A Review of Application of Vegetable Oil-Based Cutting Fluids in Machining Non-Ferrous Metals

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Abstract

In the beginning, cutting fluids consisted of simple oils applied with brushes to cool and lubricate the machine tool. However, cutting fluid formulation became more complex as cutting operations became more severe. There are several types of cutting fluids nowadays and the most common can be categorized into cutting oils or water-miscible fluids. In this paper, attention is focused on recent research work on the application of vegetable oil-based cutting fluids in machining non-ferrous metals. The efficiency of various vegetable oil-based cutting fluids based on some process parameters such as thrust force, temperature developed at the tool chip interface and flank wear during machining of some non-ferrous metals using different tool materials were highlighted. The results obtained established vegetable oil-based cutting fluids as a good metalworking fluid.

Keywords: Cutting fluid, Vegetable oils, Machining, Performance

1. Introduction

Vegetable oils are viable and renewable source of environmentally benign oils. The increased need for renewable and biodegradable lubricants can be traced to stronger environmental concerns and growing regulations over contaminations and pollution. In 2002, an estimated annual growth rate of 7 – 10 % for environmentally benign lubricants was expected on the US market for few years compared to a rate of only 2 % for the overall lubricant market (de Guzman, 2002). Reports indicate that nearly 38 million metric tonnes of lubricants were used globally in 2005, with a projected increase of 1.2% over the next decade (Kline & Company, 2006). Due to their advantages, the consumption of metalworking fluids (MWFs) is increasing in machining industry. It is reported that European Union alone consumes approximately 320,000 tonnes per year of MWFs of which, at least two-thirds need to be disposed (Abdalla et al. 2007). Despite their widespread use, they pose significant health and environmental hazards throughout their life cycle. Research reports (Bennett, 1983; HSE, 1991a; HSE, 1991b; HSE, 1994; HSE, 2000) indicate that about 80% of all occupational diseases of operators were due to skin contact with MWFs**.** Estimation says that in the USA alone about seven hundred thousand to one million workers are exposed to MWFs (Korde et al. 1993). 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 MWFs (Zeman, et al 1995), which are more harmful to the operators. To overcome these challenges, various alternatives to mineral-based MWFs are currently being explored by scientists and tribologists. Such alternatives include synthetic lubricants, solid lubricants and vegetable-based lubricants. Approximately 85% of lubricants being used around the world are mineral-based oils (Loredana et al. 2008). Enormous use of mineral based oils, created many negative effects on environment. The major negative effects is particularly linked to their use, which results in surface water and groundwater contamination, air pollution, soil contamination and consequently, agricultural product and food contamination (Birova et al. 2002).

Hence, there is a growing public interest in environmentally friendly lubricants due to awareness of environmental problems associated with conventional mineral oil-based lubricants (Choi et al. 1997). Even though the toxicity of lubricants is low, their accumulation in the environment may cause damage in the long run. A large proportion of the lubricants pollute the environment either during or after use. In many countries, there are well defined guidelines and legislations for environmentally friendly lubricants (Zeng et al. 2007). Several organizations around the world are working to improve such lubricants by evaluating their potential for environmental hazard. Examples include the German "Blue Angel", USA "Green Seal", and Canadian "Environmental Choice" (Wang and Hadfield, 2003). Mineral oil-based lubricants contain many kinds of additives such as antioxidant, anti-wear, detergents, dispersants, anti-foams, extreme pressure agents, friction modifiers and viscosity improvers. Some of these additives are toxic and harmful to human health, wildlife and environment (Kleinova, et al., 2008). The environmental and toxicity issues of mineral oil-based lubricants and their additives as well as their rising cost related to a global shortage have led to renewed interest in the use of vegetable oils, such as soybean oil, canola oil, sunflower oil, coconut oil, sesame oil, castor oil etc. as environmentally friendly lubricants and industrial fluids (Lathi and Mattiasson, 2007; Rudnick, 2009). Vegetable oils generally possess some excellent lubricating properties, for example, good inherent lubricity, low volatility, high viscosity index, excellent solvency for lubricant additives and easy miscibility with other fluids. The growing demand for biodegradable materials has opened an avenue for using vegetable oils as an alternative to mineral oil-based polymeric materials (Bisio and Xanthos, 1995; Li et al. 2001), most especially in machining operations. The public awareness in environmental issues has been constantly growing (Eichenberger, 1991). Lubricants are used in many diverse areas; therefore, their environmental acceptability has become increasingly important. As a result, research on biodegradable functional fluids emerged as one of the top priorities in lubrication in the early '90s which led to a lot of growing number of environmentally friendly fluids and lubricants in the market (Busch and Backe, 1993). Vegetable oils, especially rapeseed (Flider, 1995) and canola (Operating hydraulics in "Green" fluids, 1993) are some of the more promising candidates as basestocks for the biodegradable lubricants. They are readily biodegradable and less costly than synthetic basestocks. They often show quite acceptable performance as lubricants (Vegetable oil based tractor lubricant**,** 1994). Cutting fluids are normally classified into three main groups; that is; (i) neat cutting oils (ii) water-soluble fluids and (iii) gases. The water soluble fluids can be classified as emulsifiable oils (soluble oils), chemical (synthetic) fluids or semi-chemical (semi-synthetic) fluids. Fluids within these classes are available for light, medium and heavy duty performance (El Baradie, 1996). In general, vegetable oils are highly attractive substitutes for petroleum-based oils because they are environmentally friendly, renewable, less toxic and readily biodegradable (Norrby, 2003; Matthew et al., 2007).

Consequently, vegetable oils-based cutting fluids are more potential candidates for use in industries as lubricants. Many investigations are in progress to develop new bio-based cutting fluids from various vegetable oils available around the world. Because of environmental concerns and growing regulations over contamination and pollution, the increased need for renewable and biodegradable lubricants cannot be over stretched. Vegetable oils are a viable and renewable source of environmentally favourable oils. The majority of vegetable oils consist primarily of triacylglycerides, which are molecular structure with three long chain fatty acids attached at the hydroxyl groups via ester linkages. The fatty acids in vegetable oil triglycerides are all of similar length, between 14 and 22 carbons long, with varying levels of unsaturation (Asadauskas et al. 1997; Allawzi et al. 1998). The triglyceride structure of vegetable oils provides qualities desirable in a lubricant. Long, polar fatty acid chains provide high strength lubricant films that interact strongly with metallic surfaces, reducing both friction and wear. The strong intermolecular interactions are also resilient to changes in temperature providing a more stable viscosity, or high viscosity coefficient. The similarity in all vegetable oil structures means that only a narrow range of viscosities are available for their potential use as lubricants. The strong intermolecular interactions whilst providing a durable lubricant film also result in poor low-temperature properties. The fluid also remains biodegradable with low toxicity throughout all stages of its life. Lubricant formulations are being developed based on the benefits and limitations of vegetable oils. Without additives, vegetable oils out performed mineral oils in antiwear and friction (Asadauskas et al. 1997; Asadaukas et al, 1996), scuffing load capacity (Kozma, 1997) and fatigue resistance (Odi-Owei, 1988). Fully formulated vegetable oil lubricants, in comparison to mineral oil counterparts, display a lower coefficient of friction, equivalent scuffing load capacity and better pitting resistance, but also poorer thermal and oxidative stability (Hohn et al.1999; Arnsek and Vizintin, 1999a; Arnsek and Vizintin, 1999b; Arnsek and Vizintin, 2001; Krzan and Vizintin, 2003a; Krzan and Vizintin, 2003b). At extreme loads, vegetable oil-based lubricants become significantly less effective (Vizintin and Arnsek, 2000). Vegetable oils are particularly effective as boundary lubricants as the high polarity of the entire base oil allows strong interactions with the lubricated surfaces. Belluco and de Chiffre (2001) evaluated the performance of a range of mineral and vegetable oil-based cutting fluids in a range of machining operations and vegetable-based oil formulations displayed equal or better performance than the reference commercial mineral oil in all operations. In summary, vegetable oils display many desirable characteristics, which make them very attractive lubricants for many practical applications. Table 1 shows the advantages and disadvantages of vegetable oils as cutting fluids.

Table 1. *Advantages and disadvantages of vegetable oils as lubricants ((Fox and Stachowiak, 2007)*

Advantages	Disadvantages
High biodegradability	Low thermal stability
Low pollution of the environment	Low oxidative stability
Compatibility with additives	High freezing points
Low production cost	Poor corrosion protection
Wide production possibilities	
Low toxicity	
High flash points	

The major performance issues such as poor low temperature properties and low resistance to oxidative degradation are addressed by various methods such as (i) reformulation of additives (ii) chemical modification of vegetable based oils and (iii) genetic modification of the oil seed crop (Fox and Stachowiak, 2007; Lou, 1996). In this review, trends in the applications of vegetable-oils cutting fluids in machining non-ferrous metal are reported.

2. Development of vegetable oil-based cutting fluids

There were several reasons for inability of vegetable oil-based cutting fluids to exhibited sufficient performance for industrial applications. One of the main reasons was that vegetable oil-based cutting fluids were misformulated. Early developers in the vegetable-based lubricant market used the same chemistry that was used for mineral lubricants for vegetable oils-based. This approach was not effective as the characteristics of vegetable oils are vastly different from those of mineral-oils. Typical characteristics of vegetable oils as compared with petroleum oils are summarized in Table 2.

Table 2. *Characteristics of petroleum and vegetable oils (Miller, 2008)*

Characteristics	Petroleum oil	Vegetable oil
Lubricity	Low	High
Oxidative Stability (RPVOT*)	300	50
Viscosity Index (VI)	100	200
Hydrolytic Stability	High	High
Polarity	Low Polar	High Polar
Saturation	Saturated	Unsaturated
Flash Point (^{0}F)	200	450
Pour Point (^{0}F)	-35	-35

- RPVOT (Rotary Pressure Vessel Oxidation Test)

Similarly, conventional knowledge has focused on the limitations of vegetable oils as basestocks for lubricants, such as weakness of the oxidative stability, the cold temperature performance, and incompatibility with elastomers. For instance, all triglyceride vegetable-based lubricants have temperature limitations; there are some that are better than others. Most vegetable-based lubricants have a maximum operating temperature of 60 °C, though; there are some that offer protection as high as 104.44 °C (Miller, 2008). Therefore, vegetable oils have to be formulated for their individual characteristics. However, improvements in vegetable basestocks, performance chemistry, and formulation expertise have allowed for the development of biodegradable products with performance similar to or better than conventional petroleum fluids. When chemists began to look at colloidal system around 1905, the scientific basis of cutting fluids formulation began to unfold (McCoy, 2006). The growing body of knowledge on colloid and surfactant chemistry led to the compounding of various 'soluble oils" using natural fatty oils. This led to the granting of patent to Hutton for the process of producing water-soluble oils. He compounded sulfonated and washed castor oil with any sulfonated unsaponified fatty oil (other than castor oil), and then saponifying the sulfonated oils with caustic alkali (Hutton, 1923). These developments were the pivots on which the formulation of vegetable oil-based cutting fluids was built.

3. Application of vegetable oil- based cutting fluids in machining non - ferrous metals

Some of the factors that make machining of non- ferrous metal difficult can be addressed with the application of vegetable oil-based cutting fluids. The application of vegetable oil-based cutting fluids will help to eliminate the effect of heat and friction, provide lubrication between chip tool interfaces and flush away chips from machining of non-ferrous alloys and improve surface finish of the work material. The machinability of some non-ferrous metals using vegetable oil-based cutting fluids is discussed below:

3.1 Titanium alloys

Rahim and Sasahara (2011), studied the potency of minimum quantity lubricant palm oil (MQLPO) and minimum quantity lubricant synthetic ester (MQLSE) during drilling of titanium alloys with carbide drill coated having AlTiN insert. The holes were drilled under the action of the external air blow, minimum quantity lubricant (MQL) and flood coolant conditions (water soluble type). The first stage of the experiment involved the use of cutting speed of 60, 80 and 100 m/min, feed rates of 0.1 and 0.2 mm/rev. Thrust force, torque and workpiece temperature were measured and compared. The second stage of the experiment involved drilling of hole of a depth of 10 mm at the constant cutting speed of 60 m/min, feed rate of 0.1 mm/rev and the following tool life criteria (i) average flank wear, VB(av) = 0.2 mm, (ii) maximum flank wear, VB(max) = 0.3 mm,(iii) corner wear = 0.3 mm, (iv) chipping = 0.2 mm, (v) catastrophic failure and (vi) cutting distance = 440 mm (due to the shortage of workpiece material) to evaluate the tool life performance. The flood condition had the lowest torque among the other conditions tested. The air blow did not reduce the drilling torque as much as the other coolant-lubricant conditions as it recorded the highest torque value of 14.4 Nm. The thrust force and torque for the air blow condition were the highest followed by MQLSE, MQLPO and flood cutting conditions. The effect of various cutting speeds and feed rates on MQL conditions showed that thrust force and torque decreased with an increase in the cutting speed. MQLSE and MQLPO recorded the lowest thrust force of 2318 N and 1954 N at the cutting speed of 100 m/min and feed rate of 0.1 mm/rev, which translated into a reduction of 27 % and 19 % for MQLSE and MQLPO respectively. The torque for MQLSE at cutting speed of 100 m/min reduced significantly to 9.6 and 13.7 Nm at a feed rate of 0.1 and 0.2 mm/rev respectively. MQLPO induced the lowest torque at the cutting speed of `100 m/min and feed rate of 0.1 mm/rev, which indicated a 32% reduction when the cutting speed increased from 60 to 100 m/min. The workpiece temperature was measured at two locations. The air blow cutting condition recorded the maximum workpiece temperature at both locations. MQLSE cutting condition had lower temperature than the air blow cutting condition with a reduction of 15% and 6.5% respectively at the two locations. MQLO condition recorded at the two locations recorded the lowest temperature in comparison to the MQLSE and air blow cutting conditions.

The second experimental set up showed that, the flank wear rapidly grew and suffered from excessive chipping. A significant reduction in tool life for a drilling time of 48 s or 110 mm for the air blow conditions was recorded. The flank and corner wear rate was gradual and grew progressively for MQLSE and MQLPO. MQLPO condition produced lower tool wear rate in comparison to MQLSE condition. The flood condition also showed superior performance by having the lowest flank wear and corner wear in comparison to air blow conditions. MQLPO exhibited the lowest tool wear rate than the MQLSE and air blow conditions compared to flood condition. An increment of 554 % in tool life was achieved by MQLPO, MQLSE and flood conditions compare to the air blow condition at the cutting speed of 60 m/min and feed rate of 0.1 mm/rev.

3.2 Aluminum and copper

Ojolo et al. (2008)**,** experimentally determined the effect of some straight biological oils (groundnut oil, coconut oil, palm kernel oil and shear butter oil) on cutting force during cylindrical turning of three materials (mild steel, copper and aluminum) using tungsten carbide tool. The experiment involved the spindle speeds of 250, 330, 450 and 550 rpm at a constant feed rate of 0.15 mm/rev and 2 mm depth of cut for each of the workpiece. Their results showed that bio-oils were suitable for metalworking fluids, but the effects of the bio-oils on cutting force were material dependent as depicted in Figures 1 (a and b). Groundnut oil exhibited the highest reduction in cutting force when aluminum was turned at a speed of 8.25 m/min and feeds of 0.10, 0.15 and 0.20 mm/rev, respectively. Palm kernel oil had the best result when copper was turned at feed lower than 0.15 mm/rev. However, at higher feeds, groundnut oil had the best result for copper. Coconut oil recorded the highest cutting force in all the three materials machined followed by shear butter oil. They concluded that groundnut and palm kernel oils were effective in reducing cutting force during cylindrical turning of the three workpieces.

Fig.1a. *Variation of cutting force with feed rate on aluminum at 2 mm depth of cut using the four lubricants (Ojolo et al. 2008).*

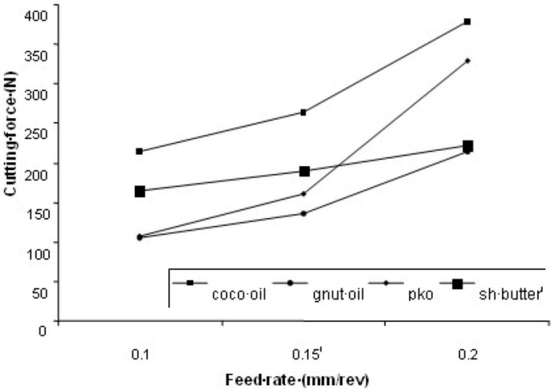
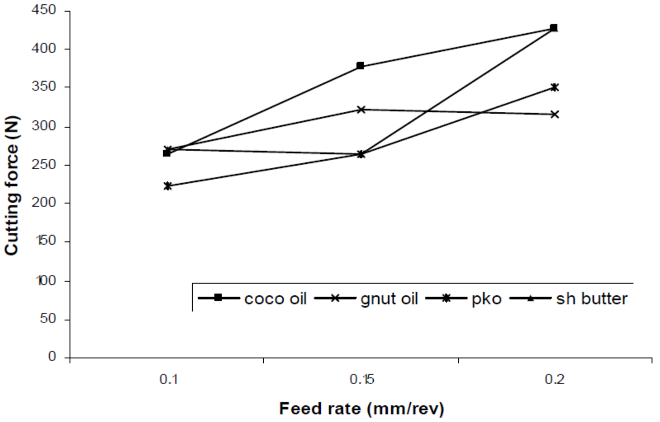


Fig.1b. *Variation of cutting force with feed rate on copper at 2 mm depth of cut using the four lubricants (Ojolo et al. 2008).*



3.3 Brass and Aluminum

Ojolo and Ohunakin (2011), investigated the effect of cutting speed, feed rate, depth of cut and rake angle on cutting force when cylindrical turning mild steel, brass, and aluminum rods with high speed steel tool using palm-kernel oil as cutting fluid. The impact of lubrication on the coefficient of friction between the chip and rake face during turning operation, assuming a negligible friction between the flank and cut surface was measured. The reduction in coefficient of friction at cutting speed of 4.15 m/s and rake angle 9^o for aluminum was 33.3 % and an increase of 13.8 % was recorded for brass. At a cutting speed of 4.15 m/s and depth of cut of 1.5 mm, there were 9.79 % reduction in coefficient of friction for brass and increment of 46.7 % for aluminum. While a reduction of 9.2% coefficient of friction was recorded for brass and an increase of 30.4 % coefficient of friction was recorded for aluminum at cutting speed of 4.15 m/s and feed 1.8 mm/rev. Similar trends were observed by varying the cutting conditions on the work parts through different selected values. The effect of palm-kernel oil as a metal cutting lubricant was more pronounced on aluminum than brass. The study established palm-kernel oil as a good metal cutting lubricant. It was observed that as turning parameters were varied, the performances of the lubricant were equally altered in term of the coefficient of friction.

4. Conclusion

Cooling and lubrication in machining are important in reducing the severity of the contact processes at the cutting tool-workpiece interfaces. Historically, water was used mainly as coolant due to its high thermal capacity and availability (McCoy, 2006; Machado and Wallbank, 1997). Krahenbuhl (2005) suggested vegetable oils as a viable alternative to petroleum, considering performance, cost, health, safety and environmental points of view. This work is therefore a review of application of vegetable oil-based cutting fluids during machining of non-ferrous metals by focusing on their machining behaviours as highlighted :

1. The potency of minimum quantity lubricant palm oil, minimum quantity lubricant synthetic ester, air blow minimum quantity lubricant and flood coolant condition during the drilling of titanium alloy with carbide drill coated AlTiN insert show that, the minimum quantity lubricant synthetic ester and minimum quantity lubricant palm oil have the lowest thrust force of 2318 N and 1954 N at cutting speed of 100 m/min and feed rate of 0.1 mm/rev. The torque for minimum quantity lubricant synthetic ester at cutting speed of 100 m/min reduced to 9.6 and 13.7 Nm at feed rates of 0.1 and 0.2 mm/rev respectively. Minimum quantity lubricant recorded the lowest torque at the cutting speed of 100 m/rev and feed rate of 0.1 mm/rev, which shows 32 % reduction when cutting speed increased from 60 to 100 m/min.
2. When groundnut, coconut, palm kernel and shear butter oils were used as cutting fluids during the cylindrical turning of copper and aluminum using tungsten carbide tool material. The lowest reduction of cutting forces of 100, 130 and 200 N were recorded for groundnut oil when aluminum was machined at cutting speed of 8.25 m/min, depth of cut of 2 mm and feed rates of 0.10, 0.15 and 0.20 mm/rev respectively. While the highest cutting forces of 210, 250 and 380 N were recorded for coconut oil respectively under the same machining conditions. The best cutting force of 220 N was reported for copper when palm kernel oil was used as cutting fluid under the same machining conditions.
3. When palm kernel oil was used as cutting fluid in cylindrical turning of brass and aluminum using high speed steel tool material, there was 9.79% reduction in coefficient of friction for brass and increment of 46.7% for aluminum at cutting speed of 4.15 m/s and feed rate of 1.8 mm/rev. The impact of lubrication of palm kernel oil with a reduction of 33.3% in coefficient of friction was noticed, when rake angle was varied for aluminum. While, brass show no effect of lubrication with 7.9% increase in coefficient of friction.

5. References

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