Journal of Cleaner Production xxx (2016) 1–17

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

# Experimental evaluation of the lubrication performance of mixtures of castor oil with other vegetable oils in MQL grinding of nickel-based alloy

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A R T I C L E I N F O

*Article history:*
Received 15 July 2016
Received in revised form 28 September 2016
Accepted 14 October 2016
Available online xxx

*Keywords:*
Castor oil
Rheological properties
Vegetable oil
Minimum quantity lubrication
Lubrication performance

A B S T R A C T

Vegetable oil is employed as base fluid in precision grinding because of its biodegradability and non-pollutant properties. Castor oil exhibits superior lubrication performance to other vegetable oils, but its high viscosity and poor flow limit its application in industrial production. In this study, castor oil was used as base oil and individually mixed with six other kinds of vegetable oils (i.e., soybean, maize, peanut, sunflower, palm, and rapeseed oils) at a ratio of 1:1 to change the rheological properties of the former. Each mixture was obtained as base oil for minimum quantity lubrication grinding. The high-temperature nickel-based alloy GH4169 was used as workpiece to evaluate the lubrication performance at the grinding wheel/workpiece interface. The mechanism of lubrication was also studied based on the molecular structure of vegetable oil. Specific grinding force, specific grinding energy, surface roughness, surface microtopography, and grinding debris were compared among the experimental and comparison groups (castor oil). The workpiece surface profile was analyzed using the correlation function and cross-correlation coefficient. Results indicated that the comprehensive lubricating performance of mixed oil was superior to that of castor oil, and soybean/castor oil exhibited the optimal performance. The specific tangential grinding force and specific normal grinding force were 0.664 and 1.886 N/mm, respectively, with 27.03% and 23.15% reduction, respectively, with respect to those of castor oil. The surface profile curves of the workpiece obtained from four kinds of working conditions (castor oil, castor/soybean oil, castor/maize oil, and castor/palm oil) were also analyzed. The amplitude of the surface profile curve in castor/soybean oil is larger and the correlation coefficient is higher (0.51) than those under other mixed oils; hence, the workpiece showed the optimal surface quality.



## 1. Introduction

With improvement in science and technology, enhanced product quality, low cost, and environmental protection have been increasingly required by consumers. In this regard, engineers seek superior methods for grinding. In such pursuit, selection of lubricating fluid is a key step. The friction of a grinding wheel against a workpiece generates substantial heat during grinding. A part of the heat generated is lost through debris. Mao et al. (2013) found that only 10% heat is removed by the debris during grinding, and most of the heat generated transfers to the grinding wheel and workpiece (Malkin and Guo, 2007). Heat also influences the service life of the grinding wheel and the performance of the workpiece. The effect of heat transfer on the grinding wheel causes surface abrasive loss, increased wear, and shortened life. The workpiece affected by the transferring heat easily generates tensile residual stress, resulting in size and shape errors. When the surface temperature reaches a certain value, the workpiece becomes burnt, leading to alterations in its microstructure, anti-fatigue property, and wear resistance (Jin and Stephenson, 2008). Therefore, the application of effective cooling lubrication technology is of great value.

To reduce the processing temperature, improve the lubrication effect, and effectively protect the environment, scholars have used the dry grinding process and minimum quantity lubrication (MQL) grinding to replace flood grinding. Shen and Shih (2009) found that water-based grinding fluid for flood cooling lubrication is

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http://dx.doi.org/10.1016/j.jclepro.2016.10.073
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**Nomenclature and abbreviation**

| | |
|---|---|
| *MQL* | minimum quantity lubrication |
| *VBCFs* | vegetable based cutting fluids |
| $v_s$ | peripheral speed of grinding wheel (m/s) |
| $v_w$ | workpiece feed speed (mm/s) |
| $a_p$ | grinding depth (mm) |
| $F_t$ | tangential grinding force (N) |
| $F_n$ | normal grinding force (N) |
| $F'_t$ | specific tangential grinding force (N/mm) |
| $F'_n$ | specific normal grinding force (N/mm) |
| $b$ | grinding width (mm) |
| $U$ | specific grinding energy (J/mm$^3$) |
| $P$ | total consumed grinding energy (J) |
| $V$ | volume of material removed (mm$^3$) |
| *Ra* | arithmetic average height (μm) |
| *RSm* | mean spacing at mean line (mm) |
| *SEM* | scanning electron microscope |
| *VI* | viscosity index |
| $u$ | dynamic viscosity (cP) |
| $\tau$ | lateral displacement (mm) |
| $L$ | evaluation length |
| $R_{xy}$ | cross-correlation function value (μm) |
| $\rho_{xy}$ | cross-correlation coefficient |

commonly used because of its cooling and lubricating effects. Hadad et al. (2012) investigated 100Cr6 grinding through MQL technique with an overhead thermocouple to measure grinding temperature; MQL grinding consumes 7%–10% less energy than dry grinding. Dhar et al. (2007) reported that MQL generates 5%–15% smaller grinding force than that of dry grinding, thereby prolonging the service life of the cutters. Li et al. (2008) experimentally evaluated the performance of MQL technology against conventional flood cooling. The proposed method does not negatively affect the surface integrity and verified the process validity. Gaitondea et al. (2008) found that MQL achieves higher workpiece surface processing quality than dry grinding. Tawakoli et al. (2009) discussed the effect of grinding parameters on workpiece surface quality. With the optimum grinding fluid dosage and feed liquid parameters, MQL grinding achieves higher workpiece surface quality but lower tangential grinding force and specific grinding energy than those of flooding grinding.

The properties of lubricating fluid have been improved using mineral oil, a synthetic ester to vegetable oil. Traditional lubricating fluids mostly use mineral oil as base oil. However, mineral oil exhibits very poor biodegradability, which may cause long-term pollution to the environment. Synthetic and semi-synthetic base oils containing chemicals with additives and diluted in water are free from mineral oil. Synthetic base oils are suitable coolants but provide insufficient lubrication compared with other cutting fluids because of the lack of oiliness in the former (Debnath et al., 2014). Vegetable oil possesses unique advantages compared with other lubricating fluids. (1) Vegetable oil is a nontoxic or slightly toxic renewable source; this type of oil is clean and widely used. The refining and processing technology of vegetable oil is mature, and its price is relatively low (Cetin et al., 2011). (2) Vegetable oil exhibits excellent biodegradability; the glycerine ester group can be readily hydrolyzed and the unsaturated double bond in the ester group chain can be easily attacked by microorganisms, resulting in further b-oxidation. Moreover, natural fatty acids in vegetable oil can promote biodegradation (Lawal et al., 2013). (3) Vegetable oil also possesses a high lubrication property, which is determined by the basic structure of its molecules and chemical components (Asadauskas et al., 1997). Vegetable oil molecules can form an adsorption film on a metallic surface; the fatty acid component of this oil can react with such metal surface, forming a monofilm of metallic soap. Both properties can influence anti-friction and anti-wear behavior. (4) Vegetable oils also exhibit high flash point, which reduces smoke formation and fire hazard. A high flash point allows the use of cutting fluid under high-temperature conditions (Kuram et al., 2013). Hence, vegetable oil-based grinding fluid satisfies the requirements of lubrication properties and holds great potential for application.

Scholars have adopted vegetable oil as MQL base oil. Zhang et al. (2015) used soybean, palm, and rapeseed oils as base oils to evaluate the grinding and lubrication properties of MQL with nanoparticles under four grinding working conditions: dry grinding, flood grinding, MQL (using three vegetable oils and liquid paraffin), and nanoparticle jet MQL (using nanoparticles of different concentrations). The results indicated that palm-oil-based nanofluid with $MoS_2$ exhibits the optimal lubrication property under nanoparticle jet MQL conditions because of the high fatty acid content and high film-forming property of carboxyl in palm oil. Zhang et al. (2016) explored the cooling performances of different kinds of vegetable oils and analyzed their underlying mechanism. Emami et al. (2014) assessed four types of lubricants (i.e., mineral, hydrocracked, synthetic, and vegetable oils) in terms of reduction in cutting force, specific energy, and surface roughness during the MQL grinding of $Al_2O_3$ engineering ceramics. MQL considerably affects cutting force, specific energy, and surface roughness and also decreases the environmental hazards of cutting fluids based on vegetable oil. Lawal et al. (2014) utilized Taguchi method to evaluate vegetable and mineral oil cutting fluids in converting AISI 4340 steel with coated carbide tools. Both palm-oil- and cottonseed-oil-based cutting fluids display superior heat conductivity and environment-friendly properties to those of other oils and hence serve as potential alternatives for machining AISI 4340 steel with coated carbide. Sharma and Sidhu (2014) investigated the effects of dry and near-dry machining on AISI D2 steel using VBCFs. VBCFs can improve the surface integrity and decrease the cutting temperature by nearly 50%. Rahim and Sasahara (2011a, 2011b, and 2011c) used palm oil and synthetic ester as MQL base oil for drilling experiments. The properties of palm oil and synthetic ester during drilling were also compared. These studies indicate that palm oil conforms to the grinding fluid standards and can replace synthetic ester as MQL base oil. With its unique properties, vegetable oil can enhance productivity and lengthen the life of the cutter. In machining, using vegetable oil as base grinding fluid enhances workpiece surface quality and tolerance precision, shortens downtime, and enhances productivity. Steigerwald (2005) reported that glyceride in vegetable oil is easily hydrolyzed, and the unsaturated double bond in the ester chain easily undergoes b-oxidation upon microbial attacks, leading to biodegradable property of vegetable oils. Asadauskas et al. (1997) comprehensively compared castor, super-refined mineral, and high-oleic acid sunflower oils in terms of viscosity, oxidation stability, deposition generation tendency, volatility, lubricity, and compatibility with additives. The results indicated that castor oil exhibits potential as biodegradable lubrication base oil. Castor oil and its derivatives can be used as lubricant base oil with different viscosity grades. Prasenjit et al. (2008) conducted an analytical study of the frictional films of