The International Journal of Advanced Manufacturing Technology (2020) 106:4143–4155
https://doi.org/10.1007/s00170-019-04695-x

ORIGINAL ARTICLE

Physicochemical properties of degradable vegetable-based oils on minimum quantity lubrication milling

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Received: 29 August 2019 / Accepted: 10 November 2019 /

Abstract

With increasing attention being paid to environmental and health problems in metal machining, developing an environmentally friendly cutting fluid is an urgent need. Degradable vegetable oils with non-toxicity and renewability are becoming increasingly popular. However, the mechanism of physicochemical properties of different vegetable oils is not clear on minimum quantity lubrication (MQL) milling. In the study, five typical vegetable oils (i.e., cottonseed, palm, castor, soybean, and peanut) were selected as base oil to experimentally evaluate the lubrication performance of the tool–workpiece interface compared with synthetic cutting fluid. With Grade 45 steel as workpiece material, the lubrication performance was evaluated in terms of milling force, surface roughness and surface morphology, as well as the composition, molecular structure, and viscosity of vegetable oils. Results showed that the vegetable-based oils achieved lower milling force and better surface quality than the synthetic cutting fluid. Among them, palm oil obtained the lowest milling force ($F_x = 309$ N, $F_y = 154$ N) at 7.76% and 13.6% lower than that of synthetic cutting fluids. The surface quality obtained by vegetable-based oils is superior to that of the synthetic cutting fluid, and the cottonseed and palm MQL acquired the best surface, while soybean obtained the worst surface. Furthermore, the results of surface roughness are consistent with those of surface morphology. Finally, according to the analysis of composition and molecular structure, palm and cottonseed with high content of saturated fatty acids are more suitable as MQL base oils.

Keywords Milling · Vegetable-based oil · Minimum quantity lubrication (MQL) · Surface micromorphology

Highlights

1. Lubrication performance under different lubrication conditions in milling Grade 45 steel was studied.
2. The surface integrity under different lubrication conditions was studied.
3. Physicochemical properties of five kinds of vegetable oils were analyzed.
4. Viscosities of five kinds of vegetable oils were analyzed to validation.
5. The best lubrication performance was obtained by palm oil and cottonseed oil MQL.

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Nomenclature

MQL	Minimum quantity lubrication
SEM	Scanning electron microscope
F_x, F_y, F_z	Cutting force components in X, Y, and Z directions, respectively (N)
R_a	Arithmetic average height (μm)
Rsm	Mean spacing at mean line (mm)
$\overline{F}_{max}$	Mean of milling force peak

1 Introduction

As an advanced processing technology in modern manufacturing industries, milling is one of the most important methods to produce mechanical parts due to advantages of high processing efficiency and good surface quality. However, the cutting area is characterized by great friction and high temperature and pressure during the processing, which determines the importance of a lubrication in tool–workpiece interface [1, 2]. A lubricant is mainly used to prevent workpiece burning, decrease surface friction, and eliminate debris [3–5]. In traditional machining, a large amount of cutting fluid is usually poured into the milling zone to reduce the cutting temperature. However, only a small proportion can enter the milling area and play the role of cooling and lubrication and cannot effectively transfer the heat [6]. Furthermore, a large amount of cutting fluid not only greatly increases the cost [7] but also causes serious environmental pollution and poses risks to human health [8].

Dry cutting is adopted to protect the environment and reduce cost, thereby causing less environmental pollution because no cutting fluid participates in the machining. However, due to the lack of lubrication in the cutting area, great friction and adhesion occur in the tool–workpiece interface, thereby leading to poor workpiece surface quality [9]. At the same time, because removing chips is difficult, they gather on the workpiece surface, and a large amount of heat is transferred to the tool and workpiece, thereby resulting in secondary hardening of workpieces, serious surface burns, and tool wear under high temperature and pressure.

Minimum quantity lubrication (MQL) is another green processing technology [10], also known as near-dry machining [11] or micro-lubrication [12], which sprays micron droplets into the processing zone after mixing high-pressure gas and micro-lubricant. The high-pressure gas performs cooling and chip removal [13], and the lubricant adheres to the surface of the workpiece to form a protective film, which performs lubrication. MQL technology can accurately control the supply of cutting fluid, and the flow rate is as low as 10–100 ml/h, much lower than that of flood cutting with the value of 1200 L/h [14, 15], which reduces the hazards to workers and the environment [16, 17]. Extensive research and experiments show that MQL technology improves the cutting performance and achieves or even exceeds the effect of flood cutting under certain experimental conditions. MQL has been widely used in the machining process. Li and Lin [18] found that compared with dry grinding, the MQL technique increased the tool life three times and produced the best surface finish. Through a series of studies, Tawakoli et al. [19] observed that MQL with oil produced good surface finish. Sadeghi et al. [20] concluded that MQL improved surface quality and reduced the grinding force and friction coefficient in grinding hardened steel. Mao et al. [21–23] found that MQL obtained similar results to wet grinding in terms of surface roughness, grinding forces, and temperature in grinding hardened 52100 AISI steel. Hadad and Sadeghi [24] found that MQL produced the best surface quality in turning AISI 4140 alloy steel. MQL machining was found to reduce the cutting force and cutting temperature and improve the surface finish compared with dry machining [25].

Most traditional lubricants use mineral oil as base oil, which includes synthetic and semisynthetic base oils. The only difference between synthetic and semisynthetic base oils is that the latter contain a small amount of oil (2%–30%) while the former contain no oil, which results in poor lubrication of synthetic base oils [26, 27]. Moreover, mineral oil is an exhaustible resource, and a large amount of bacteria and yeast is caused by chip pollution, which adversely affects the quality of the lubricant and represents a long-term environmental risk [28, 29]. With the development of science and technology and increasing public recognition of the importance of environmental protection, sustainable manufacturing with environmental friendliness, resource conservation, and energy efficient utilization occupy an increasingly prominent position. As a result, vegetable-based oil with non-toxicity [30, 31], good biodegradability [32], high flash point [33], and renewability and affordability [32, 34] are becoming increasingly popular. To evaluate the cooling and lubrication performance of vegetable oils, many studies have been conducted on grinding, turning, drilling, and milling.

Regarding grinding, Emami et al. [35] investigated the performance of four types of lubricants (i.e., mineral, hydrocracked, synthetic, and vegetable oils) and evaluated them according to cutting force, specific energy, and surface roughness in grinding Al_2O_3 engineering ceramics. The results showed that MQL based on vegetable oil considerably affected the cutting force, specific energy, and surface roughness and can also decrease the environmental hazards. Zhang et al. [36, 37] explored the lubricating property of soybean, palm, and rapeseed oils as base oils compared with liquid paraffin. In the experiment, four types of grinding working conditions were applied: dry grinding, flood lubrication (5% water-soluble grinding fluid), MQL (vegetable-based oil and liquid paraffin), and nanoparticle jet MQL. The results indicated that palm oil-based nanofluids produce the best lubricating property because of the high saturated fatty acid and high film-forming property of carboxyl groups in palm oil. Wang et al. [38, 39] studied the lubrication properties of seven types of vegetable oils using MQL technique in grinding GH4169. The results indicated that vegetable oil had better lubrication properties than mineral oil and flood lubrication. Among the vegetable oils, castor oil achieved the best lubrication property and best surface quality of the workpiece. Li et al. [40–42] compared the performances of MQL grinding by using castor, soybean, rapeseed, corn, sunflower, peanut, and palm oils as base oils. The results revealed that palm oil is the optimum base oil of MQL grinding. Guo et al. [43, 44] examined the performance of mixed vegetable oils. In the experiments, castor oil was used as base oil and individually mixed with six other types 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. 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. Gao et al. [45] investigated the dispersing mechanism of different types of surfactants and evaluated the dispersion stability and tribological performances using CNT nanofluids with palm oil. Yang et al. [46] developed a predictive model for minimum chip thickness and size effect in single diamond grain based on palm oil under MoS_2 nanofluid with different volume fraction.

Regarding turning, Khan et al. [8] presented the influence of MQL by vegetable oil-based cutting fluid in turning low alloy steel AISI 9310; they concluded that MQL was superior due to the substantial reduction in cutting zone temperature and enhanced the tool life and surface finish compared with completely dry and wet machining. Cetin et al. [30] used four different vegetable-based cutting fluids (sunflower and canola oils with different ratios of extreme pressure additives) and two commercial types of cutting fluids (semisynthetic and mineral) to evaluate the performance in reducing surface roughness and cutting and feed forces during turning AISI 304 L austenitic stainless steel. The results showed that sunflower and canola-based cutting fluids performed better than the others. Sharma and Sidhu [47] investigated the effects of dry and near-dry machining on AISI D2 steel by using vegetable oil as a lubricant. The results indicated that near-dry machining based on vegetable oil shows promising results over dry machining in terms of interface temperature and surface integrity. Kuram et al. [48] evaluated the performances of four different types of vegetable-based cutting fluids with additive of extreme pressure and a commercial mineral cutting fluid in turning of Al 7075-T6; the performance of vegetable-based cutting fluids were better than that of the commercial mineral cutting fluid. Pervaiz [49] studied the machinability of Ti6Al4V under the vegetable oil-based MQL condition and compared the performance with dry cutting and conventional flood cooling; vegetable oil-based MQL condition provided better lubrication to reduce friction. Gajrani [50] conducted a series of experiments to study the machining performances of bio-cutting fluid compared with mineral oil; the experimental results showed a significant reduction in cutting force, feed force, coefficient of friction, and surface roughness for MQL. Su et al. [51] investigated the performance of vegetable-based NMQL and ester oil-based NMQL in turning and concluded that the former outperformed the latter, especially at a high cutting speed.

Regarding drilling, Rahim et al. [52–54] conducted a series of experiments to study the performances of palm oil and synthetic ester under MQL drilling Ti-6Al-4 V compared with air blow and flood conditions; they concluded that palm oil had the best performance due to the formation of a boundary lubrication film, which reduces the friction and heat in the tool–workpiece and tool–chip interface. Nurul et al. [55] studied the surface roughness and surface integrity in the MQL drilling process using various vegetable oil-based lubricants, namely, palm, sesame, olive, and coconut oils. The results indicated that the coconut oil in this experiment had achieved better surface roughness and surface integrity than the other oils tested.

Regarding milling, Priarone et al. [56] studied the effects of lubrication strategy on machining performance in milling titanium aluminide. Vegetable-based cutting fluids achieved lower flank wear, higher tool life, and lower average surface roughness compared with dry machining and wet cutting. Pervaiz et al. [49] achieved better lubrication performance using vegetable oil-based MQL in milling titanium alloy compared with dry cutting and conventional flood cooling. Rahim and Sasahara [54] revealed that palm oil-based MQL performed better than synthetic ester-based system did in milling Ti-6Al-4 V. Li et al. [57] investigated the cooling and lubrication performances with vegetable oil-based cutting fluid in TC4 milling. Meanwhile, graphene nanoparticles were dispersed into the vegetable oil-based cutting fluid to improve the machining performance. Results showed that the graphene additive into vegetable oil was effective for improving the milling characteristics. Yin et al. [58] studied the lubrication performances under four conditions (i.e., dry, flood, vegetable-based MQL, and vegetable-based NMQL with Al_2O_3) in milling 45 steel. The results proved that vegetable-based NMQL and MQL had lower force and friction coefficient than flood and dry. Yin et al. [59], Dong et al. [60], and Bai et al. [61] explored the lubrication and cooling performance of different nanofluids with vegetable-based oil in milling Ti-6Al-4 V. The results showed the Al_2O_3 and SiO_2 nanofluids acquired a better lubrication and cooling effect than other nanofluids and MQL without nanoparticles.

After referring to a large number of studies on vegetable oil-based lubricants, scholars have proved that vegetable oil can be used as an MQL base oil in metal-cutting methods such as grinding, turning, drilling and milling, and good cooling and perfect lubrication effect has been achieved. However, except the team of Prof. Li at Qingdao University of

Technology, which studied the cooling and lubrication effects of different vegetable oils on grinding, other teams only used one vegetable oil as base oil and have not systematically evaluated the performance of various vegetable oils. As the metal removal mechanism of grinding is different from that of milling, even the same type of vegetable oil has a different influence on the cooling and lubrication performance. Furthermore, different types of vegetable oils have various compositions and molecular structures, and their lubrication and cooling effects also vary. To find the vegetable oils with the best lubrication in MQL milling, we used five different types of vegetable oils (i.e., cottonseed, palm, castor, peanut, and soybean oils) to evaluate the lubrication performance in milling Grade 45 steel compared with synthetic cutting fluids. By studying the milling force, surface roughness, and micromorphology of the workpiece surface under different lubrication conditions, we experimentally evaluated the lubrication performance of the tool–workpiece interface. The most suitable base oil for milling was selected combined with the composition, molecular structure, and viscosity of vegetable oils.

2 Experiment

2.1 Experimental setup

The experiment was conducted at the machining center of Dema ML1060B with dimensions of 3200 × 2450 × 2000 mm (*L* × *W* × *H*). The main technical parameters are spindle power of 11 KW, maximum speed of 8000 r/min, worktable driving motor power of 5 KW, cutting range of 1000 × 600 mm, and cutting feed rate of 10,000 mm/min. MQL device KS-2106 was used to convey the lubricant. Tridirectional piezoelectric dynamometer JR-YDCL-III I05B was used to measure the milling force. Contact pointer measuring instrument SC6C was used to measure the surface roughness of the workpiece. DV2TLV was used to measure the surface micromorphology of the workpiece. DV2T viscometer was used to measure the viscosity of each base oil. The experimental instruments and schematic of the milling experiment are shown in Figs. 1 and 2, respectively.

2.2 Experimental materials

The material used in the experiment is Grade 45 steel, and the size of the workpiece is 40 mm × 30 mm × 30 mm (*L* × *W* × *H*). The chemical composition and mechanical properties of the material are shown in Tables 1 and 2.

2.3 Experimental scheme

Choosing a lubricant is important because this material not only plays a vital role in the lubrication performance of the milling zone but also affects the machinability, such as tool life, milling force, and surface roughness. In the experiment, synthetic cutting fluid and five typical vegetable oils (cottonseed, palm, castor, soybean, and peanut) were used as MQL base oils, where synthetic cutting fluid was used as a group of comparative experiments. These five vegetable oils were selected because palm and cottonseed have high contents of saturated fatty acid, castor has a high quantity of monounsaturated fatty acid, and peanut and soybean have high contents of polyunsaturated fatty acid. Furthermore, saturated fatty acids, monounsaturated, and polyunsaturated fatty acids have a different influence on lubrication performance in milling.

Vegetable oil-based lubricants selected in the experiment consisted of vegetable oils, surfactants, and additives. Vegetable oil molecules contain a large number of C–C double bonds so that the oxidation stability is very poor, especially linoleic acid or linolenic acid components with two or more double bonds that can be oxidized rapidly in the early oxidation stage. In the experiment, antioxidants (vitamin E) were added into five kinds of vegetable oils with a volume fraction of 0.2%. Surfactant was added to change the interfacial state of cutting fluid system, which was adsorbed on the surface of cutting fluid to effectively reduce the surface tension of the cutting fluid and increase the lubrication performance.

Single-factor variable method was adopted in the experiment, where only the type of base oil was changed in each group of experiments, while other factors remained the same. The experimental scheme is shown in Table 3.

The milling parameters in the experiment are listed in Table 4.

3 Results and discussions

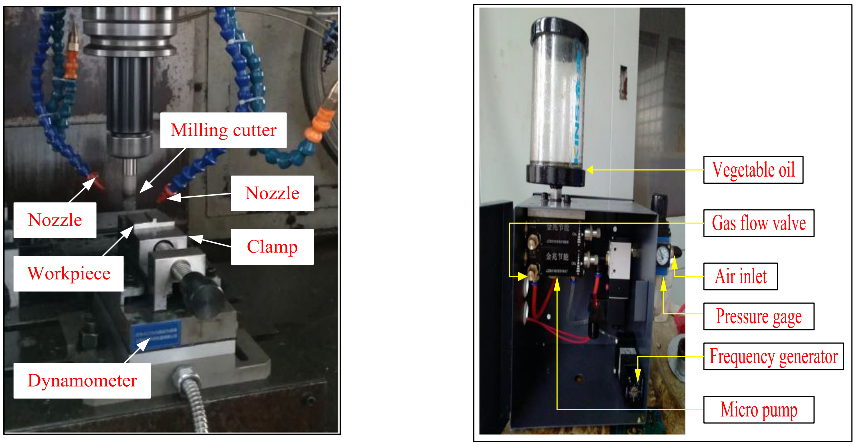
3.1 Results

3.1.1 Milling force

The milling force is one of the most important parameters in the machining process. A large milling force produces high cutting heat and adhesion between the tool and chip interface, which seriously affects the surface finish of the workpiece and the life-span of the tool. Therefore, studying the milling force is important to improve the processing. To facilitate the analysis, we divided the milling forces exerted on the workpiece into X-direction milling force Fx, Y-direction milling forceFy, and axial forceFz, which can be measured by a dynamometer. The milling forces of five types of vegetable-based oils and synthetic cutting fluid under MQL conditions measured are shown in Fig. 3.

For high-speed milling, the average value $\overline{F}_{\max}$ of peak values $F_{\max}$is typically used to determine the milling force,

Fig. 1 Experiment instruments **a** Milling force measuring device **b** MQL supply system **c** Surface roughness instrument **d** Scanning electron microscope (SEM) **e** Viscometer



（a）Milling force measuring device (b）MQL supply system

（c）Surface roughness instrument （d）Scanning electron microscope(SEM) （e）Viscometer

and the average value of the peak value of the milling force is used as the basis for discussing the influence of different base oils.

$$\overline{F}_{\max} = \frac{F_{\max}}{N} = \frac{\sum_{i=1}^{N} F_{\mathrm{pi}}}{N}, \tag{1}$$

where F_{pi} is the ith peak value of the milling force in the milling force acquisition signal. The milling forces collected by dynamometer are substituted into Eq. (1) to obtain the corresponding peak value of the milling force, as shown in Fig. 4.

As shown in Fig. 4, the milling force obtained is the largest (F_x = 335 N, F_y = 177 N) under the condition of synthetic cutting fluid as base oil. The milling force using five vegetable-based oil MQL decreases at varying degrees. The milling force of palm oil is the lowest (F_x = 309 N, F_y = 153 N) at 7.76% and 13.6% lower than that of synthetic cutting

Fig. 2 Schematic of milling experiment

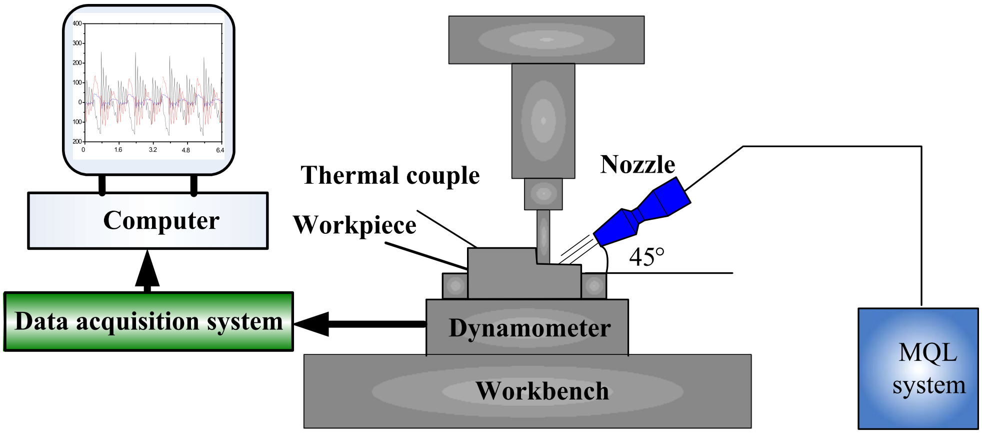


Table 1 Chemical composition of Grade 45 steel

Element	C	Si	Mn	Cu	Ni	Cr	P	S
Component (%)	0.42–0.50	0.17–0.37	0.50–0.80	≤0.25	≤0.30	≤0.25	0.035	0.035

fluid. It is followed by cottonseed oil (F_x = 312 N, F_y = 156 N), which is 6.87% and 11.86% lower than that of synthetic cutting fluid. According to the data, cottonseed and palm oils have a similar lubrication effect. The milling force of soybean oil is the greatest (F_x = 325 N, F_y = 166 N), which is only 2.99% and 6.21% lower than that of synthetic cutting fluid, which indicates that the lubrication effect of soybean oil is the worst among the five vegetable oils.

3.1.2 Surface roughness

Surface roughness is an important parameter to evaluate the surface quality of the workpiece. The value of the surface roughness determines the surface finish. The smaller the surface roughness is, the smoother the surface is. Surface roughness has an important effect on the fatigue strength, contact stiffness, corrosion resistance, and assembling of parts. It also influences the life-span and reliability of mechanical products. Poor surface quality leads to performance degradation and causes the workpiece to fail before the expected end of life.

Height characteristic parameter*R*aand spacing characteristic parameter *Rsm* are generally selected as roughness evaluation parameters.*R*ais the arithmetic average of the absolute value of offset from each point on the measured contour to the baseline within a sampling length *L*. The larger*R*ais, the greater the absolute value of the offset is. *R*ais obtained by Eq. (2):

$$R_a = \frac{1}{L}\int_0^L y(x)dx, \tag{2}$$

where *y(x)* is the ordinate of the contour curve.

*Rs*m is the average of contour irregularity distance within the sampling length L. Contour irregularity distance refers to the length of profile peak and the adjacent valley on the median. On the surface of the workpiece machined by MQL milling, *Rsm* reflects the diameter of scratches on the workpiece. A large scratch reduces the surface quality of the machined workpiece.*Rsm*is obtained by Eq. (3):

$$Rsm = \frac{1}{N}\sum_{i=1}^{N} S_i, \tag{3}$$

where N is the number of units within sampling length L and S_i is the width of every unit.

Five points are selected to measure the roughness of the workpiece surface, and six groups of related roughness values are obtained. The value of surface roughness under different lubrication conditions is shown in Fig. 5.

According to Fig. 5, *Ra* and *Rsm* obtained under synthetic cutting fluid are the highest (*Ra* = 0.469 μm, *Rsm* = 0.252 mm), indicating that the surface is the roughest and the average width of the scratches on the surface is the largest. The values of *Ra* and *Rsm* obtained under vegetable-based MQL are lower than those under synthetic cutting fluid MQL. Among them, *Ra* measured with palm oil is the lowest (*Ra* = 0.231 μm) at 50.7% lower than that of synthetic cutting fluid. *Ra* of cottonseed oil is 0.246 μm, which is 47.5% lower than that of synthetic cutting fluid. For *Rsm*, the value of cottonseed oil as base oil is the smallest (*Rsm* = 0.183 mm), 27.38% lower than that of synthetic cutting fluid MQL, and the average scratch width is the smallest. *Rsm* of palm oil is 0.189 mm, close to that of cottonseed oil, which is 25% lower than that of synthetic cutting fluid MQL. In addition, *Ra* of castor and peanut oils are 0.270 μm and 0.276 μm, and *Rsm* are 0.195 mm and 0.198 mm, respectively. Minimal difference was observed between the two lubrication conditions. *Ra* of soybean oil is 0.319 μm, 31.9% lower than that of synthetic cutting fluid. *Rsm* is 0.222 mm, 11.90% lower than that of synthetic cutting fluid MQL. Therefore, the surface obtained with soybean oil MQL is the roughest, and the scratches on the workpiece surface are the widest.

In addition, the standard deviations of *Ra* and *Rsm* obtained by palm oil MQL are small, which indicates that the dispersion degree is low, that is, the values on the entire workpiece surface are close and the precision is high. The standard deviation of *Rsm* obtained by synthetic cutting fluid and soybean oil MQL is large, which illustrates that the value of *Rsm* is discrete relative to the average value. The reason is that a higher milling force leads to a larger vibration amplitude of the tool, which makes *Rsm* vary for different points on the workpiece surface.

3.1.3 Workpiece surface morphology

SEM is an important index to evaluate the surface integrity of the workpiece surface. It can reflect not only the interaction state between tool and workpiece but also the removal mode of metal material. Observing the surface micromorphology is the most direct method to study the surface quality. It can qualitatively reflect the surface quality of the workpiece, while roughness value can quantitatively judge the surface quality. When the workpiece quality cannot be observed from the micromorphology, it can be further judged from the roughness value quantitatively, and the two complement each other. The surface micromorphology of the workpiece under synthetic

Table 2 Mechanical properties of Grade 45 steel

Modulus of elasticity (GPa)	Poisson's ratio	Tensile strength (MPa)	Yield strength (MPa)	Hardness (HRC)	Elongation (%)	Density *P* (g/m^3)
210	0.31	600	355	48–55	16	7.85

cutting fluid and five vegetable-based oil MQL are shown in Fig. 6.

As shown in Fig. 6, the workpiece surface quality obtained under palm oil MQL is the best, and the overall surface is relatively smooth, which proves that the lubrication effect of palm oil is remarkable. Similarly, cottonseed oil MQL also obtains a smooth surface micromorphology and fewer scratches, indicating that the lubrication effect of cottonseed oil is also good. MQL based on synthetic cutting fluid obtains the worst surface quality. Many burns, peelings, and scratches indicate that the lubrication effect was the worst. The surface qualities of the workpiece under soybean, castor, and peanut oil MQL are poor, and many obvious scratches and different degrees of burns are found on the surface. We can conclude that palm oil is the best base oil for lubrication, followed by cottonseed oil, and the other three vegetable oils are not ideal. As shown in Figs. 5 and 6, the surface micromorphology and surface roughness are consistent, that is, when the surface micromorphology of the workpiece is good, the corresponding roughness value is low.

3.2 Discussions

3.2.1 Comparison of lubrication performance between vegetable oil and synthetic cutting fluid

Vegetable oils are mainly composed of fatty acids and triglycerides. Both the carboxyl (-COOH) in fatty acid molecules and ester groups in triglycerides are polar groups. These polar groups and metal surface molecules with strong activity are adsorbed tightly on the metal surface by van der Waals force to form a physical adsorption film, which has an effect on antifriction and anti-wear. At the same time, in the milling process, polar molecules easily react with the metal surface under high temperature to form a metal saponification oil film. When the film is adsorbed on the metal surface, it has the characteristics of vertical orientation. They are densely coated on the metal surface because of the suction between molecules. This characteristic of vegetable oil accounts for its good boundary lubrication performance, which determines its excellent lubrication in milling fluid application [62].

Table 3 Experimental scheme

Experiment No.	Base oil
1	Cottonseed oil
2	Palm oil
3	Castor oil
4	Soybean oil
5	Peanut oil
6	Synthetic cutting fluid

Synthetic cutting fluid is a type of mineral oil. Its main component is C16–C20 n-alkanes, which are pure saturated hydrocarbons without other elements, functional groups, and carbon branched chains. Its molecules consist of several CH2 atoms and two H atoms, which are nonpolar. As it does not have polar atoms and polar groups such as vegetable oil, molecules are randomly arranged on the metal surface and cannot form a strong physical adsorption film. Therefore, the lubrication performance of vegetable oils is superior to that of synthetic cutting fluids.

3.2.2 Effect of vegetable oil composition and molecular structure on lubrication performance

The lubrication performance of vegetable oils is improved obviously compared with synthetic cutting fluid, but it varies among the five typical vegetable oils used in the experiment. Combined with the evaluation parameters of lubrication performance (milling force, surface roughness, and surface micromorphology of the workpiece), palm oil has the best lubrication performance, followed by cottonseed oil. Castor and peanut oils also show good lubrication performance, but soybean oil was not ideal. The reason is that many factors affect the difference of lubrication performance among these oils, such as different components and molecular structures of vegetable oils.

The main components of vegetable oil are triglycerides formed by one molecule of glycerol ester and three molecules of straight chain fatty acid, as shown in Fig. 7, where R_1, R_2, and R_3 are carbon chains of fatty acids, which are linked to glycerol molecules through ester bonds. Fatty acid chain length is generally between 14 and 22 carbon atoms, and unsaturated bonds occur at different degrees. The length of carbon chain in the molecule affects the total adsorption energy, which rises with the increase of the length of the carbon chain. A sufficient length of the carbon chain is necessary to obtain the maximum density of the adsorbent film. According to the research, for saturated fatty acids, when the number of C atoms is greater than 16, the adsorption capacity almost reaches the maximum, and the friction performance is no longer affected by the number of C atoms. Therefore, for fatty acids whose carbon number is larger than 16, the anti-wear

Table 4 Milling parameters

Milling parameters	Parameter setting
Milling way	Plane milling
Tool type	Machine-clamped two-tooth end milling cutter
Tool diameter (mm)	20
Spindle speed (r/min)	1,200
Feed speed (mm/min)	500
Axial depth (mm)	0.25
Radial depth (mm)	10
MQL flow rate (ml/h)	85
MQL nozzle distance (mm)	40
MQL nozzle angle (°)	45
MQL gas pressure (MPa)	0.4

and antifriction effects are the same. However, for unsaturated fatty acids, extremely unsaturated bonds are found in the molecules. Due to the adsorption of olefin bonds, the aligned adsorptive membranes are no longer dense, and the strength and lubricity of the adsorptive membranes are correspondingly worse. Therefore, compared with saturated acids, unsaturated fatty acids with the same number of C have lower adsorptive film strength and lubricity. However, for unsaturated fatty acids, unsaturated bonds with polarity in the molecules exist. Due to the adsorption of olefin bonds, the aligned adsorptive membranes are less dense, and their strength and lubricity are correspondingly worse. Therefore, the adsorptive film of unsaturated fatty acids has lower strength and lubricity compared with that of saturated acids with the same number of C. At the same time, the transverse cohesion between unsaturated fatty acids becomes very crucial. As the cohesion is proportional to the number of C atoms, the longer the carbon chain length is, the stronger the strength and lubricity are. In addition, the strength of film formed by fatty acids containing only one carbon–carbon double bond (monounsaturated fatty acids) is higher than that formed by fatty acids containing multiple carbon–carbon double bonds (polyunsaturated fatty acids).

Typical fatty acids are classified as saturated and unsaturated fatty acids. Saturated fatty acids have a significant role in the reduction of friction and wear. The different amounts and structures of saturated fatty acids result in various cohesion between molecules adsorbed on the metal surface and

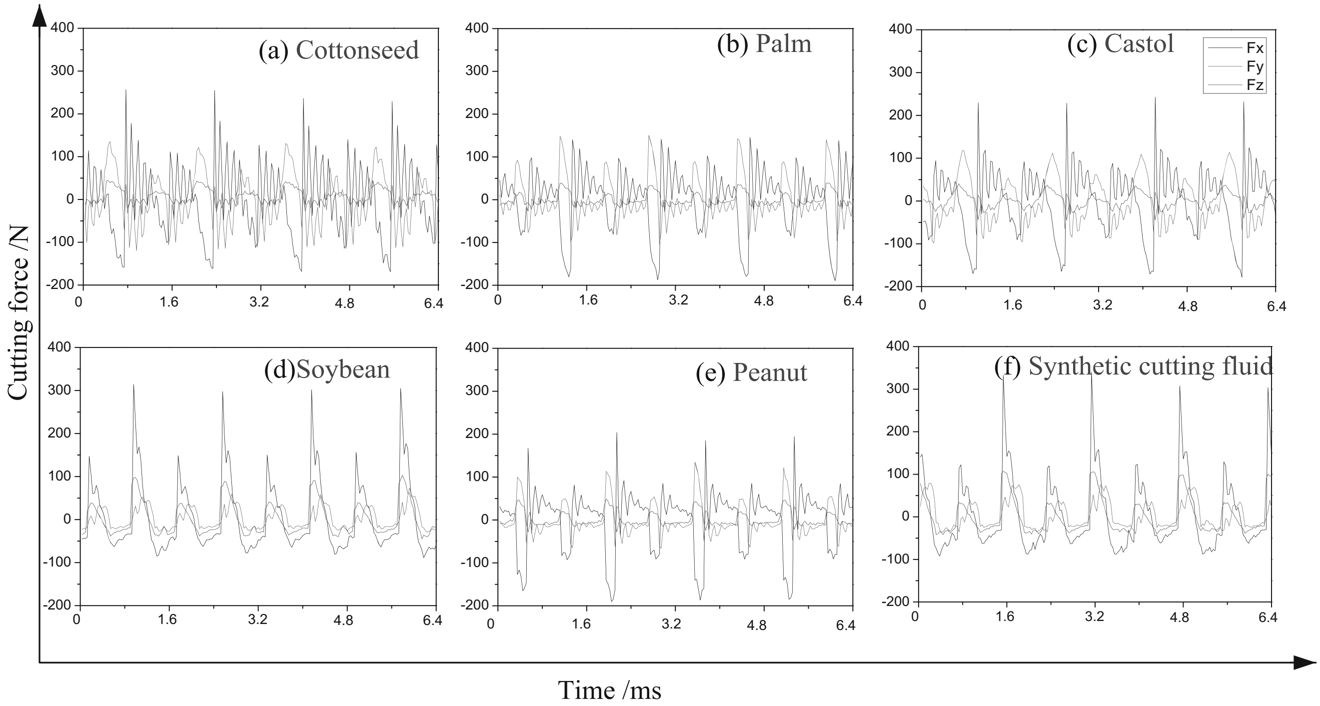


Fig. 3 Milling forces of different lubricants

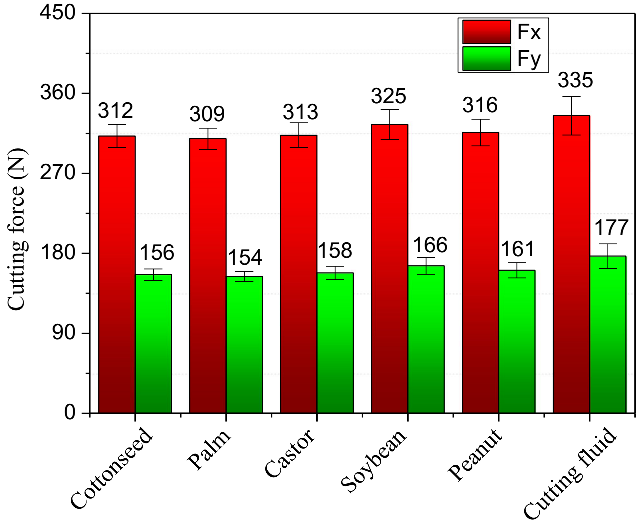


Fig. 4 Schematic of milling force

densities of adsorbed membranes, which leads to unequal adsorption energies and affects the strength of adsorbed membranes. The double bonds in unsaturated fatty acids are relatively unstable and prone to chemical reactions such as oxidation. Moreover, the double bonds of unsaturated fatty acids weaken the interaction between molecules, resulting in the deterioration of lubrication performance correspondingly, especially the polyunsaturated fatty acids containing two or more double bonds. The reason is that the double bond produces a certain degree of hardness in the molecule, which prevents the fatty acid chains from bonding closely with each other and leads to the weakening of intermolecular forces. Saturated fatty acids, by contrast, are free of double bonds and have lower hardness, making them more closely integrated [63]. Table 5 lists the basic components of five vegetable oils. Figure 8 shows the molecular formulas of six fatty acids, where palmitic acid C16 and stearic acid C18 belong to saturated fatty acids, oleic acid C18 and castor acid C18 belong to monounsaturated fatty acids, and linoleic acid C18 and linolenic acid C18 belong to polyunsaturated fatty acids.

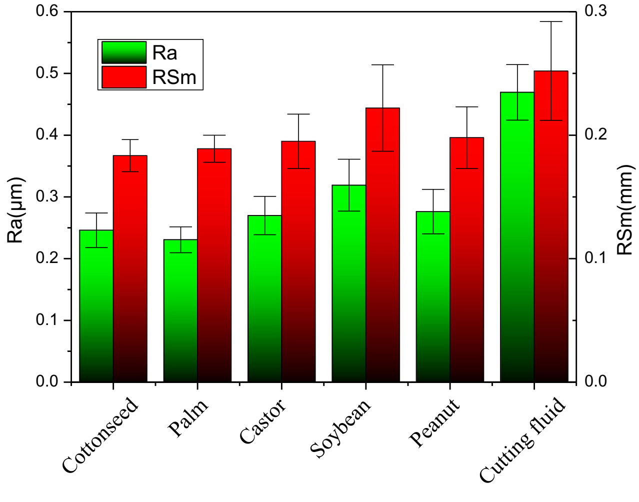


Fig. 5 *R*a and *Rsm* under different lubrication conditions

Table 5 and Figure 8 show that among the five types of vegetable oils, the main fatty acid of palm oil is palmitic acid with content up to 45.1%, which belongs to saturated fatty acid. The saturated fatty acid has good stability and is not easy to oxidize, so the oil film formed is the most stable. Furthermore, the number of carbon atoms is 16, up to the maximum the strength of the adsorbed oil film can reach [36]. Therefore, the lubrication film formed by palm oil has the best durability and strength, and the lubrication performance is the best.

The content of palmitic acid in cottonseed oil is 21.9, and its lubrication performance is after that of palm oil. The content of palmitic acid and stearic acid in castor oil is only 1.36%. Therefore, the lubricity of castor oil is lower than that of cottonseed oil. However, the content of castor acid, i.e., monounsaturated fatty acid, is as high as 90.85%, while that of linoleic acid and linolenic acid, i.e., polyunsaturated fatty acid, is only 4.01%, the lowest among the five base oils. The stability of monounsaturated fatty acids is better than that of polyunsaturated fatty acids, and the carbon chain length of castor acid reaches 18. Moreover, the fatty acid contains two polar groups (-COOH and -OH), so that castor oil has a strong polarity and metal adsorption, which is easily adsorbed on the surface of metal workpieces to form a lubricating oil film. Therefore, the lubricity of castor oil is better than that of soybean and peanut oils.

The main types of fatty acids in soybean oil are linoleic and linolenic acids, i.e., polyunsaturated fatty acid, which is the highest among the five plant oils with an amount of up to 63%. However, the content of saturated fatty acid is low (12.7%). Therefore, the oil film formed by soybean oil has the worst stability, strength, and lubrication performance, followed by peanut oil.

3.2.3 Effect of vegetable oil viscosity on lubrication performance

The viscosity of vegetable oil is an important factor in the lubrication performance. In the milling process, the viscosity mainly affects the lubrication and heat exchange performance of cutting fluid and also has a certain influence on the formation of lubricating oil film. When vegetable oil-based cutting fluid is injected into the tool–workpiece interface through the nozzle, the cutting fluid with higher viscosity can stay in the milling zone for a longer time to reduce friction and prevent rapid tool wear. The cutting fluid with low viscosity does not easily form a lubricant film with enough thickness and strength on high temperature, which results in low load capacity of the oil film and tendency to be damaged easily by friction force at the tool–workpiece interface. Therefore, the lubrication effect decreases and the friction becomes larger. Thus, exploring the

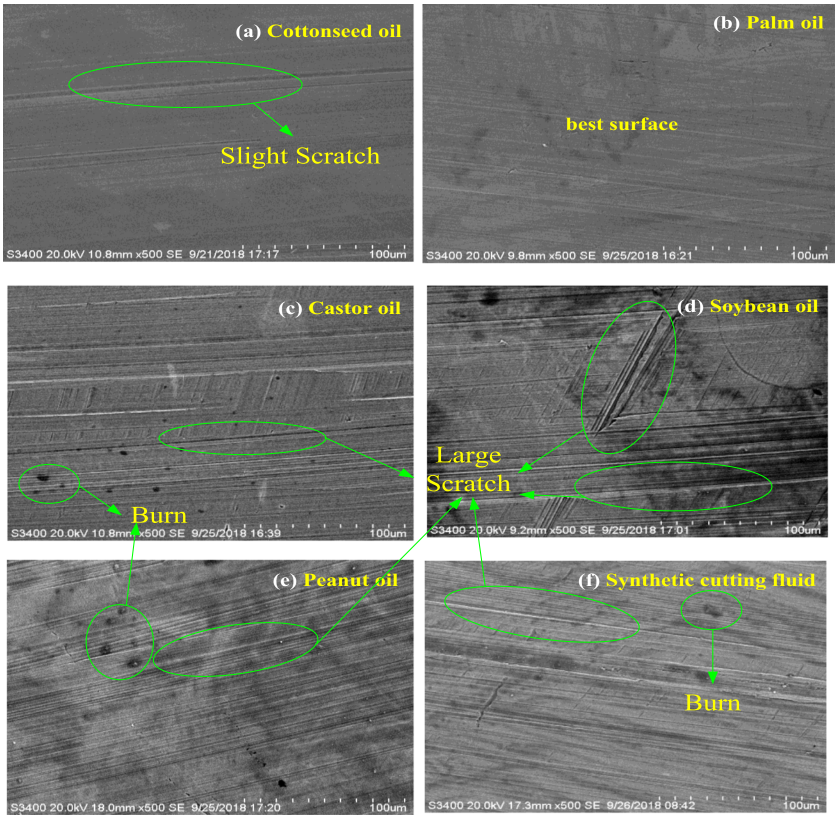


Fig. 6 SEM under different lubrication conditions

viscosities of different vegetable oils and the mechanism of their effects on processing properties is an important task.

The viscosities of five different vegetable oils are shown in Fig. 9. According to this figure, the viscosity decreases with the increase of temperature. The reason is that the distance between the molecules of vegetable oil increases with the temperature increase. Thus, the molecular interaction force decreases and so does the viscosity. The viscosities of various vegetable oils range from 41.8 mP.s to 535.3 mP.s at the temperature of 25°C. The viscosity of soybean oil is the lowest, while that of castor oil can reach 535.3 mP.s, which is the highest. The viscosity of peanut, cottonseed, and palm oils increases in turn. Combined with the experimental results, the order of lubrication performance of the seven types of vegetable oils is as follows: soybean oil < peanut oil < castor oil < cottonseed oil < palm oil. Soybean oil has the lowest viscosity and the worst lubrication performance. Although castor oil has the highest viscosity, the lubrication performance is not the best. In general, the lubrication performance of cutting fluid increases with the increase of viscosity, but when the viscosity of base oil is extremely high, the flow almost stops and becomes equivalent to the solid film, which is similar to dry milling; thus, the lubrication performance is poor. With viscosity of 61.6, palm oil is the most viscous vegetable oil except castor oil, and it does not cause flow stagnation. Therefore, a greater colloidal force between molecules can prevent the flow of the cutting fluid itself, which is conducive to the formation of oil film and enhancement of the thickness and strength of the lubricating oil film. Moreover,

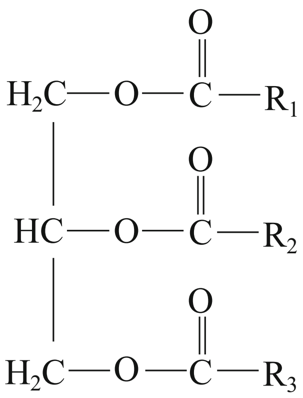


Fig. 7 Molecular structure of triglyceride [38]

Table 5 Fatty acid composition of five types of vegetable oil

Parameters	Cottonseed	Palm	Castor	Soybean	Peanut
Palmitic acid (%)	21.9	45.1	0.72	8.9	11.92
Stearic acid (%)	2.09	4.8	0.64	3.8	4.3
Oleic acid (%)	14.86	36.8	2.82	23	40.84
Castor acid (%)	–	–	90.85	–	–
Linoleic acid (%)	57.24	10.2	3.74	52.4	34.54
Linolenic acid (%)	0.20	–	0.27	10.6	–

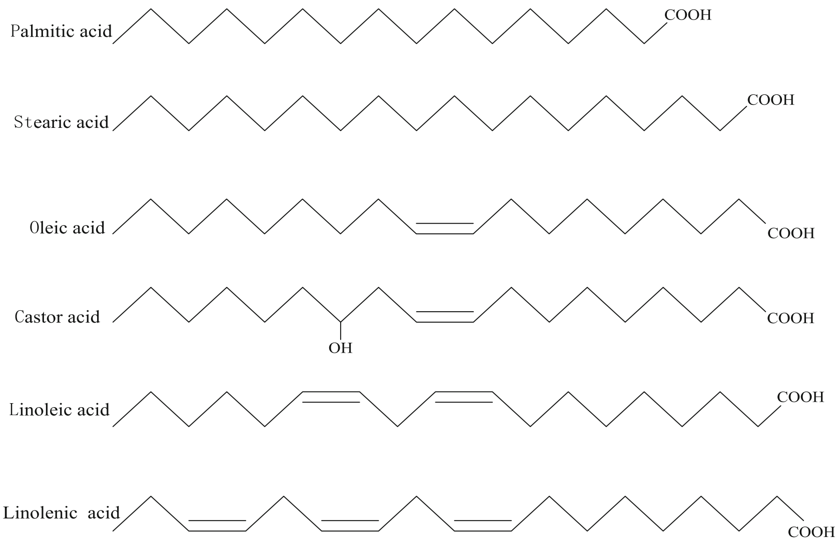


Fig. 8 Molecular structure of different fatty acids

the oil film can stay on the workpiece surface for a long time, increase the lubrication stability and lubrication of the milling cutter/workpiece, prevent tool wear, and ensure the best lubrication performance.

4 Conclusions

The lubrication performance of vegetable oils (i.e., cottonseed, palm, castor, peanut, and soybean) as MQL base oil was compared with that of synthetic cutting fluid from such parameters as milling force, surface roughness (*Ra*,*Rsm*), and surface morphology of the workpiece. The following conclusions can be drawn from the analysis of the molecular structure, composition, and viscosity of vegetable oils:

(1) Compared with synthetic cutting liquid, vegetable oil as MQL base oil has a lower milling force and better lubrication performance. The milling force obtained by palm oil was the lowest (F_x = 309 N, F_y = 154 N) at 7.76% and 13.6% less than that of synthetic cutting fluid, followed by cottonseed oil (F_x = 312 N, F_y = 156 N) at 6.87% and 11.86% less than that of synthetic cutting fluid, which indicates the similar lubrication effect of cottonseed and palm oils. The greatest milling force is obtained by soybean oil (F_x = 325 N, F_y = 166 N) at only 2.99% and 6.21% lower than that of MQL with synthetic cutting fluid, which indicates that soybean oil has the worst lubrication effect among the five vegetable oils.

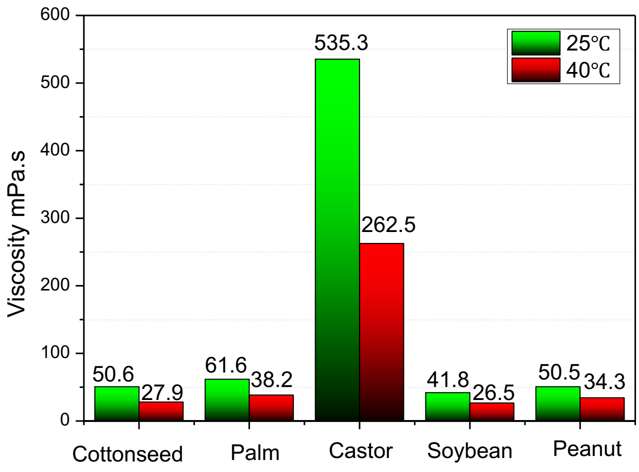


Fig. 9 Viscosity of five vegetable-based oils

(2) According to *Ra* and *Rsm*, the surface quality of the workpiece obtained by MQL milling with synthetic cutting fluid is the worst (*Ra* = 0.469 μm,*Rsm* = 0.252 mm), and they are improved with vegetable oils. Among them, palm oil obtained the best surface quality (*Ra* = 0.231 μm, *Rsm* = 0.189 mm). The surface quality obtained with cottonseed oil is similar to that of palm oil (*Ra* = 0.246 μm, *Rsm* = 0.183 mm). The surface roughness is consistent with the results of the micromorphology of the workpiece. The micromorphology of the workpiece with synthetic cutting fluid is the worst with serious burns, peeling, and a large number of scratches. The micromorphology is improved with vegetable oil. The surface quality of the workpiece milling with cottonseed oil and palm oil MQL is better and smoother than that of the other vegetable oils.

(3) We can conclude that vegetable oil has better lubrication performance than synthetic cutting fluid. As saturated fatty acids have superior lubrication properties compared with unsaturated fatty acids, palm and cottonseed oils with a larger amount of polysaturated fatty acids are more suitable MQL base oils.

Acknowledgments This research was financially supported by the following organizations: the Scientific Research Development Project of Shandong Higher Education Institutions, China (J18KA017 and J17KB016), the National Natural Science Foundation of China (51806112); Shandong Provincial Natural Science Foundation, China (ZR2017PEE002 and ZR2017PEE011).

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