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Vegetable Oil-Based Lubrication in Machining: Issues and Challenges

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Abstract. The use of vegetable oil as a replacement for conventional mineral-based lubricant has gained many interests in recent years from the machining industries. This is due to the problematic issues with the use of conventional mineral-based lubricant that can cause negative effects on the manufacturing cost, operators' health and the environmental. As vegetable oil is renewable, biodegradable, and non-toxic and has remarkable tribological characteristic from its triglycerides structure, it has been identified as the best replacement for mineral-based cutting lubricant. However, formulating vegetable oil into machining lubricant has its challenges where it must overcome its nature of poor low-temperature properties and low oxidative stability. Therefore, this paper will elaborate the present issues and challenges in formulating green machining lubricant using vegetable oil and its stand under sustainable machining. This includes the method and technique of formulating vegetable-based lubricant and the output performance obtained from vegetable-based lubricant under machining in comparison to the conventional mineral-based lubricant. The result shows that utilizing the vegetable-based lubricant at minimum quantity has comparable or better performance to conventional mineral-based lubricant in terms of surface finish. Therefore, the use of vegetable oil has its challenges and issues as machining lubricant, but it is one of the current best viable alternatives to the mineral-based lubricant in promoting sustainable machining.

Keywords: *Vegetable oil, triglycerides, palm kernel oil, machining lubricant, sustainable machining.*

1. Introduction

The cutting lubricant has three basic actions, which are cooling, reducing friction and minimizing the shear strength [1]. These actions contribute to low cutting force, longer cutting tool life and highly desirable surface finish. The use of lubricant is so important in machining, that it is reported, approximately 320,000 tons of cutting lubricant was being consumed by the European Union annually which mostly were made of mineral oil [2]. Moreover, the quantity of lubricant keeps on increasing over the years. This fact has raised awareness since the use of the mineral-based cutting lubricant can bring negative impact on the environment and the operators' health. Several studies have proven that mineral-based lubricant may contain carcinogenic additives and impurities in their formulation, which causes dermatitis, and skin cancer [3]. Furthermore, mineral oil is very poor in terms of biodegradability, with the range of 15 - 50% biodegradation. The said biodegradation values are below than the acceptable guideline for environmental friendly lubricant, which is at 80% [4]. Thus, to properly dispose of the mineral based cutting lubricant is very difficult and challenging that involves



numerous processes at a high cost. Hence, an alternative to mineral oil should be considered and the effort should be concentrated on minimizing the lubricant usage.

The rise in environmental issues and health concerns from the use of mineral oil causes the increased use of vegetable as the base oil of a lubricant. Triglycerides inside the chemical structure of vegetable oils are three long chains of fatty acids that contributed the said oil to have the desirable lubricating properties. Furthermore, vegetable oils have high viscosity index and low volatility making it the best alternative to mineral oil. The main factor of using vegetable oils is that it is safe toward the environment and to the operators handling as the vegetable oils is highly biodegradable and low in toxicity. The said oil has been used as a lubricant since the ancient time, however, the usage stopped due to low oxidation properties and poor low temperature properties.

1.1 Low oxidative stability

Vegetable oils are known to be low in oxidative stability due to the presence of double bond (C=C) in their fatty acid composition. The higher the composition of unsaturated fatty acids (double bond), the more susceptible vegetable oils to the oxidation process. Vegetable oil that undergoes the process of oxidation will increase in their viscosity and produces deposits of varnish and sludge, which degrades the quality of vegetable oils. Table 1 shows the composition of unsaturated and saturated fatty acid inside several types of vegetable oils. Looking at Table 1, most of the vegetable oils have a high composition of unsaturated fatty, which means that most of the vegetable oils are susceptible to the process of oxidation.

Several methods were identified to improve the oxidative stability of vegetable oils. One of the ways is to add additives such as anti-oxidant in the formulation of lubricant. Anti-oxidant works by delaying the viscosity increase of vegetable oils, which consequently helps in decreasing the rate of oxidation. Third-butyl hydroquinone (TBHQ) is one of the additives that can significantly improve the oxidative properties of vegetable oils, by almost 6 times the original performance [5]. Furthermore, the modification can be made on the chemical structure of vegetable oils through ring-opening process to further improve their oxidative stability [6]. Nonetheless, it is important to note that the inclusion of anti-oxidant and modification of the chemical structure will increase the lubricant's formulation cost and time.

Table 1. The composition of fatty acids of vegetable oils

No.	Vegetable oils	Fatty acids (%)	
		Saturated	Unsaturated
1.	Grapeseed	15.2	84.8
2.	Sunflower	15.4	84.6
3.	Soya bean	20.7	79.3
4.	Corn	19.5	80.5
5.	Canola	11.5	88.5
6.	Olive	21.9	78.1
7.	Hazelnut	13.8	86.2

1.2 Poor low temperature properties

The other issue of using vegetable oils as lubricant is that it will have poor low-temperature properties. This can cause the lubricant to exhibit cloudiness, precipitation, poor flowability, and solidification at room condition temperature (24°C). There is contradicting opinion on the source of poor properties of vegetable oils at low temperature. One opinion stated that the composition of saturated fatty acid in the chemical structure of vegetable oils contribute to the poor low-temperature properties [7]. On the other hand, stated that the presence of polyunsaturated fatty acids (multiple double bonds in one chain of fatty acid) is the caused for the said poor performance [8]. However, most researchers are favoring the theory that the composition of saturated fatty acid as the main influence on the poor low temperature performance. This is because, at low-temperature, the carbon atoms of saturated fatty acid chains tend to bundle rapidly than the unsaturated fatty acid, turning into crystalline form. The low temperature

properties of vegetable oils are identified by examining the pour point temperature of the vegetable oils.

Efforts have been made in increasing the low temperature properties of vegetable oils. The most popular method is the process of transesterification [9]. This process is conducted by adding alcohol and a catalyst to the vegetable oil. The process helps in reducing the percentage of saturated fatty acid by changing those fatty acids to the monounsaturated fatty acids by increasing the amount of double bond. Thus, the product of this process is vegetable oils that are high in the composition of monounsaturated fatty acids. Tests have been conducted on the product and it is proven that the low temperature properties have increased. However, a new challenge will emerge to this product as it is now high in the composition of unsaturated fatty acid, making the newly produce product prone to the oxidation process.

1.3 Sustainable machining

Sustainable machining refers to improvement in the aspect of environmental protection, profitability and societal benefit. It is an upgrade toward the conventional 3R (reuse, reduce and recycle) concept in promoting green machining (environmentally) to an upgraded 6R (reuse, reduce, recycle, redesign, recover and remanufacturing) for the concept of sustainable machining (innovative). Figure 1 shows the development of sustainable machining over the years. Implementing vegetable oil as the based oil cutting lubricant poses healthy benefits towards the environment and operators' health due to its biodegradability and low toxicity properties [10]. This action achieved the concept of environmental green machining; however, this is not considered as the action under the umbrella of sustainable machining. In terms of the economic view, the use of cutting fluid consumes a significant amount of energy and the production cost. Furthermore, once the cutting fluid is used, the cost is taken to properly dispose of the used cutting fluid. If not properly conducted, it can accumulate bacteria and fungi that can consequently lead to ecological damage and contamination. Therefore, the innovative invention is needed in utilizing the vegetable-based lubricant to meet the expectation of sustainable machining.

Suggestion has been raised to perform machining in dry condition to attain the sustainable machining concept. Dry conditions eliminate the cost of cutting lubricant and its expenses on waste disposal treatment. This would greatly benefit in the economic point of view as it reduces around 15 % of machining cost. However, machining under dry conditions degrades the tool life performance due to the excessive increase in cutting temperature, especially in machining difficult-to-cut materials. Therefore, the best condition in machining hard-to-cut materials is to use cutting lubricant at the least amount, which is called minimum quantity lubrication (MQL) where an average 50 mL/H cutting lubricant delivered to the cutting regions. The amount of lubricant usage under MQL is far less than the conventional flooded cooling at an average of 120,000 mL/H of flowrate. According to Amrita, the utilization of MQL is able to greatly improve the result of a turning process [11]. This is because, under MQL system, the lubricant is forced to penetrate the small gap between the cutting tool and workpiece, which the flooded cooling is unable to achieve. With far less amount of lubricant usage, the system able to perform better than machining under the conventional flooded and dry condition. Although the initial production cost of utilizing vegetable based lubricant under MQL is slightly higher, this is compromised with the superior performance and results that can be obtained, which makes it the best approach in turning under the umbrella of sustainable machining.

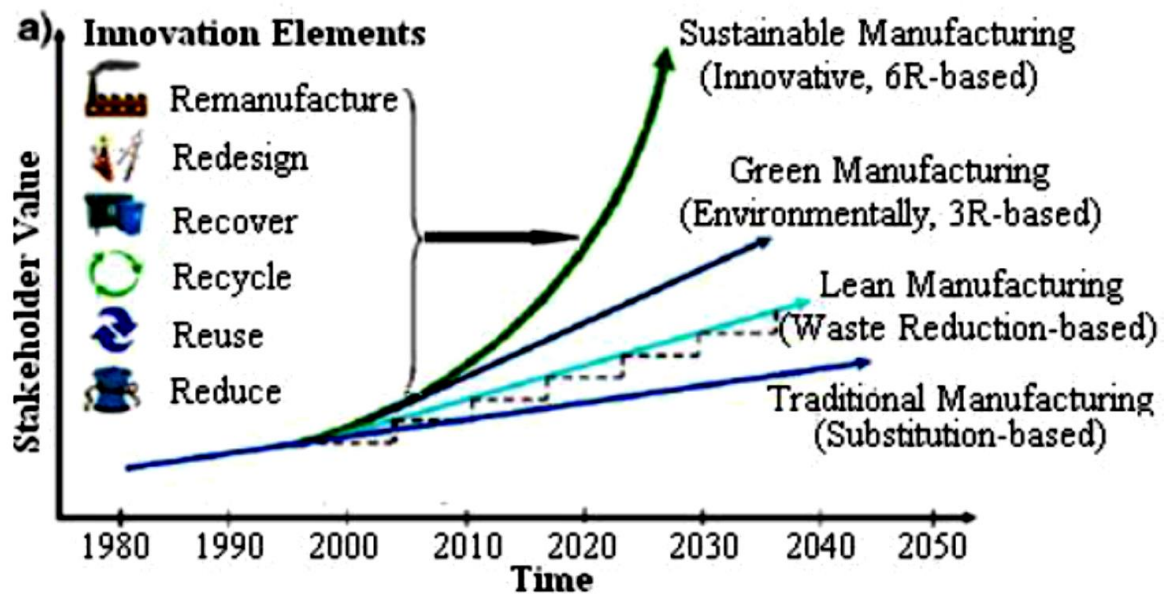


Figure 1. The development of sustainable machining [12]

In this study, the formulation of the vegetable-based cutting lubricant is briefly explained with the brief clarification on the selection of additives. Then, the formulated vegetable oil under MQL mode was tested their performance in comparison to conventional mineral-based cutting lubricant under flooded cooling. The testing was conducted with the help of 2^4 full factorial design of experiment with cutting speed, feed rate, depth of cut and type of lubricant as the variable factors. Then, each experimental run was conducted in turning AISI431 stainless steel and the surface finish of the workpiece was examined.

2. Experimental procedure

2.1 Formulation of lubricant

Vegetable based lubricant for this study was formulated using a mechanical stirrer rotating at 750 – 760 rpm for 1 hour and the materials used were palm kernel oil, several additives, and water. The steps in the formulation process were based on the work of Lawal et al. [13]. The additives used in this formulation were emulsifiers (Polyoxyethylene Sorbitan Monostearate, TWEEN 60), anti-oxidant (2,6-Di-tert-butyl-4-methylphenol), anti-corrosion (ethanolamine) and aluminium oxide nano-powder (20 nm particle size). As the lubricant was a soluble type, emulsifier was required to mix the vegetable oil and water together at the ratio of 1:10. Palm kernel oil was selected as the base oil because of its high saturated fatty acids content. As previously mentioned, a high composition of saturated fatty acids inside the chemical structure of vegetable oils can reduce the rate of oxidation, thus making palm kernel oil as the suitable candidate. Since the temperature and humidity at the current location were high, poor low temperature properties of the vegetable oil should not bring any harm towards the performance of the lubricant. Furthermore, the said oil was selected due to their abundance and accessibility in this country.

Anti-oxidant in this study was used to reduce the rate of oxidation of the palm kernel oil. Even though the oil has a high content of saturated fatty acid, there are still traces of unsaturated fatty acid that can lead to the process of oxidation, thus requiring the use of the anti-oxidant agent. Anti-corrosion was used as a long-term corrosion resistance that provides protection to the ferrous and non-ferrous surface. Furthermore, the additive was used as a stabilizing agent for a stable emulsion and thereby slowing down the rate of separation between palm kernel oil and water. Lastly, aluminium oxide nano-powder was included in the formulation to increase the performance of the vegetable-based lubricant. Researchers have investigated on the utilization of nano-powder in lubricant, and mostly were indicating that the inclusion of nano-powder has significantly increased the lubricant's

performance [14]. This is because inclusion of nano-powder increases the thermal conductivity of lubricant, which can extract heat from the cutting region at a much faster rate and thereby increasing the lubricant's cooling capabilities. Moreover, the spherical shape at nano level of the aluminium oxide powder will increase the lubricating properties of the lubricant by providing the rolling effect between the cutting tool and the workpiece.

Before conducting experiments, the formulated vegetable-based lubricant was tested for their wetting capabilities (wetting angle). The wetting angle is the ability of such liquid to cling on to a surface. Low wetting angle ($<90^\circ$) indicates high wettability, meanwhile high wetting angle ($>90^\circ$) indicates low wettability. Favourably, the cutting lubricant should have a low wetting angle (high wettability) to provide a better rate of heat transfer from the cutting region to the surroundings [15]. This is because at low wetting angle, a constant volume droplet will exhibit high surface coverage in comparison to high wetting angle. According to Fourier's law, high surface coverage can increase the rate of heat transfer from one position to other. Figure 2 shows the wetting angles of the formulated vegetable-based lubricant and the conventional mineral-based lubricant at constant volume. Observing those figures, the formulated vegetable-based lubricant produces much lower wetting angle in comparison to the conventional mineral-based lubricant. Therefore, the formulated vegetable-based lubricant was expected to provide better cooling than the conventional mineral-based lubricant, which is favorable in the turning process.

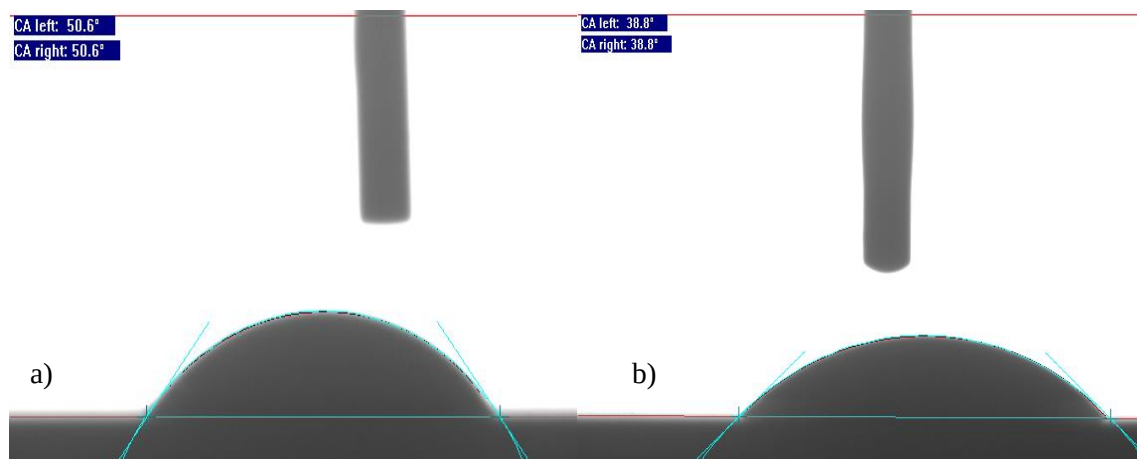


Figure 2. The wetting angle a) conventional mineral based lubricant; b) formulated vegetable-based lubricant.

2.2 Turning process

This experimental process was conducted on a lathe machine (Colchester VS Master 3250) and the AISI 431 stainless steel was used as the work material. The cutting tool used was PVD coated carbide inserts that features multi-layered coating with ultra-thin layers of TiAlN and AlCrN, type: TNMG160408-SU AC520U. The experiment was conducted with the aid of full factorial design of experiment (DOE). The said design will be able to determine the effect of each variable factor at every level of the response, as well as the effects of interactions between factors. In this work, three cutting parameters (cutting speed, depth of cut, and feed rate) and type of lubricants were considered as the variable factors. The lubricants used were the formulated vegetable-based lubricant and the mineral based lubricant. The vegetable-based lubricant was delivered onto the work material by MQL system (KENCO KNPMB 400), while the mineral based lubricant was by flooded cooling. Table 2 shows the parameters and their levels adopted in this experimentation. As this study considered four variable factors at two level experiments, the DOE created a 2^4 matrix that consists of a total of 16 experimental runs. The surface roughness was recorded and analysed for each experimental run using

a portable surface roughness tester from Mitutoyo (Surftest SJ-210). Table 3 shows the experimental runs including the variable factors and the recorded surface roughness value.

Table 2. The variable factors and their levels.

No	Variable factors	Unit	Low level (-1)	High level (+1)
1.	Cutting speed, V	m/min	150	200
2.	Depth of cut, d	mm	1.0	2.0
3.	Feed rate, f	mm/rev	0.18	0.24
4.	Type of lubricant, l	-	M	V

M = Conventional mineral based lubricant (flooded cooling)

V = Formulated vegetable based lubricant (MQL)

Table 3. The experimental run and the surface roughness results.

No	Variable factors				Surface Roughness, μm
	V	D	f	l	
1.	-1	-1	-1	-1	2.609
2.	+1	-1	-1	+1	2.492
3.	-1	+1	-1	-1	2.451
4.	+1	+1	-1	-1	2.414
5.	-1	-1	+1	-1	4.783
6.	+1	-1	+1	-1	4.707
7.	-1	+1	+1	-1	4.569
8.	+1	+1	+1	-1	4.669
9.	-1	-1	-1	+1	2.470
10.	+1	-1	-1	+1	2.500
11.	-1	+1	-1	+1	2.137
12.	+1	+1	-1	+1	2.362
13.	-1	-1	+1	+1	4.645
14.	+1	-1	+1	+1	4.738
15.	-1	+1	+1	+1	4.372
16.	+1	+1	+1	+1	4.491

3. Experimental results

3.1 Analysis of variance (ANOVA)

The measured values of surface roughness from Table 3 were used to determine the variables that significantly influence the surface roughness. Table 4 shows the ANOVA results for surface roughness. From the ANOVA analysis, factors that significantly influence the surface roughness are the feed rate with 98.6%, followed by the depth of cut (0.7%), type of lubricant (0.3%), and cutting speed (0.04%). The results are similar to other research findings that concluded that the feed rate significantly affects the surface finish of a machined workpiece [16,17]. It appears that the type of lubricants whether flooded or MQL does not affect surface roughness.

Table 4. The ANOVA for surface roughness

Source	DOF	Adj SS	Adj MS	F -value	Contribution, %
Model	4	19.429	4.8574	866.76	
Linear	4	19.429	4.8574	866.76	

Cutting speed	1	0.0071	0.0071	1.27	0.036
Depth of cut	1	0.1367	0.1367	24.40	0.701
Feed rate	1	19.226	19.226	3430.6	98.63
Type of lubricant	1	0.0599	0.0599	10.69	0.310
Error	11	0.0056	0.0056		
Total	15	19.491			

3.2 Surface roughness

Figure 3 shows the effect plot of each variable on the surface roughness at every level. Based on the most influential factors, the surface roughness increases as the level of feed rate increase from 0.18 mm/rev to 0.24 mm/rev. At a higher feed rate, a larger cross-sectional area was being cut consequently increasing the friction between the cutting tool and workpiece. Therefore, with the increase of friction from increasing the feed rate, higher surface roughness will be seen on the workpiece. In terms of depth of cut, the surface roughness decreases as their level increases from 1.0 mm to 2.0 mm. This result is contradictory to the other's findings [18]. This is because at a higher depth of cut, the higher amount of material being removed from the workpiece creating more friction as that of higher feed rate. This action consequently will result in higher surface roughness value. For cutting speed, increasing their levels from 150 m/min to 200 m/min slightly increases the value of surface roughness. However, as the influence is so minimal, increasing the cutting speed or decreasing it would not make any difference.

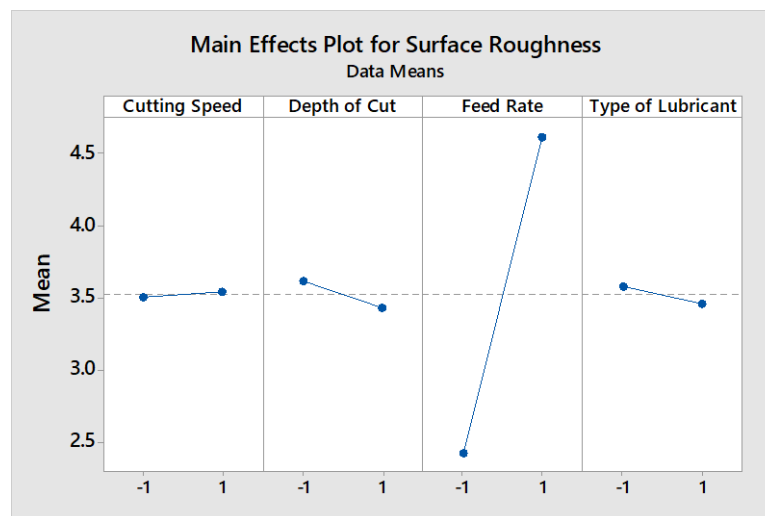


Figure 3. The main effects plot for surface roughness

Focusing on the type of lubricant, better surface finish (low surface roughness) was obtained when utilizing the vegetable-based lubricant under MQL. Even though the percentage of contribution was 0.310 %, it worth noting that the quantity of vegetable-based lubricant used during the study was far less than the mineral based lubricant because of MQL system. With the low amount of lubricant usage, the formulated vegetable-based lubricant was still able to outperform the mineral based lubricant. This result was contributed to the high wettability properties of the vegetable-based lubricant and the presence of nanopowder, which improves the rate of heat transfer from the cutting region to the surrounding due to large surface coverage and high thermal conductivity of nanoparticles [19]. Other than that, the aluminium oxide powder provides additional lubricating properties by exhibiting rolling effects between the cutting tool and machined workpiece, hence reducing the coefficient of friction [20]. Furthermore, the nanopowders usually form a thin film layer on the surface of the workpiece, which reduces the contact pressure and act as a protection layer for the workpiece as the nanopowder will receive the highest contact pressure of the cutting instead of the workpiece. Hence these actions contribute to having low surface roughness value in utilizing the formulated vegetable-based lubricant.

4. Conclusion

The study addresses the current issues and challenges in formulating the vegetable oil into a cutting lubricant for machining applications. An attempt has been made to formulate vegetable base lubricant addressing their wettability issues. A comparison has been made between the formulated vegetable-based oil and conventional mineral-based lubricant in turning process under identical cutting conditions. Based on the results, following conclusions can be drawn.

- The formulated vegetable oil produced low wetting angle (38°) compared to mineral based lubricant (50°). This will ensure better wettability in the cutting zone and improve heat transfer rate from the cutting zone.
- Feed rate is the most significant factor affecting surface roughness. Its contribution is about 98% compared to other factors. The depth of cut and cutting speed have relatively no effects on the surface finish.
- The results from the experimental study showed that the formulated vegetable-based lubricant was able to outperform the mineral based lubricant by 0.31%. Even though, the difference is small, the amount of vegetable-based lubricant (MQL) used was far less than the mineral based lubricant under flooded cooling. Therefore, the study supports that the used of vegetable base oil as cutting lubricant has comparable or even better lubricating performance than the conventional mineral-based lubricant with the least amount of usage.

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