Performance evaluation of eco-friendly nanofluids in machining

KRISHNA MOHANA RAO. G\textsuperscript{1}, PADMINI. R\textsuperscript{2}, VAMSI KRISHNA. S\textsuperscript{3}

\textsuperscript{1}\textsuperscript{Mechanical Engineering, JNTUH College of Engineering, Hyderabad, INDIA}
\textsuperscript{2,3}\textsuperscript{Mechaincal Engineering, GITAM University, Visakhapatnam, INDIA}

kmrgurram@jntuh.ac.in

Abstract

This paper focuses on the application of eco friendly nano fluids in machining. One of the most critical factors which determine the work piece quality is the heat generated at cutting zone during machining operations. Conventional cutting fluids are vastly employed to dissipate the heat generated during machining. In spite of their wide use, conventional cutting fluids do cast a check to the health of workers and ecological balance. Owing to this reason, researchers have initiated the search for ecologically safe and user friendly alternatives to conventional cutting fluids. In this context, experiments are being carried out by researches to assess the performance of vegetable oil based nano cutting fluids in machining. An attempt is made in this paper to present the affirmative performance of nano solid lubricant suspensions in vegetable oils in turning of AISI1040 steel in minimum quantity lubrication (MQL).

Characterization of nano particles is done by X-Ray Diffraction (XRD) to confirm their purity. Particle size analyzer is used to check the particle size of nano solid lubricant. To check the viability of nano lubricants in machining, variation of basic properties like thermal conductivity, specific heat and heat transfer coefficient are evaluated from empirical relations. The 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 cutting fluids. It has been observed that results are encouraging, especially among all the oils used coconut oil based nano fluid has exhibited better performance.

Key words: Nano particles; Boric acid; Vegetable oils; Machining.

1. Introduction

Friction at the tool and work piece interface generates high temperatures during machining. These high temperatures affect dimensional accuracy and surface quality of the work piece. 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. Dermatitis to operators, environmental and water pollution, and soil contamination during disposal are the adverse effects of usage of conventional cutting fluids [1, 2]. In USA alone about 700,000 to one million workers were exposed to cutting fluids [3]. In water soluble cutting fluids even microbial toxins are generated by bacteria and fungi present [4], which are further harmful to the operators. Besides these factors, cutting fluids incur a major portion of the total manufacturing cost of industry. Thus these factors became the basic reasons, which prompted investigators to extensively search for eco-friendly cutting fluids in
order to counteract the adverse effects of conventional cutting fluids.

In this process, various alternatives to petroleum-based cutting fluids are currently being explored by scientists and tribologists. These 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 vegetable oil based nano 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. Status of Research in Vegetable oil based nano cutting fluids in drilling, milling and turning operations prepared by using nano solid lubricants.

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. Investigations were tried carried with solid lubricant molded grinding wheels by including lubricant in the wheel structure during the molding stage [5]. 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. Reddy and Rao [6] 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 zone [7]. The remarkable reduction of cutting force, specific energy and surface roughness is observed.

Jianhua et al [8] studied the friction coefficient at the tool-chip interface in dry cutting of hardened steel and cast iron with an Al$_2$O$_3$/TiC/CaF$_2$ ceramic tool and reported reduction in friction coefficient with the addition of CaF$_2$ solid lubricant. Rao and Singh [9] 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 [10] 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 [11-13] used boric acid during turning of AISI 1040 steel using HSS and carbide cutting tools. Process performance was improved by using boric acid solid lubricant through reduction in cutting forces and tool wear, surface finish was also improved. Machining performance was improved with reduced particle size while using dry solid lubricants. An improvement in machining performance with boric acid suspension in SAE-40 oil has been reported by them.

Jianxin et al [14] 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. Wenlong et al. [15] 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%. Ioan et al [16] presented the first experimental results on lubricating capacity of rapeseed oil. Belluco and De Chiffre [17] 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 [18] 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 [19] 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°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 [20]. Putra et al [21] 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 [22] have reviewed a number of applications of nano fluids ranging from coolants in automobiles to medical devices. Krishna et al [23] 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.

From 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 imparts good lubricity to the cutting fluid. However, earlier works dealt with micro particle size or nano particle suspensions in coconut oil and SAE oil; the impact of nano particles in other vegetable oils was not studied, though nano fluids are known to be more effective coolants compared to any other suspensions or fluids. This work is an attempt to focus on the investigations conducted to study the affect of nano solid lubricants in turning. Boric acid particles of 100 nm particle size are used as suspensions in castor oil, sunflower oil, sesame oil, canola oil and coconut oil.

Analysis of basic properties by taking nano boric acid suspensions in all the oils was done, experimentation was done using coconut, canola oils to save time and cost of experimentation and machining was carried out with varying proportions of solid lubricant suspensions i.e. 0.25%, 0.5%, and 1% by weight. Influence of the newly formulated lubricants on cutting temperatures, tool flank wear, and surface roughness was studied with respect to cutting conditions.

3. The Process of Experimentation

3.1. Preparation of nano particles of solid lubricant

High energy ball mill (INSMART make) is used to obtain boric acid particles of 100 nm particle size were obtained through mechanical milling. For this purpose a planetary ball mill (40-400 rpm
table speed) was used to produce particles in the nano scale size range.

3.2. Synthesis and characterization of nano particles

Through XRD analysis purity of the sample taken is assessed and particle size of nano boric acid particles is confirmed through particle size analyzer.

3.3. Preparation of vegetable oil based nano cutting fluid

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 1 hour.

3.4. Machining

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. 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. The temperature is sensed by the embedded thermocouple (K type shielded). A thermocouple is placed at the bottom of the tool insert in the tool holder as shown in Fig 1.

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). The experimental setup was developed for liquid lubricant supply at the machining zone (Fig. 2). After ensuring the flow rate of 10 ml/min, experiments were conducted.

4. Results and Discussion

4.1 Basic Properties. (Table 1)

Evaluation of basic properties forms the basis for assessment of viability of the oils taken as base fluids in machining. Basic properties were calculated from empirical relations. Heat transfer coefficient was evaluated using Nusselt number, Nu, obtained from the Hilpert equation for flow over cylinders, due to its analogy with turning process.

\[
Nu = \frac{hD}{k_{nf}} = C\cdot Re^{m}\cdot Pr^{1/3}
\]

where, Re and Pr are Reynold’s number and Prandtl number respectively, h is the heat transfer coefficient, D is the diameter of the work piece and C & m are constants that depend on the value of Re [24]. Thermal conductivity and specific heat of nano lubricants increased slightly with percentage increase of nano particles compared to base

![Figure 1. Tool holder with provision for thermocouple](image)

![Figure 2. Lubricant supply system for nano cutting fluid](image)
oil (table 1(a) & (b)). This is because of the high specific heat and thermal conductivity of boric acid compared to canola oil and coconut oil. Heat transfer coefficient increased slightly with percentage increase of nano particles in base oil at specific cutting speed (table 1 (c)). The evaluation of basic properties helps in selecting the most suitable oils for the purpose of experimentation. It was inferred that among all the oils, canola and coconut have shown consistent improvement in basic properties, thus experimentation was carried using these two oils and machining performance was assessed.

Table 1: Properties of vegetable oil based lubricants containing nano boric acid suspensions

(a) Thermal conductivity in kW/m-K

<table>
<thead>
<tr>
<th>Type of oil</th>
<th>Percentage of nano boric acid suspensions</th>
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<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Castor</td>
<td>.18</td>
</tr>
<tr>
<td>Sunflower</td>
<td>.168</td>
</tr>
<tr>
<td>Sesame</td>
<td>.176</td>
</tr>
<tr>
<td>Soya bean</td>
<td>0.17</td>
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<tr>
<td>Canola</td>
<td>0.179</td>
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<tr>
<td>Coconut</td>
<td>0.35</td>
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(b) Specific heat J/kg-K

<table>
<thead>
<tr>
<th>Type of oil</th>
<th>Percentage of nano boric acid suspensions</th>
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<tbody>
<tr>
<td></td>
<td>0</td>
</tr>
<tr>
<td>Castor oil</td>
<td>1800</td>
</tr>
<tr>
<td>Sunflower oil</td>
<td>1833</td>
</tr>
<tr>
<td>Sesame oil</td>
<td>1630</td>
</tr>
<tr>
<td>Soya bean oil</td>
<td>2230</td>
</tr>
<tr>
<td>Canola oil</td>
<td>1910</td>
</tr>
<tr>
<td>Coconut oil</td>
<td>2100</td>
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(c) Heat transfer coefficient W/m²-K

<table>
<thead>
<tr>
<th>Type of oil</th>
<th>Cutting Velocity (m/min)</th>
<th>Percentage of nano boric acid suspensions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0.25</td>
</tr>
<tr>
<td>Castor oil</td>
<td>60</td>
<td>459.37</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>524.66</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>581.74</td>
</tr>
<tr>
<td>Sunflower oil</td>
<td>60</td>
<td>433.61</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>495.23</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>549.12</td>
</tr>
<tr>
<td>Sesame oil</td>
<td>60</td>
<td>423.45</td>
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<tr>
<td></td>
<td>80</td>
<td>483.63</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>536.26</td>
</tr>
<tr>
<td>Soy bean oil</td>
<td>60</td>
<td>455.171</td>
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<tr>
<td></td>
<td>80</td>
<td>519.864</td>
</tr>
</tbody>
</table>
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). It can be seen from results that coconut oil suspensions are consistently better than the canola and oil suspensions. This is because of the high heat transfer coefficient of coconut oil based lubricants than the canola oil and oil based lubricants. At elevated temperatures solid lubricant softens and forms a film, more over at 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 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.
4.3 Variation of 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. When high cutting temperatures are induced during machining, the solid lubricant creates a thin lubricating film on the work piece 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. 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 increased with increase in feed rate and same trend is observed as discussed above.

4.4 Investigation of 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 thereby reducing the temperatures developed and ultimately preventing tool wear, thus prolonging tool life, resulting in surface quality improvement.

5. Conclusion

With reference to past research, an attempt has been made through experimentation to test the performance of vegetable oil based nano lubricant prepared with nano boric acid suspensions. The following conclusions can be drawn:

1. Thermal conductivity and specific heat increased with nano boric acid suspensions in all vegetable oils.
2. Heat transfer coefficient increased slightly with increase in percentage of nano boric acid in base oil and cutting speed.
3. 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.
4. 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.

References

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