI [1]1040 steel with carbide tool. Coconut oil is taken as base lubricant and boric acid solid lubricant of 50 nm particle size are added as suspensions. Boric acid nanoparticles are added to the oil on weight-percentage basis and the variation of its basic properties like flash point, fire point, viscosity, thermal conductivity and heat transfer coefficient are analysed. Variation of cutting tool temperatures, average tool flank wear and the surface roughness of the machined surface are studied with nano solid lubricant suspensions in lubricating oil.

KEYWORDS

Nanolubricant;
Solid lubricant;
Boric acid;
Machining;
Coconut oil.

INTRODUCTION

Machining experiences high temperatures due to friction between the tool and workpiece thus influencing the workpiece dimensional accuracy and surface quality. Cutting fluids are the conventional choice to act as both lubricants and coolants by reducing the friction between tool-workpiece, tool-chip interface with the help of effective lubrication and by controlling the machining temperatures. But, their application has several adverse effects such as environmental pollution, dermatitis to operators, water pollution and soil contamination during disposal[1,2]. 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. Hence, as an alternative to cutting fluids, researchers experimented dry machining, coated tools, cryogenic cooling, vegetable oils, minimum quantity lubrication (MQL) and solid lubricants.

MQL is a promising technique adopted by the researchers wherein tool wear is reduced, dimensional accuracy and surface finish are improved through reduction in cutting zone temperature and favorable conditions in the chip-tool and work-tool interaction[3]. MQL is shown to result in over all superior performance compared to dry and wet turning on the basis of cutting forces, tool life, cutting temperature and surface finish[3-6]. For effective implementation of MQL, fluids with high thermal conductivity are desired. In this context, nanofluids have gained importance.

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. The general chemical composition of coconut oil is lauric acid (51%), myristic acid (18.5%), caprilic acid (9.5%), palmitic acid (7.5%), olcic acid (5%), capric acid (4.5%), stearic acid (3%) and linoleic acid (1%). Coconut oil is one of the vegetable oil that remains as white crystalline solid at temperature below 20^0C. More than 90% of fatty acids of coconut oil are saturated. The iodine value of coconut which is a measure of un-saturation in coconut oil is 7–12. The saturated character of the oil imparts a strong resistance to oxidative stability. The specific density of coconut oil is 0.93 g/cm^3 and the Cetane number is 37. The flash point and viscosity index of coconut oil is 294^0C and 130, respectively.

LITERATURE REVIEW

Many researchers have been working to achieve eco-friendly sustainable manufacturing. As an alternative to cutting fluids, solid lubricants like MoS_2, graphite, etc. were used by many researchers. Shaji and Radhakrishnan[7] investigated the effect of graphite in surface grinding. Improvement in surface finish is reported with the application of solid lubricant. In another study[8], they reported improvement in process results using graphite, CaF_2, BaF_2 and MoS_2 in grinding. Venugopal and Rao[9] outlined the surface finish improvement with the application of graphite in grinding SiC. Jianhua et al[10] studied the friction coefficient at the tool-chip interface in dry cutting of hardened steel and in 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. Reddy and Rao[11] 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. Rao and Singh[12] 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 compared to dry hard turning. Krishna and Rao[13,14] investigated the performance of boric acid in machining experimentally. Machining performance is improved with reduced particle size while using dry solid lubricants. Then, a 50 micrometer particle size boric acid suspension in SAE-40 oil is tested and performance improvement is observed compared to conventional cutting fluids and dry machining. Cutting forces, cutting temperatures and tool flank wear are reduced and surface finish improved.

Ioan et al[15] presented the first experimental results on lubricating capacity of rapeseed oil compared to that obtained for a usual mineral oil. Belluco and De Chiffre[16] 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 fluid was found to have a significant effect on surface integrity and thickness of the strain hardened layer in the sub-surface, as well as part accuracy. Cutting fluids based on vegetable oils showed better performance than mineral oils. The efficiency of six cutting oils was evaluated in drilling AISI 316L austenitic stainless steel using conventional HSS-Co tools by measurements of tool life, tool wear, cutting forces and chip formation. All vegetable-based oils produced better results than the commercially available mineral oil in terms of tool life improvement and reduction in thrust force. Skerlos and Hayes[17] studied canola, soybean and rapeseed vegetable oil as cutting fluids. Their work 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. The developed metalworking fluids have found application in variety of manufacturing operations. Jayadas and Prabhakaran[18] compared the cooling behavior, thermal and oxidative sta-

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bilities 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.

Kulkarni et al[19] 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:

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

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:

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

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.

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

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. An attempt is made in the present work to investigate the affect of nano solid lubricants in turning. Boric acid particles of 50 nm particle size are used as suspensions in coconut oil and machining was carried out with varying proportions of solid lubricant suspensions i.e. 0.25%, 0.5%, 0.75% 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.

EXPERIMENTATION

Experiments were conducted to evaluate the performance of nano boric acid powder suspension in coconut oil during turning. All the experiments were conducted three times and average value is taken as response value. Boric acid particles of 50 nm particle size are obtained through mechanical milling with high energy ball mill. Solid lubricant particles of 50 nm size were manually mixed in coconut oil in different weight proportions at room temperature, followed by mixing with a sonicator for 1hour.

These suspensions along with pure coconut oil were used as lubricants in machining. Flash and fire points were measured by standard method using a Cleveland open cup flash and fire point apparatus. The viscosity of the nano-lubricant was measured using a Redwood Viscometer. Thermal conductivity, specific heat and heat transfer coefficient of nano lubricants are calculated from equations 1-3 and presented in TABLE 2 to understand their performance. ‘n’ in equation 1, is taken as 3, a value typical for spherical nano particles[19]. For calculation of heat transfer coefficient, Nusselt number, Nu, is obtained from the Hilpert equation for flow over cylinders, due to its analogy with turning process.

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

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[20].

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):	Ø50×400 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
Environment:	Solid lubricant (boric acid)
Lubricating oil:	Coconut oil
Solid lubricant particle size:	50 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
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:	-250^0C- 1260^0C.
Tolerance:	± 2.2^0 C or ± 0.75% (Whichever is greater between 0 ^{o}C -1250^{o}C).
Talysurf	
Stylus material:	Diamond
Stylus radius:	0.0025 mm
Cut-off length:	0.08 – 2.5 mm
Accuracy:	± 3% of reading

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 workpiece. 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 Figure 1. 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 (Figure 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.

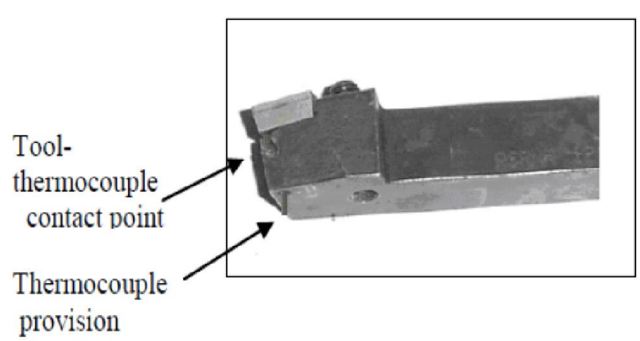

Figure 1 : Tool holder with provision for thermocouple.

RESULTS AND DISCUSSION

Basic properties

TABLE 2 shows that both flash point and fire point are increased with addition of boric acid suspensions in coconut oil. As expected, the viscosities generally decrease with the increase in temperature. From the experiments it is observed that the kinematic viscosity increased to some extent by the addition of nanoparticles (TABLE 3) This is because of the combined effect of coconut oil and solid lubricant powder.

TABLE 2 : Properties of coconut oil with nano boric acid suspensions. Fire point and flash point, ^{0}C.

Percentage of nano boric acid suspensions	0%	0.25%	0.5%	0.75%	1%
Flash point	220	245	266	270	310
Fire point	250	280	282	290	327

TABLE 3 : Properties of coconut oil with nano boric acid suspensions. Kinematic viscosity, st (cm^2/sec).

Temperature (^{0}C)	Percentage of nano boric acid suspensions				
	0%	0.25%	0.50%	0.75%	1%
30	0.0310	0.0350	0.0522	0.0574	0.0608
35	0.0207	0.0227	0.0326	0.0374	0.0431
40	0.0169	0.0190	0.0245	0.0278	0.0314
45	0.0085	0.0126	0.0152	0.0173	0.0237
50	0.0039	0.0092	0.0119	0.0143	0.0161

Thermal conductivity of nano lubricants increased slightly with percentage increase of nano particles compared to base oil (TABLE 4) whereas, from TABLE 5 it is observed that the specific heat decreased with increase in nano particles percentage in base oil. Heat transfer coefficient increased slightly with percentage increase of nano particles in base oil at specific cutting speed (TABLE 6). However, significant improvement is observed in heat transfer coefficient with increase in cutting speed at particular quantity of nano particle suspensions.

TABLE 4 : Properties of coconut oil with nano boric acid suspensions. Thermal conductivity, kW/m-K.

Percentage of nano boric acid suspensions	0%	0.25%	0.5%	0.75%	1%
Thermal conductivity	0.5	0.5004	0.5009	0.5014	0.5018

TABLE 5 : Properties of coconut oil with nano boric acid suspensions. Specific heat, J/kg-K.

Percentage of nano boric acid suspensions	0%	0.25%	0.5%	0.75%	1%
Specific heat	3500	3494.5	3489.09	3483.6	3478.2

TABLE 6 : Properties of coconut oil with nano boric acid suspensions. Heat transfer coefficient, W/m^2-K.

Percentage of nano boric acid suspensions		0%	0.25%	0.5%	0.75%	1%
Heat transfer coefficient	60 m/min	662.38	662.69	663.0	663.32	663.61
	80 m/min	727.75	728.09	728.42	728.78	729.09
	100 m/min	782.97	783.34	783.7	784.04	784.42

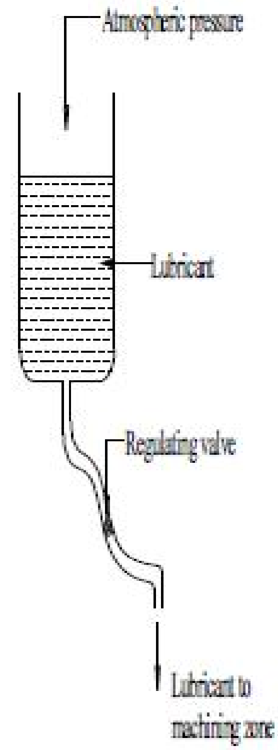

Figure 2 : Lubricant supply system for coconut oil with solid lubricant suspensions.

Cutting temperatures

Variation of cutting temperatures with cutting speed is presented in Figure 3. Cutting temperatures increased with cutting speed irrespective of the lubricant. The high lubricating property of coconut oil is due to by the fundamental composition of the vegetable oil molecules as well as the chemical structure of oil itself. 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. 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 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. This may be because, 0.25% boric acid cannot provide the adequate lubricating effect compared to 0.5%; 0.75% and 1% inclusions may reduces the flowability of the lubricant and prevents it from entering the cutting zone, thus decreasing its effectiveness.

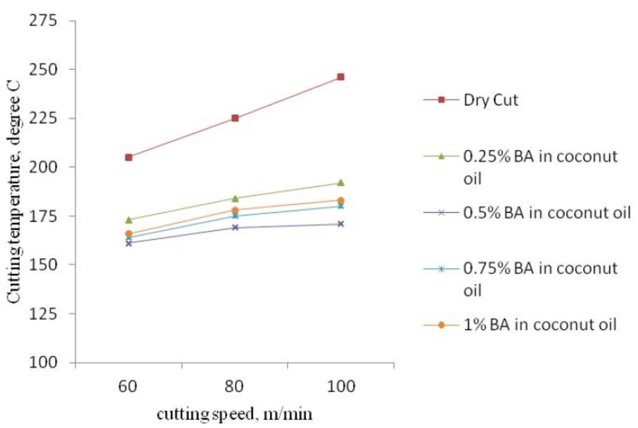

Figure 3 : Variation of cutting temperatures with cutting speed. (feed= 0.2 mm/rev, d.o.c= 1 mm, time= 15 min).

Tool flank wear

Tool flank wear measured at different lubricating conditions with cutting speed is shown in Figure 4. 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. The combined effect of solid lubricant and vegetable oil, as explained above, leads to reduction in flank wear with 0.5% nano boric acid particles suspensions in coconut oil compared to remaining conditions, due to similar reasoning as in case of cutting temperatures.

Surface roughness

Surface roughness initially reduced and then increased with increase in cutting speed at all the lubricating conditions (Figure 5). Among the selected lubricating conditions, surface roughness reduced with coconut oil with 0.5% nano boric acid suspensions. This is because of the lubricating action of the solid lubricant and coconut oil. The reduction in surface roughness in case of nano boric acid suspensions in coconut oil 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.

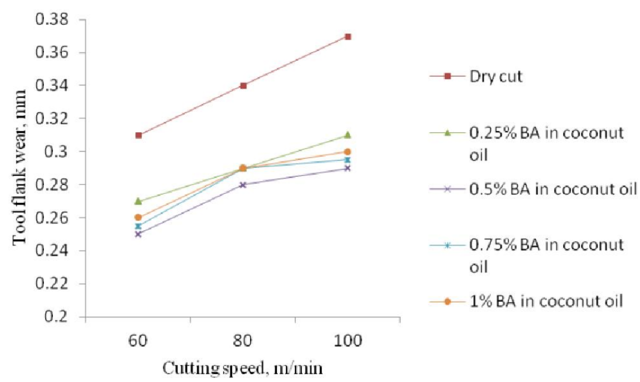

Figure 4 : Variation of tool flank wear with cutting speed. (feed= 0.2 mm/rev, d.o.c=1 mm, time=15 min).

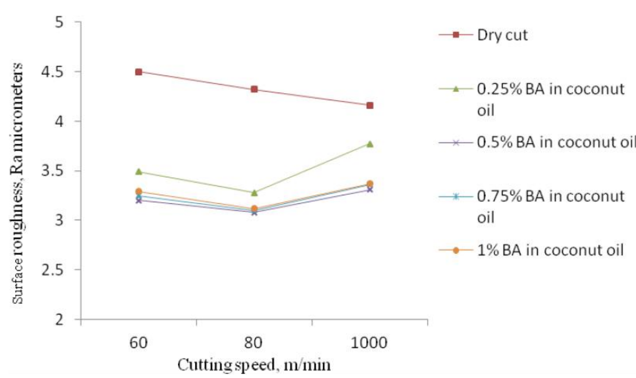

Figure 5 : Variation of surface roughness with cutting speed. (feed= 0.2 mm/rev, d.o.c= 1 mm, time= 15 min).

CONCLUSION

Nano boric acid suspensions in coconut oil provide adequate lubrication in machining. Flash and fire points increased with increase of nano boric acid content. Kinematic viscosity increased with increase in nano boric acid content. Thermal conductivity of nano lubricants increased slightly with percentage increase of nano particles. Heat transfer coefficient increased with addition of nano boric acid. Specific heat decreased with addition of nano boric acid. Compared to 0.25%, 0.5%, 0.75% and 1% nano boric acid inclusions, 0.5% showed better performance in terms of machining parameters like cutting temperatures, tool wear and surface roughness.

REFERENCES

[1] T.D.Howes, H.K.Toenshoff, W.Heuer; Environmental aspects of grinding fluids, Annals of CIRP, **40(2)**, 623-629 **(1991)**.

[2] G.Byrne, E.Scholta; Environmentally clean machining processes- a strategic approach, Annals of CIRP, **42(1)**, 471-474 **(1993)**.

[3] M.M.A.Khan, N.R.Dhar; Performance evaluation of minimum quantity lubrication by vegetable oil in terms of cutting force, cutting zone temperature, tool wear, job dimension and surface finish in turning AISI-1060 steel, Journal of Zhejiang University-Science A, **7(11)**, 1790-1799 **(2006)**.

[4] H.Bagchi, N.P.Mukharjee, S.K.Basu; Investigation of metal cutting using molybdenum disulphide as a cutting fluid, Industial Lubrication and Tribology, 239-243 **(1972)**.

[5] G.S.Lathkar, S.K.Basu; Clean metal cutting process using solid lubricants, proc. 19th AIMTDR Conf., IIT Madras, Narosa Pub., 15-31 **(2000)**.

[6] A.S.Varadarajan, P.K.Philip, B.Ramamoorthy; Investigations on hard turning with minimal cutting fluid application and its comparison with dry and wet turning, International Journal of Machine Tools and Manufacture, **42(2)**, 193-200 **(2002)**.

[7] S.Shaji, V.Radhakrishnan; An investigation of surface grinding using graphite as lubricant, International Journal of Machine Tools and Manufacture, **42(6)**, 733-740 **(2002)**.

[8] S.Shaji, V.Radhakrishnan; Investigations on the application of solid lubricants in grinding, Proc.Inst.Mech.Eng.B Journal of Engineering Manufacture, **216(10)**, 1325-1343 **(2002)**.

[9] A.Venugopal, P.V.Rao; Performance improvement of grinding of SiC using graphite as a solid lubricant, Materials and Manufacturing Processes, **19(2)**, 177-186 **(2004)**.

[10] Deng Jianhua, Cao Tongkun, Yang Xuefeng, Lin Jianhua; Self-lubrication of sintered ceramic tools with CaF_2 additions in dry cutting, International Journal of Machine Tools and Manufacture, **45**, 1-7 **(2005)**.

[11] N.Suresh Kumar Reddy, P.V.Rao; Experimental investigation to study the effect of solid lubricants on cutting forces and surface quality in end milling, International Journal of Machine Tools and Manufacture, **46**, 189-198 **(2006)**.

[12] Singh Dilbag, P.V.Rao; Performance improvement of hard turning with solid lubricants, International Journal of Advanced Manufacturing Technology, **32**, 170-177 **(2007)**.

[13] P.Vamsi Krishna, D.Nageswara Rao; The influence of solid lubricant particle size on machining parameters in turning, International Journal of Machine Tools and Manufacture, **48(1)**, 107-111 **(2008)**.

[14] P.Vamsi Krishna, D.Nageswara Rao; Performance evaluation of solid lubricants in terms of machining parameters in turning, International Journal of Machine Tools and Manufacture, **48(10)**, 1131-1137 **(2008)**.

[15] I.S.Ioan, C.Camelia, C.George; On the future of biodegradable vegetable lubricants used for industrial trybosystems, The Annals of University Dunarea De Jos of Galati Fascicle, **8**, 1221–4590 **(2002)**.

[16] W.Belluco, L.De Chiffre; Surface integrity and part accuracy in reaming and tapping stainless steel with new vegetable based cutting oils, Tribology International, **35**, 865–870 **(2002)**.

[17] S.Skerlos, K.Hayes; Vegetable based cutting fluid-a new dimension in research, http://www.engn.umich.edu/alumni/engineer/03FW/research/holography/index.html.

[18] N.H.Jayadas, K.Prabhakaran Nair; Coconut oil as base oil for industrial lubricants-evaluation and modification of thermal, oxidative and low temperature properties, Tribology International, **39**, 873–878 **(2006)**.

[19] Devdatta P.Kulkarni, Praveen K.Namburu, Debendra K.Das; Comparison of heat transfer rates of different nanofluids on the basis of the mouromtseff number, Electronics Cooling, **13(3)**, 28-32 **(2007)**.

[20] William S.Janna; Engineering heat transfer, 2nd Edition, CRC Press LLC, Boca Raton, Florida, **(2000)**.