New bio-based nanolubricants for turning of Inconel 718 towards improvement of tool wear resistance and specific cutting energy

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Abstract. Substitution of traditional metal cutting fluid with newly formulated bio-based nanolubricants for machining hard-to-cut material such as Inconel 718 can be advantageous in reducing the impact on environmental as well as on the overall operating or machining expenditure. Added to that, combination of nano-lubricants with Minimum Quantity Lubricant (MQL) system provides benefit towards controlling fluid consumption along with the aim of cooling and lubricating effectively at the cutting zone. Until now, research studies on the ability of bio-based nano-lubrications for cutting fluids application on hard metal alloys are still at infancy. Hence, in this work, newly formulated bio-based nano-lubrications were tested while machining Inconel 718 with uncoated carbide tool. Performances of different cutting fluids namely; Solcut oil, coconut oil, pure bio-based oil, bio-based oil + 0.2% Al2O3, bio-based oil + 0.5% Al2O3 and bio-based oil + 0.8% Al2O3 were evaluated with respect to tool wear and specific cutting energy. Overall, bio-based oil + 0.8% Al2O3 exhibited excellent wear resistant which prolong the cutting time or the tool life expectancy. Meanwhile, bio-based oil + 0.5% Al2O3 was superior in lowering the specific cutting energy for machining Inconel 718 as compared to other five types of cutting fluids.

1. Introduction

One of the recent research interests in improving cutting efficiency for metal cutting industries is the development of nano-lubricants. These new types of metal cutting fluids are aimed to enhance tribological characteristics during machining operation through reduction of internal and external heat generation within the cutting zone. Several studies [1–3] have been proved by the ability of nano-lubricants in many aspects of machining output. As explained by Talib and Rahim [3], internal heat generation was due to internal friction that occurs as result of material deformation process in the shear zone. Whereas, the friction due to metal-to-metal contact of chip surface and tool surface is another source of heat generation in metal cutting environment. Several research articles have highlighted that the addition of nanoparticles in a based oil led to reduction of wear and friction

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mechanisms which were induced during cutting operation [1-3]. This is attributed to the formation of protective films of the smaller-size nanoparticles onto the other friction surface, rolling effect of the small spherical nanoparticles at the contact surfaces, and ability of nanoparticles to withstand compressive stress concentration due to high contact pressure [1, 4].

Many of industrial practice and previous research works combined the petroleum and synthetic based cutting lubricants with nano-particles for achieving efficiency in machining process. However, due to the adverse effects of petroleum and synthetic based cutting fluids on environment (such as toxicity and non-biodegradability) and human health, other potential alternatives are actively being explored by research communities [7]. Among many solutions, vegetable-based oil has been proposed and deemed suitable due to several important tribological characteristics. These characteristics are high viscosity index, greater molecular weight, lower volatility, higher flash point, higher boiling point, long and polar fatty acid carbon chains with rapid biodegradability [6, 7]. Furthermore, research on reformulation of additives and chemical modifications on the vegetable lubricants further improved their characteristics toward machining efficiencies [2,4,8]. Extending to this existing works, alterations on vegetable lubricants with addition of nanoparticles have also been explored by several researchers [1,2,9]. These lubricants are derived from edible and non-edible vegetable oils and possess high lubricity, viscosity index and flash point. Since they come from natural resources, bio-based oils can be class as renewable, low toxicity and biodegradability. However, these lubricants have poor cold flow properties and oxidation stability, which leads to polymerisation and degradation. The aforementioned drawbacks can be somehow overcome by chemical modifications of vegetable oils or by special formulation of fluids [10-11]. Thus, the present study aims to elucidate the effects of newly formulated bio-based nanolubrications on the growth of wear on cutting tool and specific cutting energy in the turning of Inconel 718 with uncoated cemented carbide inserts.

2. Experimental method

2.1. Preparation of bio-based lubricants

Three main ingredients, i.e. coconut oil, water and aluminum oxide (Al$_2$O$_3$) nanoparticles were used to prepare the bio-based lubricants. The amount of ingredient and method of mixing were decided based on preliminary experiments, which were repeatedly conducted until a stable cutting fluid was obtained. A batch of four bio-based lubricants consisting of 50% oil-emulsion and 50% of water were prepared. Virgin coconut oil was used as the based lubricant with two additives were added to it so as to produce the oil-emulsion. Coco-amido propylbetaine, CAPB was used as an emulsifying and bacterial control agent, while sodium dodecyl benzene sulfonate, SDBS as a thickener agent. The oil-emulsion was prepared at 2:1:0.5 ratio by volume fraction. CAPB and SDBS were first mixed using a magnetic stirrer at 350 rpm. Coconut oil was then slowly added into the solution and the mixing process continued for 10 minutes. Subsequently, distilled water was added into the oil-emulsion and the mixing speed was increased to 500 rpm. The pH value of lubricant was kept at 9.2 with addition of amino methane (Tris) as a pH buffer agent. Three out of the four lubricants were added with aluminium oxide (Al$_2$O$_3$) nanoparticles at 0.2%, 0.5% and 0.8% of concentration prior to sonication process of 3 hours at 15% amplitude.

2.2. Lubricant properties

Density, viscosity index (VI), kinematic viscosity and thermal conductivity for all samples were measured according to ASTM D4052, ASTM D2270, ASTM D445 and ASTM D5334, respectively. Density was determined by the ratio of weight over volume of oil using a pycnometer at 15°. Kinematic viscosity was measured by a viscometer machine at 40° and 100°. Viscosity index was calculated based on the results of kinematic viscosity at both tested temperatures. Thermal conductivity at three different temperature; 40°, 70° and 100° were measured using KD2 Pro thermal analyser. All measurements were repeated for three times before the average value were recorded in Table 1.
Table 1. Physicochemical properties and thermal conductivity

| Coolant          | pH  | Density (g/cm³) | Viscosity index (VI) | Kin. Vis @ 40°C | Kin. Vis @ 100°C | Thermal Conductivity (W/mK) |
|------------------|-----|-----------------|----------------------|-----------------|------------------|----------------------------|
|                  |     |                 |                      |                 |                  | 40°C  | 70°C  | 100°C |
| SolCut           | 8.17| 0.909           | 71.5                 | 14.96           | 3.25             | 0.233 | 0.215 | 0.204 |
| Bio-based        | 6.1 | 0.913           | 130                  | 24.9            | 5.12             | 0.187 | 0.163 | 0.154 |
| Bio-based 0.2% Al₂O₃ | 9.2 | 0.985           | 1058.12              | 24.7            | 41.86            | 0.328 | 0.302 | 0.300 |
| Bio-based 0.5% Al₂O₃ | 9.2 | 0.983           | 1109.91              | 22.32           | 40.05            | 0.333 | 0.355 | 0.352 |
| Bio-based 0.8% Al₂O₃ | 9.2 | 0.986           | 1226.37              | 18.93           | 37.65            | 0.346 | 0.363 | 0.356 |
| Coconut oil      | 9.2 | 0.989           | 1342.83              | 15.54           | 35.24            | 0.352 | 0.367 | 0.363 |

2.3. CNC machines, turning inserts and workpiece material
Machining experiments were conducted using Chevalier FCL-608 CNC turning machine with 2-axis in the x and z directions. The inserts used for the experiments were Sandvik CNMG 120408 H13A uncoated carbide inserts with nose radius of 0.794 mm. The toolholder was ECLNR-2020K12 type from CHAIN with (-) rake angle. The turning process was performed on 50-mm-diameter and 100-mm-length Inconel 718 workpieces.

2.4. Lubricating condition and cutting parameters
All cutting processes were carried out under minimum quantity lubrication (MQL) condition. To ensure effective delivery of lubricant via MQL system, a 6-bar inlet air pressure was set. Based on this air pressure, the flow rate for the MQL was determined to be 80 ml/hr. The machining conditions were; 80 m/min cutting speed, 0.1 mm/rev feed rate and 0.1 mm depth of cut. During the cutting process, 0.2 mm diameter of material was removed in each cutting length of a 30 mm. The process was continued until 1 mm of the diameter of the workpiece has been removed.

2.5. Experimental measurement procedure
Tool wear and specific cutting energy are the machining outputs that have been selected. Specific cutting energy result were obtained through calculation based on following equations 1-3. For each cutting process, tool wear growth was consistently measured at a predetermined interval using Xoptron XST60 stereomicroscope at 35x optical magnifications.

\[ MRR = 3.142 \times D_{AVG} \times d \times f \times N \quad (1) \]
\[ Power = 3.142 \times V\text{elocity} \quad (2) \]
\[ Specific\ cutting\ energy = \frac{Power}{MRR} \quad (3) \]

Where; \( d \): Depth of cut, \( f \): Feed rate, \( N \): Spindle speed, \( MRR \): Material removal rate

3. Results and Discussion

3.1. Tool wear
The trend of tool wear growth (Figure 1) shows a typical tool wear curve for metal cutting process, in which tool wear increases with respect to cutting time. In accordance with ISO 3685:1993, the tool wear criterion of 0.3 mm was selected to determine the tool useful life. In specific, the tool useful life was decided when the maximum width of the flank wear land was equal or greater than a \( V_B \) of 0.3mm. Among the six types of cutting fluids, bio-based oil with 0.8% Al₂O₃ nanoparticle was effective and efficient for tool wear resistant as it recorded the longest cutting time of 43.3 min, Table
2. Whereas, the cutting time for bio-based oil + 0.8% Al₂O₃, bio-based oil + 0.5% Al₂O₃, bio-based oil + 0.2% Al₂O₃, bio-based oil, and coconut oil recorded an increase of 40.2%, 26.8%, 7.4%, 7.3% and 2.1%, respectively, as compared to that of the SolCut oil. The results showed that the benefits of using bio-based oil with 0.8% Al₂O₃ nanoparticles is with respect to a lengthened tool life for all test conditions. The cooling and lubrication characteristics of bio-based nanofluids improved the lubrication and wetting characteristics at the flank regions, and accordingly, it provided better heat and friction dissipation as discussed by previous studies [1,4,12,13]. As can be seen from Figure 2, friction and heat development generated from the friction between tool and workpiece, led to abrasion and material adhesion onto the cutting edge which causes the generation of BUE. Plus, the occurrence of notch wear was also restrained.

![Graph showing tool wear progression against cutting time for different cutting lubricants.](image1)

**Figure 1.** Tool wear progression against cutting time for difference cutting lubricants.

![Flank surface of cutting tool.](image2)

**Figure 2.** Flank surface of cutting tool; a) Solcut, b) Bio-based, c) Bio-based 0.2% Al₂O₃, d) Bio-based 0.5% Al₂O₃, e) Bio-based 0.8% Al₂O₃ and f) Coconut oil.
3.2. Specific cutting energy and coefficient of friction
The energy consumed in removing a unit volume of material is defined as the specific cutting energy, SCE \((k)\). \(k\) is calculated by dividing the cutting power (W) with the volume of material removed, MRR \((\text{mm}^3/\text{s})\). Understanding value of \(k\) is an alternative approach to quantitatively measuring the efficiency of the metal cutting process or the machinability of a workpiece. Specific cutting energy is material dependent, as well as related to the cutting tool, machining parameters and type of machining; hence, it can represent very well the cutting phenomenon. Table 2 represents the value of \(k\) for all the lubricating condition. It was found that value of \(k\) was the highest in SolCut condition with 8.57 Ws/mm\(^3\) and the lowest was for bio-based + 0.5% Al\(_2\)O\(_3\) with 7.47 Ws/mm\(^3\).

Table 2. Tool life and specific cutting energy for different cutting fluid

| Coolant     | Tool life (min) | Specific cutting energy (Ws/mm\(^3\)) |
|-------------|-----------------|--------------------------------------|
| SolCut      | 19.20           | 8.57                                 |
| Bio-based   | 23.56           | 8.50                                 |
| Bio-based 0.2% Al\(_2\)O\(_3\) | 23.62 | 8.38 |
| Bio-based 0.5% Al\(_2\)O\(_3\) | 35.28 | 7.47 |
| Bio-based 0.8% Al\(_2\)O\(_3\) | 43.30 | 7.54 |
| Coconut oil | 20.43           | 8.35                                 |

4. Conclusion
In this work, the cooling and lubrication capabilities of new formulated bio-based oil with addition of Al\(_2\)O\(_3\) nanoparticles have been tested in machining of Inconel 718. Specifically, the tests have been carried out to study the effects on tool wear resistance and specific cutting energy for different formulation of bio-based oils. For tool wear; bio-based oil with 0.8% Al\(_2\)O\(_3\) nanoparticles exhibited excellent wear resistant which prolong the tool life expectancy. Whereas, the inclusion of 0.5% Al\(_2\)O\(_3\) nanoparticles in the bio-based oil was found superior in reducing the specific cutting energy. The effective cooling and lubrication properties of the new bio-based nanofluids were capable in lowering the friction and heat generation during machining hard to cut alloy.

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