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REGULAR PAPER

Effects of Physicochemical Properties of Different Base Oils on Friction Coefficient and Surface Roughness in MQL Milling AISI 1045

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Abstract

Minimum quantity lubrication (MQL) is an emerging green and resource-saving machining technique jetting minute amount lubricants and gas after mixing and atomization. However, MQL development is restricted to mineral oils because of its undegradability and threat to the environment and human health. Vegetable oils can replace mineral oils as base oil for MQL benefitting from its biodegradability and renewable property. Nevertheless, the lubrication mechanism at the tool-workpiece interface of different vegetable oils with various physicochemical properties has not been revealed systematically. In order to verify the interfacial lubrication characteristics of different vegetable oils, MQL milling experiments of AISI 1045 based on five vegetable oils (cottonseed, palm, castor, soybean, and peanut oils) were carried out. The experimental results showed that, palm oil obtained the lowest milling force ($F_x = 312$ N, $F_y = 156$ N), friction coefficient (0.78), and surface roughness values ($Ra = 0.431$ µm, $RSm = 0.252$ mm) and the smoothest surface of workpiece. Furthermore, the physiochemical properties (composition, molecular structure, viscosity, surface tension, and contact angle) of vegetable oil were analyzed. Palm oil with high content of saturated fatty acid, high viscosity and small contact angle can form the lubricating oil film with the highest strength and the largest spreading area at the tool-workpiece interface. Therefore, palm oil can achieve the optimal lubrication effect.

Keywords Milling · Minimum quantity lubrication · Different base oil · Physicochemical property · Sustainable machining

Abbreviations

MQL	Minimum quantity lubrication
SEM	Scanning electron microscope
W_s	Rotation rate (r/min)
V_f	Feed rate (mm/min)
V	Cutting speed
a_p	Axial depth of cut (mm)
a_e	Radial depth of cut (mm)

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α	Angle of the nozzle and the tool feeding direction
β	Angle of nozzle and horizontal direction
γ	Cut in angle
t	Processing time
F_x, F_y, F_z	Cutting force component in the X, Y, and Z directions (N)
F_t, F_r	Tangential and radial cutting force components (N)
F	Resultant cutting force (N)
$\overline{F_{\max}}$	Mean of milling force peak (N)
R_a	Arithmetic average height (μm)
RS_m	Mean spacing at mean line (mm)
R_{mr}	Bearing length ratio
μ	Friction coefficient
μ_n	Viscosity of the nanofluid
μ_{bf}	Viscosity of the base fluid
φ	Noparticle volume fraction
γ_{sv}	Surface tension at the solid–gas interface
γ_{s1}	Surface tension at the solid–liquid interface
γ_{v1}	Surface tension at the gas–liquid interface
θ	Contact angle

1 Introduction

As an advanced processing technology in modern manufacturing, milling has the characteristics of high material removal rate and surface quality. The AISI 1045 is a common medium carbon steel in machinery manufacturing and is highly appreciated in many industrial fields due to its excellent performance, high strength, plasticity and toughness, and rich reserves [1]. High friction, high temperature, and high pressure can be detected in the cutting zone of AISI 1045, which can further lead to thermal damages on the workpiece surface [2, 3]. Therefore, lubrication and cooling are crucial in the cutting zone [4, 5].

Minimum quantity lubrication (MQL) has shown remarkable advantages and development prospects in replacing the traditional flood cooling [6–8]. MQL is a processing technique under cooling lubrication, which is performed by spraying high-pressure atomized minimum cutting fluid onto the cutting zone. The high-pressure gas can cool the cutting zone and remove chips to protect the workpiece surface from damages caused by chips. The cutting fluid enters the cutting zone and forms a dense lubricating oil film on workpiece surface, which can reduce friction on the tool-workpiece and tool-chip interfaces. The lubrication effect of MQL is similar to that of flood cooling lubrication [9, 10]. Moreover, the cutting fluid flow of traditional flood cooling lubrication is 60 L/h, but that of MQL is only 30–100 mL/h [11, 12], indicating that MQL saves cutting fluid considerably, and it is a resource-saving and environment-friendly processing technique [13, 14].

Substantial research on MQL has been reported around the world. Mineral oils are mainly used as traditional base oil of MQL. Lv [15] investigated the influencing laws of lubrication mode during the milling of hard steels through an orthogonal experiment. They found that MQL can decrease milling force and residual stress effectively and improve surface roughness. Silva et al. [16] showed that MQL can increase the material removal rate and effectively prolong the service life of the grinding wheel. Liao et al. [17, 18] studied the influences of lubrication mode on the tool wear and workpiece surface roughness during high-speed face milling. Their results showed that MQL can effectively prolong the service life of the tool and improve the surface roughness of the workpiece. Dhar et al. [19] discovered that MQL can remarkably reduce the tool wear rate and workpiece surface roughness during the turning of AISI 4340 steel and decrease the temperature of cutting zone simultaneously. Shahrom et al. [20] studied the influences of lubrication mode on the surface roughness of a workpiece during AISI 1060 milling and found that MQL achieved better surface roughness at a lower cost and caused less environmental pollution compared with flood lubrication. Kishawy et al. [21] have shown that the cutting force and tool wear obtained MQL cutting aluminum alloy are smaller than the flood type.

Nevertheless, mineral oils have poor biodegradability and may cause long-term environmental pollutions. Furthermore, mineral oils contradict the concept of sustainable manufacturing. To address environmental pollution caused by cutting fluid and reduce processing cost, some scholars have attempted to use vegetable oils as base oil for MQL. Many associated studies have been reported.

Zhang et al. [22] compared the lubrication performances of different base oils for MQL and conducted a grinding experiment. According to the experimental analysis, palm oil presented good lubrication performance. Li et al. [23] and Wang et al. [24] obtained the same conclusion when grinding GH4169. Guo et al. [25] further analyzed the tribological properties of base oils comprising multiple vegetable oils. The cutting fluid of the soybean and castor oil mixture exhibited the best lubricating and cooling performance, and it was the most appropriate base oil for MQL. Emami et al. [26] grinded Al_2O_3 engineering ceramics by using palm oil as the base oil for MQL. The surface roughness of the workpiece after MQL based on palm oil was higher than that after MQL based on synthetic ester due to the poor oxidation stability of palm. Ueda et al. [27] conducted turning and milling experiments of MQL based on vegetable oils and found that it can lower the cutting temperature to some extent compared with dry grinding. Sultana et al. [28] investigated the MQL milling performance of 42 CrMo4 steel by using different base oils (water-soluble cutting fluid, vegetable oil, and VG68 cutting oil). Their results showed that vegetable oil exhibited lower surface roughness and tool wear compared with soluble cutting fluid.

Khan et al. [29, 30] performed milling experimental studies, which proved the good cooling and lubrication performance of MQL based on vegetable oils. Rahim et al. [31] performed a contrast analysis on MQL milling outcomes by using palm oil and synthetic ester as the base oils. The cutting force, temperature, and specific energy in MQL milling based on palm oil were low. Their results were related to the high viscosity and good lubricating effect of palm oil. Obikawa et al. [32] implemented high-speed cutting of AISI 1045 through MQL based on vegetable oils. They pointed out that MQL decreased tool wear loss compared with flood lubrication and proved that transportation mechanism was the major influencing factor of tool wear loss. Araujo et al. [33] conducted a confirmatory experiment for MQL milling of AISI 1045 steel. Cottonseed, canola, sunflower, corn, and soybean oils were used in MQL. Their results showed that cottonseed and canola oils presented better cooling performance and longer tool life compared with the others. These two vegetable oils also have excellent heat transfer coefficient and perform better in the scanning electron microscope (SEM) analysis of the workpiece.

However, different vegetable oils have different physicochemical properties. The influencing mechanisms of compositions, fatty acid structure, viscosity, surface tension, and contact angle of vegetable oils on friction coefficient and surface roughness remain unknown. Therefore, exploring different vegetable oils as base oil of MQL and analyzing their lubrication effect are necessary. This experiment used five vegetable oils as the base oil for MQL milling of AISI 1045. Milling force, friction coefficient, surface roughness, chip microstructure, and workpiece surface after MQL milling based on different vegetable oils were discussed. Furthermore, the physicochemical properties (composition, fatty acid structure, viscosity, surface tension, and contact angle) of different vegetable oils were analyzed, through which the tribological properties of different vegetable oils were disclosed. The research results can help realize high-efficiency, low-consumption, environment-friendly, and resource-saving green manufacturing.

2 Experimental

2.1 Experimental Setup

The experiment was performed on a Dema ML1060B CNC milling machine. The parameters of the milling machine are presented in Table 1. Minimum lubrication oil was transmitted by the JinZhao KS-2106 minimum lubrication system. During data collection, the three-phase milling force was measured by a piezoelectric three-phase measuring dynamometer. The sampling frequency of the milling force was 2000 Hz. Three repeated trials were collected under different working conditions to reduce the contingency of the experiment. The roughness of the processed surface was measured by a contact pointer measuring device (TIME3220). Microstructure of workpiece and chip was measured by SEM (DV2TLV). The viscosity of different vegetable oils was measured by a viscometer (Brookfield DV2T). The surface tension of different base oils was measured by a automatic surface tension meter (BZY-201). The contact angle of different base oils on the AISI 1045 was measured by a contact angle instrument (JC2000C1B). The experimental and analysis equipment are shown in Fig. 1.

2.2 Experimental Materials

In the experiment, AISI 1045 was used as the workpiece material. The AISI 1045 is a type of high-quality carbon structural steel. The chemical composition and performance parameters of the AISI 1045 are listed in Tables 2 and 3. The experiment used a machine-clamped milling tool and the blade material is high-speed steel.

The base oils applied in this experiment were vegetable oils and synthetic cutting fluids. Synthetic cutting fluids were used as the control group. Synthetic cutting fluids, as a water-based cutting fluid, are made of chemicals. Different vegetable oils have different lubricating performance as a consequence of different physicochemical properties. In this study, cottonseed, palm, castor, soybean, and peanut oils were selected as basic vegetable oils. The fatty acid composition and physical properties of five vegetable oils are listed in Tables 4 and 5.

2.3 Experimental Scheme

Vegetable oils have a high content of unsaturated C = C bonds. In particular, linoleic acid contains two C = C bonds, and linolenic acid contains three C = C bonds. A certain amount of antioxidants (vitamin E, volume fraction: 0.2%) must be added into vegetable oils, because unsaturated C = C bonds are oxidized quickly. This concentration was selected

Table 1 Parameters of Dema ML1060B CNC milling machine

Machine parameters	Value
Principal axis power	11 KW
Motor power driving the workbench	5 KW
Highest rotating speed	8000 r/min
Cutting range	1000 mm × 600 mm × 600 mm
Maximum cutting feed rate	10,000 mm/min

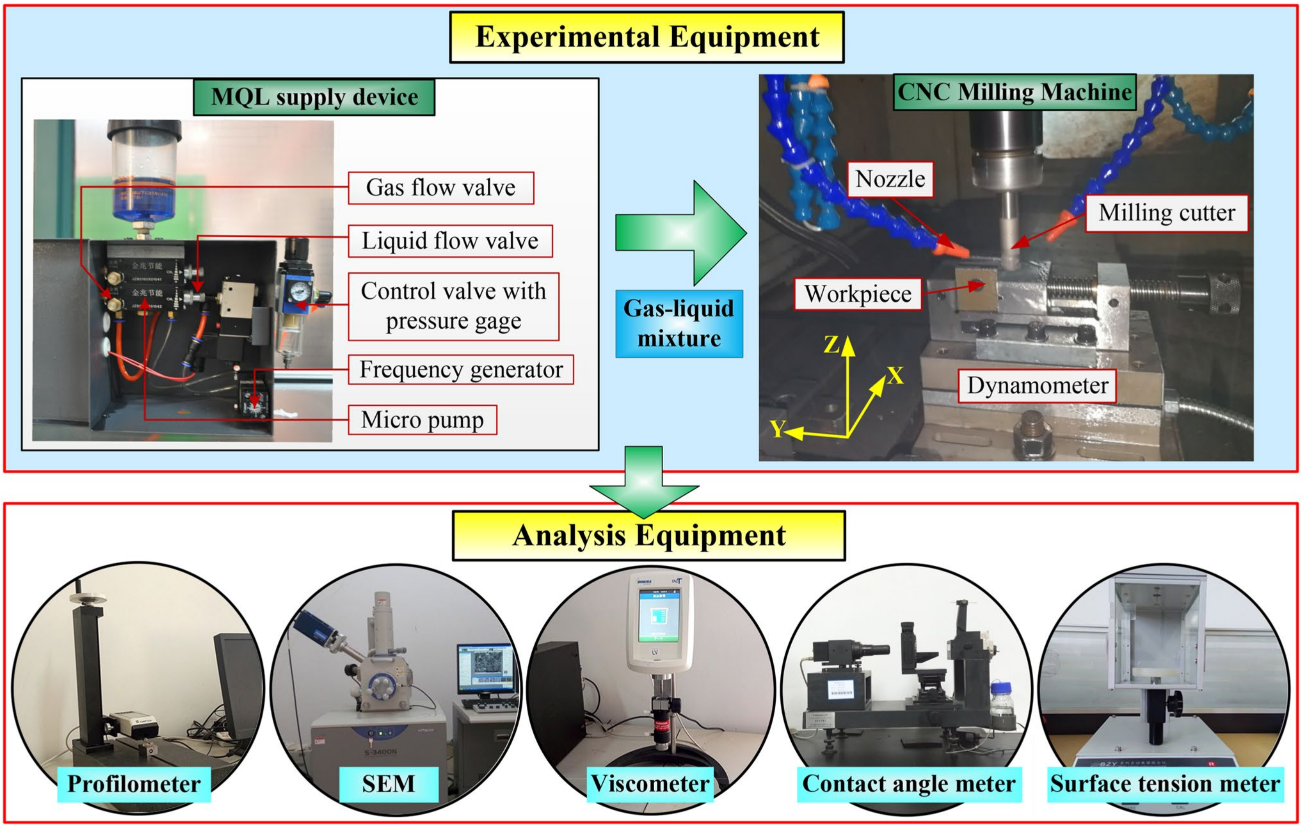

Fig. 1 Experimental and analysis equipment

Table 2 Chemical composition of the workpiece

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

Table 3 Mechanical properties

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

on the basis of a previous research. Wang et al. [34] reported that the optimal nanofluid concentration was 0.2 vol%.

Different lubrication conditions are listed in Table 6. The different base oils were used in pure form in MQL. In each experiment, only the type of base oil was changed. Uniform milling parameters were applied to analyze the effects of lubrication conditions on milling force and surface roughness (Table 7). Three repeated milling processes were conducted under different working conditions to reduce the contingency of the experiment, and the corresponding experimental data were collected.

3 Experimental Results

3.1 Milling Force

Milling force can reflect not only the milling state in processing but also the lubrication performance of cutting fluids. Excellent lubrication will weaken the cutting force, thereby improving the cutting performance [35]. Therefore, studying milling force is important to improve the processing of the AISI 1045.

Table 4 Fatty acid composition of five kinds of vegetable oil

Parameter	Cotton oil	Palm oil	Castor oil	Soybean oil	Peanut oil
Oleic acid (%)	14.86	36.8	2.82	23	40.84
Linoleic acid (%)	57.24	10.2	3.74	52.4	34.54
Palmitic acid (%)	21.9	45.1	0.72	8.9	11.92
Stearic acid (%)	2.09	4.8	0.64	3.8	4.3
Erucic acid (%)	–	–	–	–	–
Octadecanoic acid (%)	–	–	–	–	–
Linolenic acid (%)	0.20	–	0.27	10.6	–
Ricinic acid (%)	–	–	90.85	–	–
Saturated fatty acid (%)	25.12	49.9	1.36	15	21
Monounsaturated fat acid (%)	16.19	50.1	93.67	24	49
Polyunsaturated fatty acids (%)	57.44	50	4.97	61	30

Table 5 Physical properties of five kinds of vegetable oil

Physical property	Cotton oil	Palm oil	Castor oil	Soybean oil	Peanut oil
Relative density (°C)	0.92 (20 °C) 0.93 (30 °C)	0.92 (20 °C)	0.955 (20 °C)	0.915 (15 °C)	0.911 (20 °C)
Refractive index (*n* D 40)	1.46–1.47	1.453–1.459	1.473–1.477	1474–1478	1.468–1.472
Iodine value (g/100 g)	99–113	44–58	81–91	120–141	94–96
Flash point (°C)	324	240	229	> 230	282
Freezing point (°C)	5	15	− 10	− 8–18	0–3
Saponification value	191–199	190–202	176–187	189–195	188–197
Viscosity (mPa s)	50.6 (25 °C) 27.9 (40 °C)	61.6 (25 °C) 38.2 (40 °C)	535.3 (25 °C) 262.5 (40 °C)	41.8 (25 °C) 26.5 (40 °C)	50.5 (25 °C) 34.3 (40 °C)

Table 6 Experimental scheme

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

Table 7 Experimental parameters

Milling parameters	Numerical value
Milling method	End milling
Rotation rate W_s (r/min)	1200
Feed rate V_f (mm/min)	500
Axial depth of cut a_p (mm)	0.25
Radial depth of cut a_e (mm)	10
MQL flow rate (mL/h)	50
MQL nozzle distance (mm)	30
Angle of the nozzle and the cutter feeding direction α (°)	50
Angle of nozzle and horizontal direction β (°)	30
MQL air pressure (MPa)	0.5

Dramatic changes in milling force due to the discontinuity of tool–workpiece contact. The variation law of cutting forces under different lubrication conditions is shown in Fig. 2. Milling force evidently presents periodic variation law. F_x is the force in the direction of cutting and the main undertaker of the cutting force in the metal milling process. F_y is the force in the direction of the feed and the resistance of the workpiece against the forward movement of the tool and is in contact between the workpiece and rear face. F_z is the force in the axial direction and the acting and counter forces of the workpiece and tool on the principal axis of the miller. The lubrication performance of vegetable oil in the cutting process was studied, which mainly affected the main cutting force (F_x) and feed resistance (F_y) in milling force. From the Fig. 2, we can see that most F_z are positive. Due to the inevitable vibration of tool and machine tool in machining, the F_z fluctuates up and down, and there will be negative direction, but its value is not very large (the maximum value is − 15 N). Different vegetable oils had little effect on the force and reaction force of the workpiece and tool on the spindle (F_z). In high-speed milling, milling force is generally determined by the mean of the peak (F_{max}). The mean of milling force peak ($\overline{F}_{max}$) is used as reference to discuss the effects of the six working conditions on the milling force.

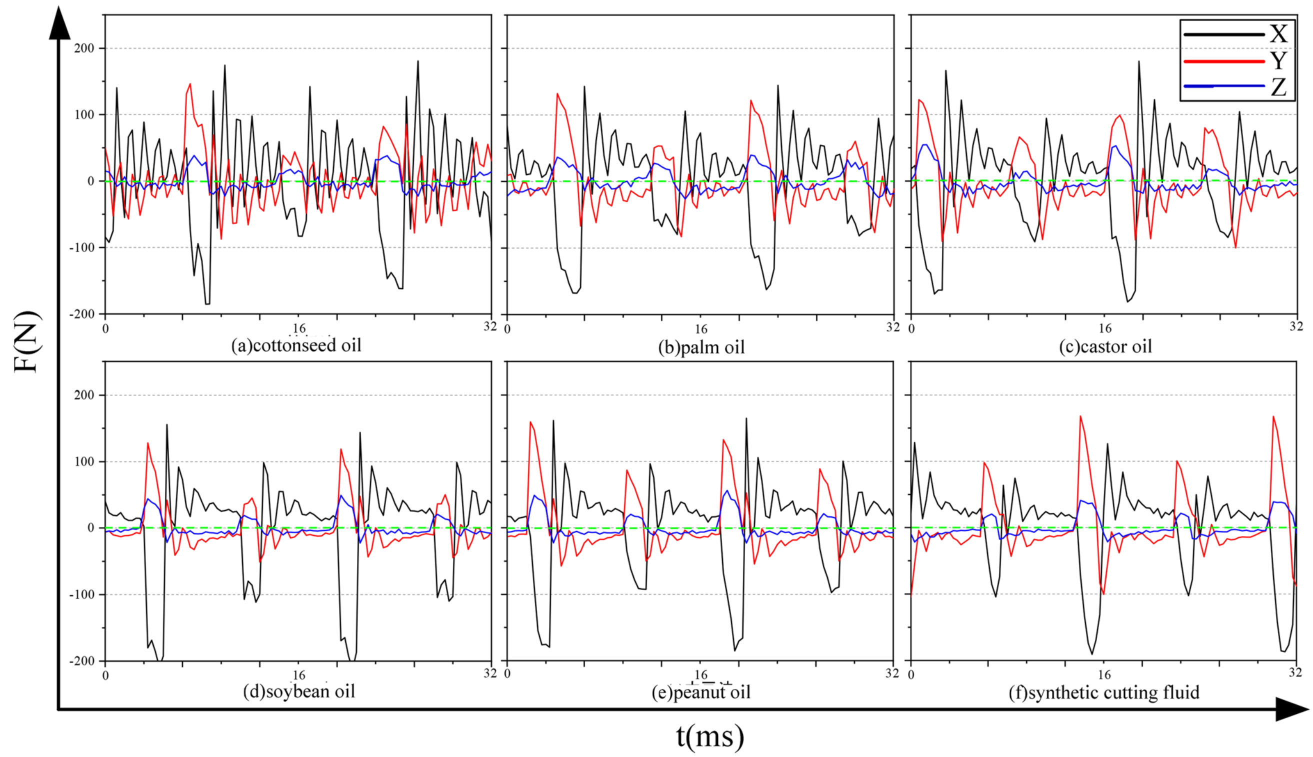

Fig. 2 Original data schematic of the force

$$\overline{F}_{\max} = \frac{F_{\max}}{N} = \frac{\sum_{i=1}^{N} F_{pi}}{N}, \quad (1)$$

where F_{pi} is the ith milling force peak in the collection signal of the milling force.

F_x, and F_y, which are collected by the measuring dynamometer and the calculated resultant milling forces, are brought into Eq. (1) to obtain the corresponding milling force peaks (Fig. 3).

As shown in Fig. 3, the milling force in MQL milling based on synthetic cutting fluids (hereinafter referred to as the control group) has the highest milling force ($F_x = 340$ N, $F_y = 170$ N). The milling forces in MQL milling based on vegetable oils are decreased to different extents. The milling force in MQL milling based on palm oil ($F_x = 308$ N, $F_y = 153$ N) is decreased by 9.41% and 10% compared with that in the control group. The milling force in MQL milling based on cottonseed oil ($F_x = 312$ N, $F_y = 156$ N) is decreased by 8.24 and 8.24%, respectively. These results indicate that cottonseed and palm oils have a similar lubricating effect. The milling force in MQL milling based on soybean oil ($F_x = 330$ N, $F_y = 168$ N) is only 2.94 and 1.18% lower than that in the control group, indicating the poorest lubricating effect among the five vegetable oils.

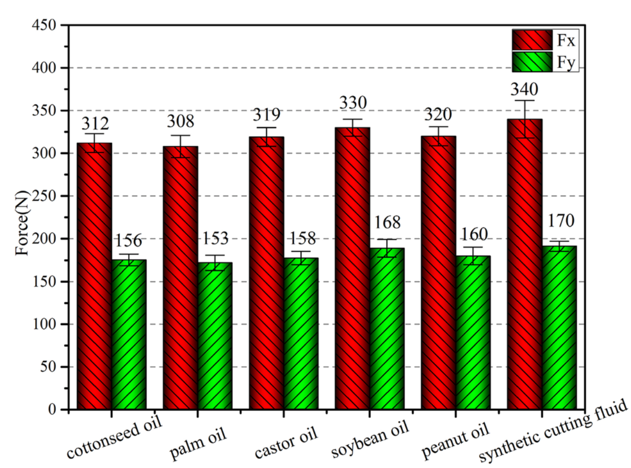

Fig. 3 Schematic of component force

3.2 Friction Coefficient (μ)

The value of friction coefficient reflects the lubrication effect of the tool–workpiece interface. A small friction coefficient results in an improved lubrication effect. The cutting force measurement is obtained in the workpiece coordinate system; however, the calculation of friction coefficient (μ) requires radial cutting force (F_r) and tangential cutting force

(F_t) under the cutting coordinate system. The directional cutting force (F_r, F_t) can be calculated by experimental cutting force (F_x, F_y) with the following transformation method: In the end milling, friction coefficient is the ratio of F_r to F_t. The calculation formulas are [36]

$$\begin{bmatrix} F_r \\ F_t \end{bmatrix} = \begin{bmatrix} \sin(\gamma - \omega_s \cdot t) & -\cos(\gamma - \omega_s \cdot t) \\ \cos(\gamma - \omega_s \cdot t) & \sin(\gamma - \omega_s \cdot t) \end{bmatrix} \begin{bmatrix} F_x \\ F_y \end{bmatrix}, \tag{2}$$

$$\mu = \frac{F_r}{F_t}, \tag{3}$$

where γ is the cut in angle, and *t* is the processing time (ms).

The comparison of friction coefficients among different groups of experiments is shown in Fig. 4. The friction coefficient in the control group is the highest (0.9485), whereas the friction coefficient in MQL milling based on palm oil is the lowest, and it is decreased by 17.76–0.78%. The friction coefficient in MQL milling based on cottonseed oil is the second highest (0.8185), which is 13.71% lower than that in the control group. The friction coefficient in MQL milling based on soybean oil is higher than those in MQL milling based on other vegetable oils, which is decreased by 5.31–0.8981% compared with that in the control group. Besides, the friction coefficients in MQL milling based on castor and peanut oils are 0.8360 and 0.8458, respectively.

3.3 Surface Roughness

Surface roughness is an important parameter for workpiece surface quality evaluation and determines surface smoothness. Low surface roughness reflects high surface smoothness. Surface roughness can influence the fatigue strength, contact stiffness, and corrosion resistance of the workpiece and considerably improve cooperation. Moreover, surface roughness influences the service life and reliability of machinery products. Poor surface quality will deteriorate workpiece performance, and the workpiece will fail before the expected life.

Ra is the arithmetic mean of absolute deflection distance (*Z*) between the profile points and baseline in one sampling length (*L*). A high R_a indicates a large absolute value of profile deflection distance. *Ra* is calculated with Eq. (4).

$$R_\alpha = \frac{1}{L}\int_0^L |y(x)|\left|d_x\right|, \tag{4}$$

where y(x) is the vertical coordinate of the profile curve.

RSm is the mean of profile irregularity distance in the sampling length *L*. Profile irregularity distance refers to the length of profile peak and the adjacent profile valley on the median. This parameter can be calculated from the following equation:

$$RS_m = \frac{1}{N}\sum_{i=1}^{n} S_i, \tag{5}$$

where *N* is the number of profile peaks at the mean line (Fig. 5).

Five points on the workpiece surface acquired under each working condition are selected to measure surface roughness, thereby obtaining four groups of correlated roughness values. *Ra*, *RSm*, and their standard deviations are selected as evaluation parameters of roughness. Surface roughness value (*Ra*) is gained under different lubrication conditions, and its standard deviation is measured by a roughness measuring device (Fig. 6). *RSm* and its standard deviation are shown in Fig. 7.

Figure 6 shows that the surface roughness (*Ra*) in the control group is the highest (0.431 μm) among those of the other groups, indicating the poorest surface quality of workpiece. By contrast, *Ra* in the MQL milling based on vegetable oils is decreased to different extents. The lowest *Ra* (0.231 μm) is observed in MQL milling based on palm oil, which is 46.40% lower than that of the control group. The second lowest *Ra* (0.242 μm) is in MQL milling based on cottonseed oil, which is 43.85% lower than that of the control group. Moreover, *Ra* in MQL milling based on castor and peanut oils is similar, valuing 0.269 μm and 0.276 μm. *Ra* in MQL milling based on soybean oil is 0.319 μm, which is decreased by 25.99% compared with that of the control group. Soybean oil leads to the roughest workpiece surface after MQL milling compared with other vegetable oils. Meanwhile, the *Ra* standard deviation in MQL milling based on palm oil is the lowest, which reflects the small dispersion degree of the mean *Ra*. In other words, *Ra* is relatively even in the whole workpiece surface, and the machining precision is high.

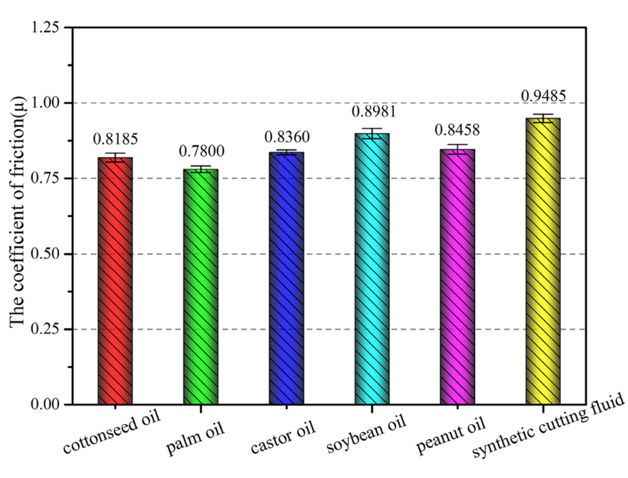

Fig. 4 Friction coefficient under different working conditions

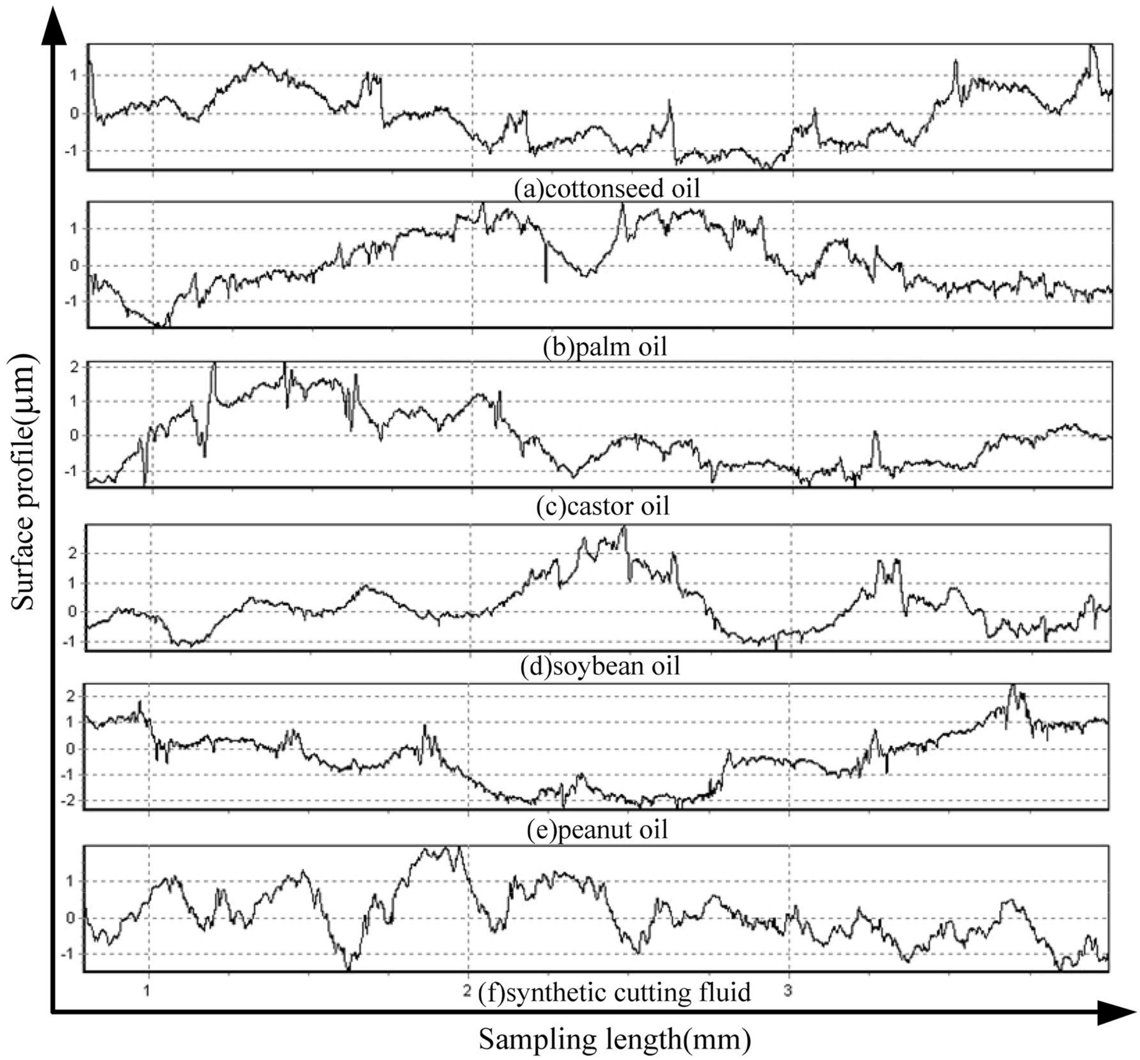

Fig. 5 Typical signal image of surface roughness measurement

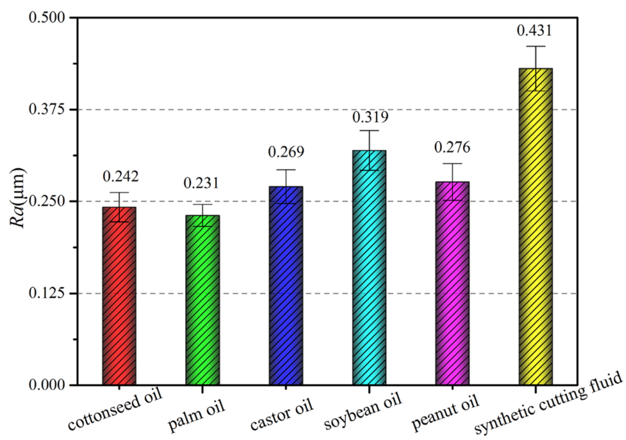

Fig. 6 R_a under different working conditions

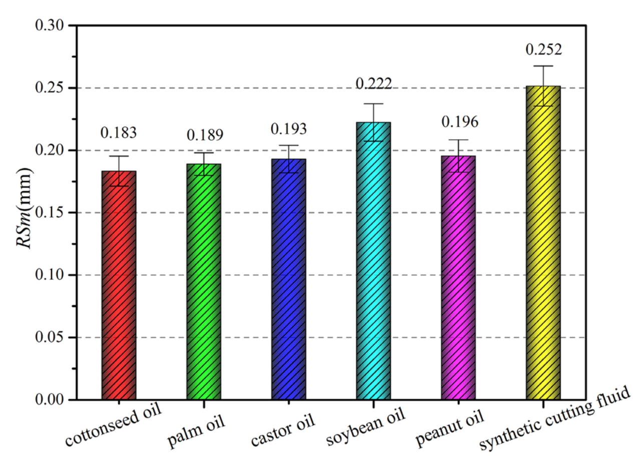

Fig. 7 RS_m under different working conditions

RSm reflects the diameter of scratches on the workpiece surface after MQL milling. A high *RSm* can reduce the surface quality of the processed workpiece. As shown in Fig. 7, the *RSm* of the control group is the highest (0.252 mm) among the others, indicating the largest average width of scratches on the workpiece surface. On the contrary, the *RSm* in MQL milling based on cottonseed oil is the lowest (0.183 mm and 27.38% lower compared with that of the control group), followed by *RSm* in MQL milling based on palm oil (0.189 mm and 25%). The *RSm* in MQL milling based on cottonseed oil and palm oil are similar. In addition, the *RSm* in MQL milling based on castor and peanut oils are similar at 0.193 and 0.196 mm, respectively. The *RSm* in MQL milling based on soybean oil is 0.222 mm, which is 11.90% lower than that of the control group. This result reflects that scratches on the workpiece surface in MQL based on soybean oil are thicker than those in MQL milling based on the other vegetable oils. Moreover, the standard deviations in MQL milling based on the synthetic cutting fluids and soybean oil are high, indicating a high discretion degree of the mean *RSm*. The violent vibration of a tool caused by a strong milling force is reflected by the increasing transverse differences of *RSm* on the workpiece surface.

3.4 Chip Surface Topography

In the process of metal cutting, especially in the process of high-speed cutting, the shape of chips is important, and its change affects the surface quality of the workpiece and the service life of the tool [37]. The formation process of chips is the essence and foundation of physical and chemical phenomena in the cutting process, such as cutting force and temperature [38, 39]. Different cooling methods can also affect the chemical diffusion at the tool–chip and tool–workpiece interface by analyzing the element deposition on the chip and machine surface [40]. Therefore, the morphological characteristics of chips must be studied to understand the mechanism of high-speed cutting and improve machining efficiency [41, 42]. SEM was used to analyze the shape of chips and the surface morphology on the back of the chips. SEM images of milling chips under different lubrication conditions are shown in Fig. 8.

As shown in Fig. 8, chips under all six lubricating conditions are smooth strips, and the front face of the chips contacts with the rake face of the tool. According to the analysis of the front face of the chips, scratches on the front face are caused by cohesive actions between the AISI 1045 and the tool. When chips flow, hard particles on the tool surface may scratch the workpiece, thus leaving scratches on the contact surface. High temperature during the process intensifies scratch production [43]. Scratches caused by hard particles easily induce mechanical wear [44]. Therefore, thick scratches reflect poor processing conditions. The back face of the chips is the noncontact surface of the chips and the tool. The uneven back face of the chips appears as hairy layers, accompanied with abundant dense stripes caused by shearing plastic deformation. The irregular hairy shearing surfaces formed by multiple uneven layers determine different shapes and sizes of shearing surfaces. Besides, dislocation intersections are found among local shearing surfaces. According to further observations, scratches on front face of the chips are evident, indicating that chips are cut and squeezed by the rake face of the tool when they flow along the rake face. Later, straight scratches along the outflow direction are formed upon high contact and shearing stress.

In MQL milling based on palm oil, only a few narrow scratches on the chip surface is produced without other obvious phenomena, implying the uniform metal deformation on the cutting layer, low unevenness on the free surface of the chips, and basic constant thickness of the chips. In addition, the contact between the tool and chips changes from conventional local adhesion into tight adhesion. The number of frictional scratches on the chip surface decreases, and the bottom surfaces of the chips become increasingly smooth. Surface roughness is low. In conclusion, palm oil can improve the processing morphology of chips to some extent, thus improving the surface quality and prolonging the service life of the tool.

Although chips are relatively smooth in MQL milling based on cottonseed oil, deep scratches are found on the chips. Furthermore, wide scratches are produced on the chip surface in MQL milling based on castor oil. These wide and deep scratches are caused by hard particles on the tool surface. Therefore, the lubricating effects of cottonseed and castor oils are poorer than that of palm oil.

Numerous black spots, which indicate burn damages, are observed on the chip surfaces in MQL milling based on soybean oil and synthetic cutting fluids. Under these two lubricating conditions, high milling force and temperature not only increase the strain rate of materials but also strengthen the thermal softening effect. The interaction of these two effects changes the fragility of materials. Cutting heats, which are accumulated on the shearing surface, are released immediately upon a small disturbance in the cutting process, which is conducive to shear slip and causes serious deformation of chips. The lubricating effects under these two conditions are poor accordingly. Moreover, the chip surface in MQL milling based on peanut oil has the most scratches. These scratches are deep and have a large node interval. Therefore, the chip surface is rough. Plastic has accumulated on the chip surface, and the surface integrity of the chips is poor, reflecting that hard points on the rake surface of the tool can produce quite serious scratches on the chip surface in MQL milling based on peanut oil. The lubricating effect of peanut oil is relatively poor.

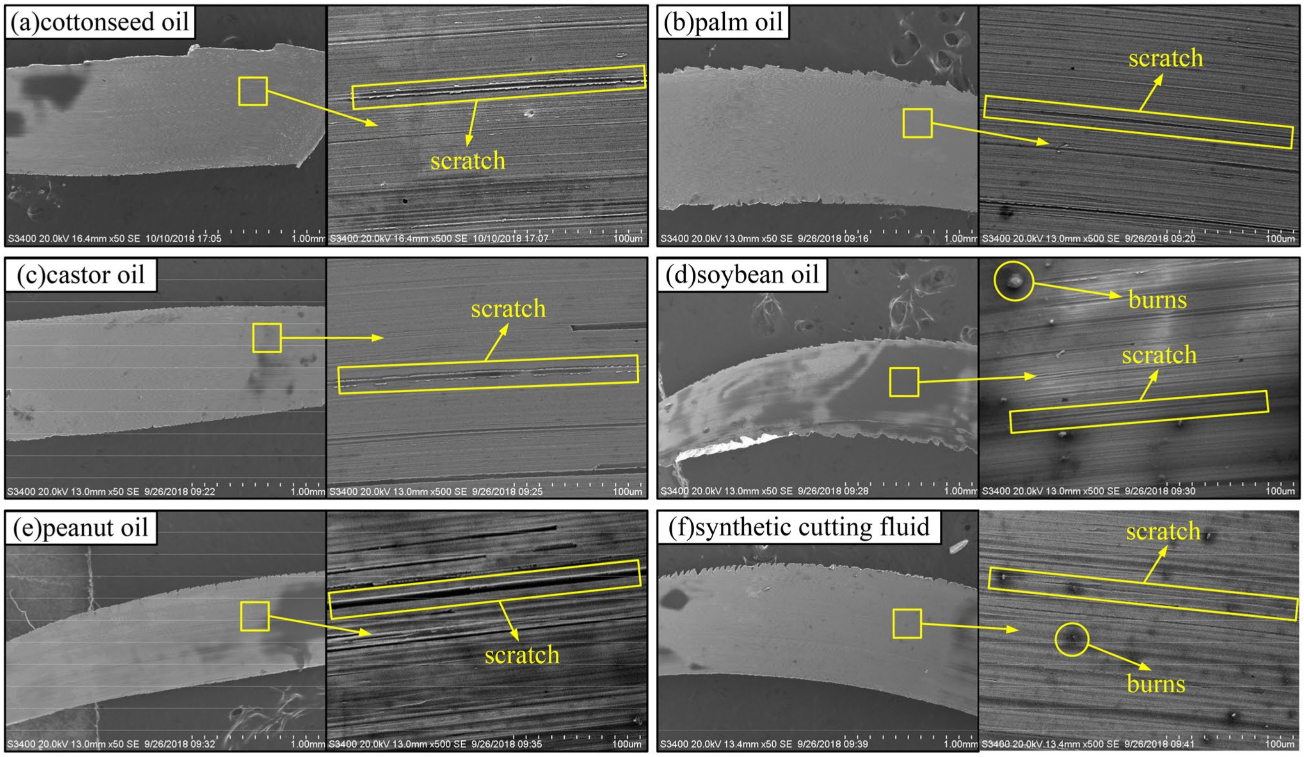

Fig. 8 SEM images of chips surfaces under different working conditions

3.5 Workpiece Surface Topography

Surface morphology is an important index to evaluate and reflect the surface quality of the workpiece [45]. It is the collaborative consequence of multiple random factors in the part processing, including mechanical vibration, temperature changes of the tool, and material deformation, etc. Surface morphology can influence the performance of parts directly, such as abrasive resistance, corrosion resistance, and fatigue strength. Figure 9 shows the SEM diagram of the workpiece surface under different working conditions.

Figure 9 shows that the workpiece surface has developed corrugated textures, which are the surface morphology caused by a relative movement between the tool and the workpiece. Corrugated textures reflect the motion trajectory of the cutting edge. The shape of the cutting edge is duplicated on the workpiece surface. The displacement of each ridge with a uniform interval along the feeding direction is equivalent to feed engagement in milling parameters.

The MQL milling based on palm oil achieves the best surface quality of the workpiece. Although a few peel-offs are found on the workpiece surface, scratches are small in quantity and depth. The overall workpiece surface is relatively smooth, which proves the remarkable lubricating effect of palm oil. The surface quality of the workpiece after MQL milling based on cottonseed oil is relatively good, manifested by few scratches and peel-offs. This result confirms the good lubricating effect of cottonseed oil.

The surface quality of the workpiece after MQL milling based on synthetic cutting fluids is the poorest among that of the other conditions. Burn damages, peel-offs, and abundant scratches are found on the workpiece surface, which are caused by the serious ploughing behavioral characteristics of hard particles on the tool surface. The lubricating effect of synthetic cutting fluids is the poorest among that of the other conditions. In addition, the protuberant edges are not in the same straight line, but many small ploughing ridge belts are formed. Ploughing ridges not only affect surface roughness of the processed workpiece but also act on the tool surface to produce additional grooves, thus intensifying the tool wear and forming a vicious circulation.

The surface qualities of the workpiece in MQL milling based on castor and soybean oils are relatively poor, including many obvious scratches. Two close scratches are caused by tool wear. The highest *Ra* corresponds to the most serious ploughing on the workpiece surface by hard particles on the tool surface. Moreover, the rough grooves on the wear surface of the tool are duplicated onto the workpiece surface. The squeezing and friction on the cutting edge–workpiece interface is strong. The workpiece surface in MQL milling based on castor oil is covered with substantial burn damages,

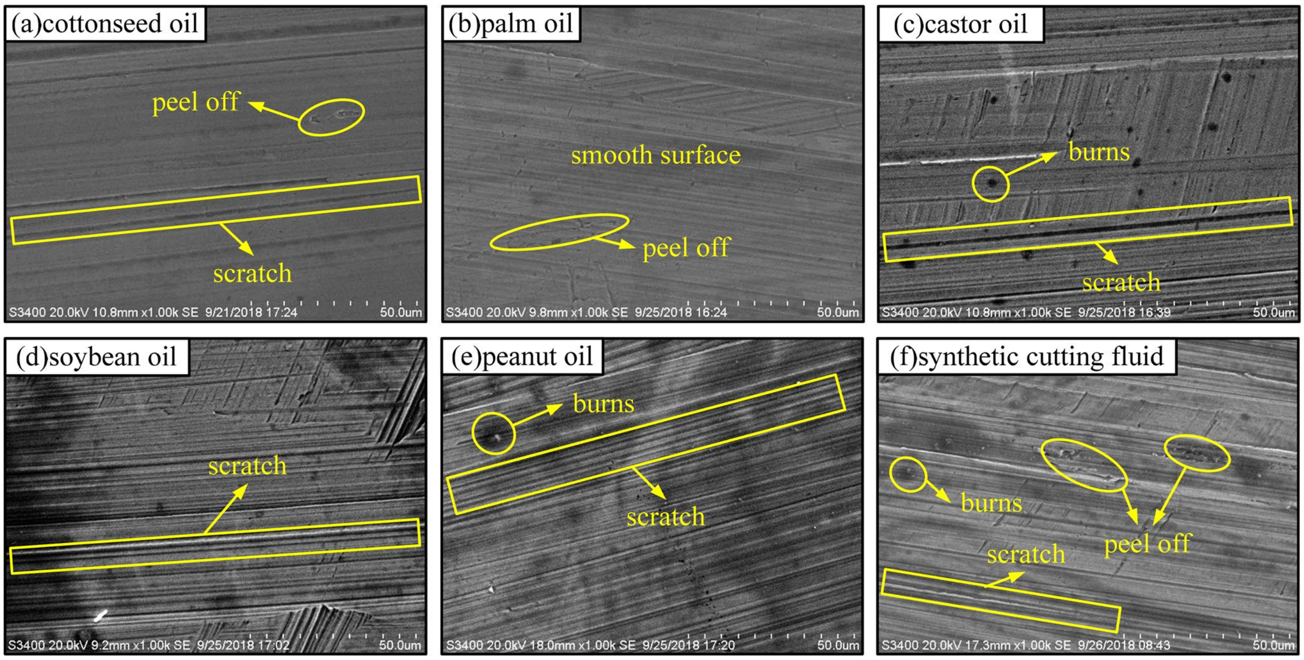

Fig. 9 SEM images of the workpiece surfaces under different working conditions

which reflect the poor cooling effect of castor oil in addition to its poor lubricating effect.

4 Discussion

4.1 Molecular Structure

Vegetable oils contribute to lubrication and antifriction during the friction process. Effective molecules in vegetable oils are adsorbed onto the metal surface physically and chemically, forming a lubrication film effectively. These properties are closely related with the adsorption capacity and reaction activity of molecules and the characteristics of the oil film and naturally related with molecular structures [46, 47].

Vegetable oil is the compound of triglycerides and fatty acids. Triglycerides are composed of one glyceride molecule and three fatty acid molecules (Fig. 10). Ester groups and carboxyl (-COOH) are polar groups, which have extreme affinity to the material surface of the workpiece. Polar groups are adsorbed onto the metal surface through the van der Waals force and thereby form a molecular film against friction and wearing [48]. This process involves the lubrication mechanism of vegetable oils. Besides, polar molecules can react with metals to produce metallic soap that is adsorbed as a boundary film on the workpiece surface. The lubricating film of vegetable oils is shown in Fig. 11. Physical adsorption film and chemical reaction film are conducive to lubrication [49, 50]. Therefore, vegetable oils are characterized by good lubricating effect, biodegradation, and sustainable use. They are resource-saving and environment-friendly base oils for MQL.

Categories and contents of fatty acids vary in different vegetable oils [51]. Different fatty acids have different molecular structures and lengths of carbonic acid (Fig. 12). Fatty acids are mainly divided into two types, namely saturated and unsaturated fatty acids. Saturated fatty acids involve no C = C bonds. Myristic, palmitic, and lauric acids are common saturated fatty acids. Unsaturated fatty acids contain at least one C = C bond. Linoleic, oleic,

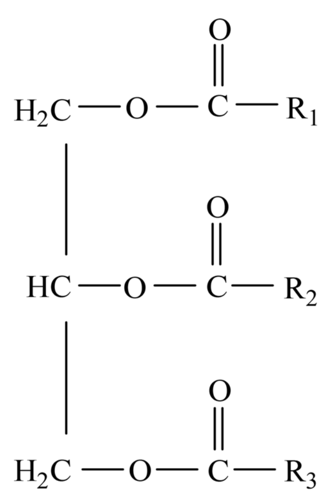

Fig. 10 Chemical structure of typical triglyceride

linolenic, and arachidonic acids are common unsaturated fatty acids.

The strength of the lubricating oil film is related with the categories and content of fatty acids in vegetable oils.

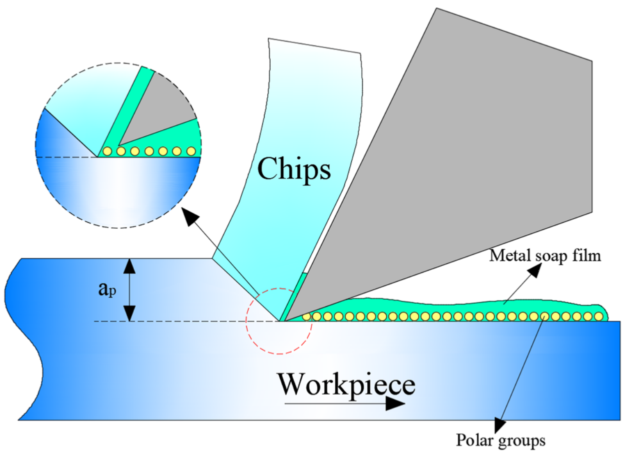

Fig. 11 Schematic of lubrication in the milling interface

As a result, the cooling and lubricating performance of vegetable oils on the tool–workpiece interface is different. The lubricating oil film formed by vegetable oils with high content of saturated fatty acids during milling is stronger than that formed by vegetable oils with high content of unsaturated fatty acids. Therefore, the vegetable oil with high content of saturated fatty acids is favorable to reduce the cutting force and friction coefficient; meanwhile, the surface roughness of the workpiece is low. The lubricating film formed by fatty acids with only one C = C (monounsaturated fatty acid) is stronger than that formed by fatty acids with multiple C = C bonds (polyunsaturated fatty acid); therefore, the better the surface quality of the workpiece, the better the surface quality. The number of carbons influences adsorption energy. In general, the total adsorption energy is positively related with the number of carbons and the strength of oil film. The maximum number of carbons is required to form an oil film with high density and strength. For saturated fatty acids, the friction resistance and wear resistance reach the peak and remain consistent when the number of carbons is higher

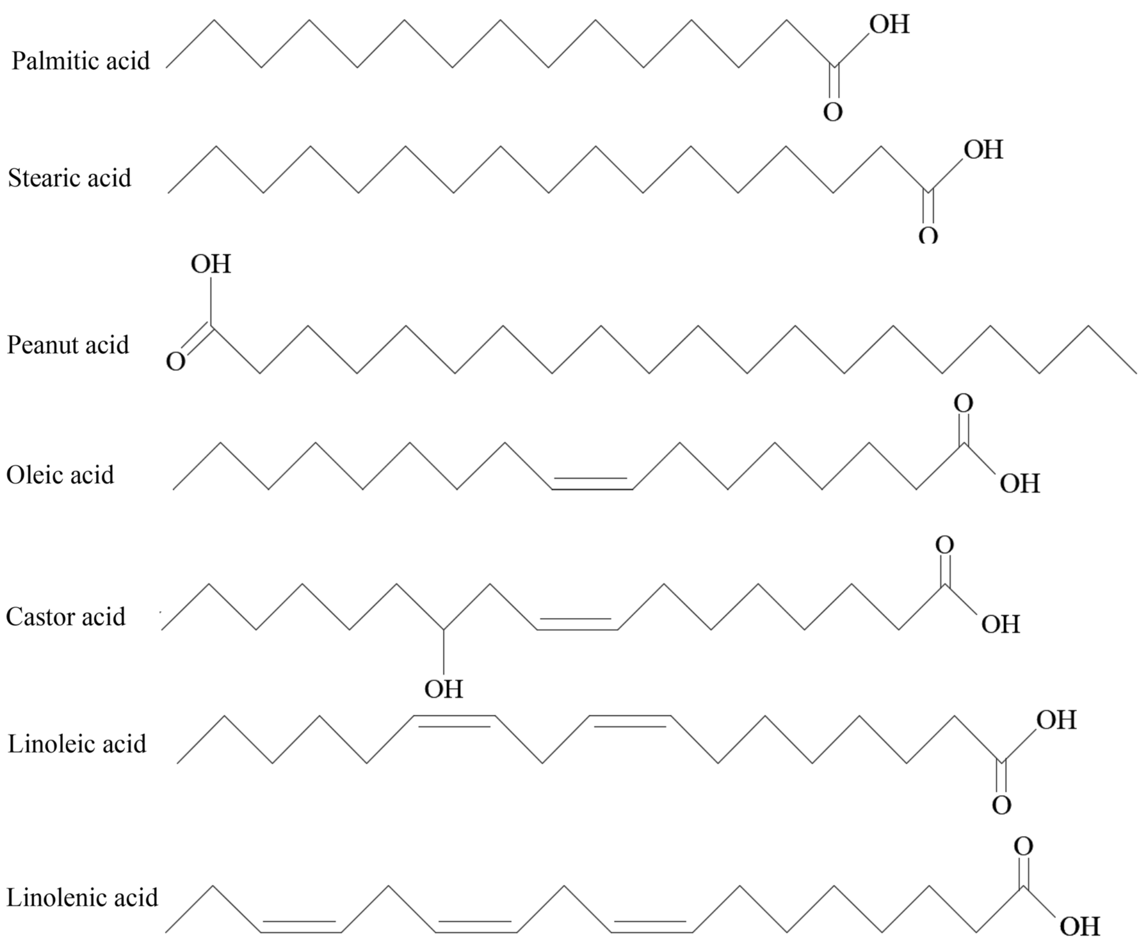

Fig. 12 Molecular structure of different fatty acids

than 16. Under this circumstance, the lubricating effect remains basically the same with the increase in the number of carbons. For unsaturated fatty acids, the C = C weakens the oil film. The strength of the oil film is influenced by molecular cohesion. Given a long carbon chain, the oil film becomes stronger, and the lubricating effect of fatty acids is improved [52].

The saturated fatty acid content of palm oil reaches as high as 49.9%, which is the highest among all five vegetable oils. Saturated fatty acids are stable and difficult to oxidize. Accordingly, the lubricating oil film formed by saturated fatty acids is the most stable. The palmitic acid content of palm oil is 45.1%. Palmitic acid is a type of saturated fatty acid, and the number of carbons is 16. The strength of the adsorption oil film formed by palmitic acid can reach the peak strength of film formed by saturated fatty acids. Given the same number of carbons, the lubricating effect of saturated fatty acids is better than that of unsaturated fatty acids. Therefore, the lubricating oil film formed by palm oil is the most durable and strongest. In addition, the lubricating effect of palm oil is the best.

The saturated fatty acid content of cottonseed oil is 25.12%, including 21.9% of palmitic acid. Hence, the adsorption oil film formed by cottonseed oil is strong and stable. The lubricating effect of cottonseed oil is only next to that of palm oil. Although the content of saturated fatty acids in castor oil is only 1.36%, the content of single unsaturated fatty acids is 93.67%. The content of multiple unsaturated fatty acids is 4.97%, which is lower than those in the other four vegetable oils. The single unsaturated fatty acids are more stable than multiple unsaturated fatty acids. In addition, the carbon chain of castor acid is C18 long and has two polar groups (–COOH and –OH), which determine the strong polarity of the castor oil. Castor oil is easy to adsorb onto the metal workpiece to form a lubricating oil film due to strong metal absorption. This characteristic reflects that the castor oil presents a stronger lubricating effect compared with soybean and peanut oils. The lubricating film formed by soybean oil, which has a low content of saturated fatty acids (15%) and a high content (61%) of multiple unsaturated fatty acids, is unstable and weak. In a word, soybean oil provides the poorest lubricating effect, followed by peanut oil.

4.2 Viscosity Analysis

Viscosity is the ratio between shearing stress and shearing rate. It is defined as the energy exchange caused by molecular adhesion forces and irregular movement in the cutting liquid. Viscosity is a method that measures resistance to liquid flow. The viscosity of cutting fluid is an important factor that influences its lubricating effect [53].The relative movements of the workpiece and the tool produce shearing stress in the cutting fluid on the tool–workpiece interface during workpiece processing, thus producing an internal friction in the cutting fluid. The expression of internal friction by the mobilizing force of fluid is called viscosity. High viscosity reflects large internal friction. Viscosity mainly affects the lubricating effect of the cutting fluid on the tool–workpiece interface and the heat exchange on the tool–chip interface. It also imposes certain effects on the formation of lubricating oil film. Cutting fluids with small viscosity have difficulty forming thick and strong lubricating oil film on a high-temperature friction surface. This lubricating oil film has a small bearing capacity due to low strength and thickness. It can be easily destroyed by frictional force on the tool–workpiece interface, thus decreasing the lubrication effect and increasing the friction force between the tool and the workpiece. Therefore, studying the influence of the viscosity of different base oils on processing performance has important implications to the positive selection of base oils for MQL. Vegetable oils have different viscosity values due to molecular structures of fatty acids. The viscosity temperature curves of different vegetable oils are shown in Fig. 13.

The viscosity of vegetable oil decreases with the increase of temperature. Initially, the lubricating effect of the cutting fluid increases with the increase in viscosity, but it decreases after the viscosity reaches a certain numerical value [54]. When the viscosity of base oils is extremely low, the lubricating film is thin, which is equal to dry grinding. When the viscosity of base oils is too high, base oils are almost not flowing, and they are equal to solid films. The process is similar to dry grinding, and the lubricating effect is unsatisfying [55]. As shown in Fig. 13, castor oil has the highest viscosity, which is nearly ten times that of other vegetable oils. Castor oil stops the flow and thereby provides poor lubricating effect. The viscosity of palm oil is next to castor oil. However, palm oil is not high enough to stop the flow. Under this viscosity, the cohesion between molecules is large, and the Brownian movement is strong enough to stop the flow of cutting fluid. This viscosity is beneficial to the formation of a thick and strong oil film. Moreover, palm oil can stay on the workpiece surface to offer stable lubricating effects between the tool and the workpiece and to prevent tool wear. This phenomenon explains the excellent lubricating effect of palm oil. The lubricating effect of cottonseed oil is only next to that of palm oil, which is related with viscosity. Soybean oil has the lowest viscosity, and the corresponding oil film is thin. It easily breaks during the process, thus decreasing the lubricating effect.

4.3 Surface Tension and Contact Angle

A surface layer is formed at the contact between liquid and gas, in which mutual attractions occur, that is, surface tension. Surface tension helps the liquid surface shrink automatically and maintain a spherical morphology. Surface

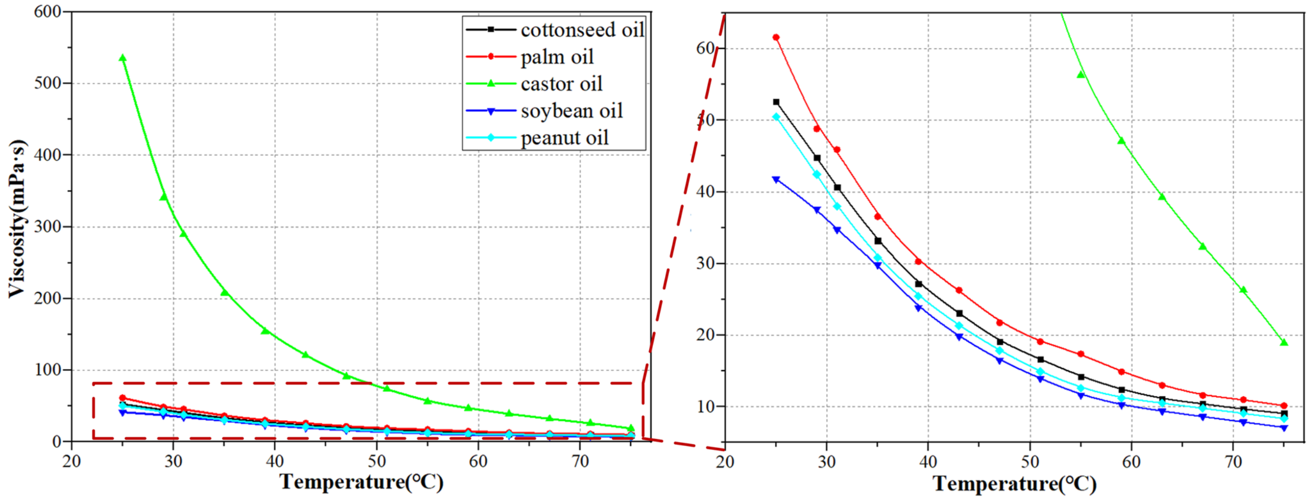

Fig. 13 Viscosity temperature curves of different vegetable oils

tension is caused by the cohesion between liquid molecules. Molecules in the surface layer of liquids are sparser than those in the liquid. These molecules bear a force pointing into the liquid, which causes a shrinkage trend of the surface layer, thereby decreasing the surface area of liquid as much as possible. The surface tension of different vegetable oils is shown in Fig. 14.

MQL cutting fluid is sprayed by a nozzle onto the cutting zone as mist. Therefore, the state of mist on the workpiece, or known as the contact angle between fogdrop and workpiece surface, determines the lubricating effect. The contact angles of different base oils are shown in Fig. 15. In Fig. 15(a), the contact angle refers to the included angle (θ) between the tangent line of the gas–liquid interface and the solid–liquid boundary line. The tangent line of the gas–liquid interface is drawn according to the point of intersection of gas, liquid, and solid. A small contact angle of fog drop represents a large infiltration area of mist [56]. The infiltration area of mist is called the effective lubrication area of the MQL cutting fluid. A large, effective lubrication area brings a good lubricating effect. The effective lubrication area of cutting fluid is too small to provide sufficient lubrication effects when the contact angle of mist is excessively large. The contact angle of mist is related with “solid–liquid surface tension”, “solid–gas surface tension” and “liquid–gas surface tension”. Among them, the “liquid–gas surface tension” is the surface tension. From the Young equation, the contact angle between the mist and the workpiece surface can be expressed as [57]

$$\cos(\theta)=\left(\gamma_{sv}-\gamma_{sl}\right)/\gamma_{vl}, \tag{6}$$

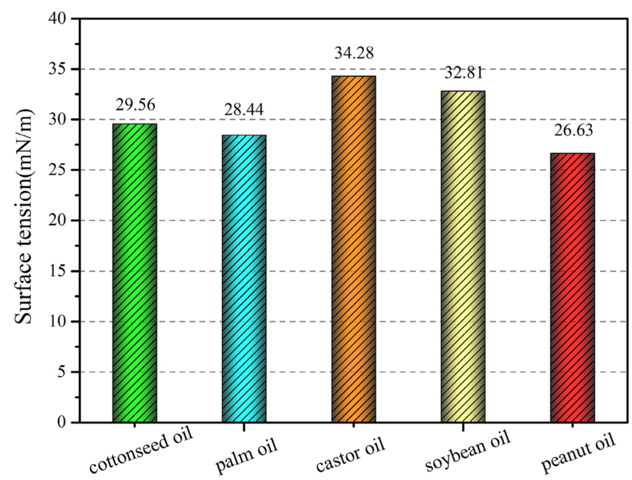

Fig. 14 Surface tension of different vegetable oils

where γ_{sv}, γ_{sl}, and γ_{vl} are solid–gas surface tension, solid–liquid surface tension, and gas–liquid surface tension, respectively.

A positive relationship between surface tension and contact angle can be observed from the above equation. When the contact angle is small, the mist of vegetable oils is not only small in size and distribute more evenly but also achieve large wetting areas per unit of grain size volume [58]. Finally, the infiltration performance of the MQL base oils on the tool–workpiece interface is improved [59].

Figures 14 and 15 reveals that the surface tension and contact angle of different vegetable oils present the same orders: castor oil > soybean oil > cottonseed oi 1 > palm oil > peanut oil. In Fig. 15, peanut oil has the lowest surface tension (26.63 mN/m) and contact angle (23.5°), followed by palm oil (28.44 mN/m and 25.5°). Castor oil has the

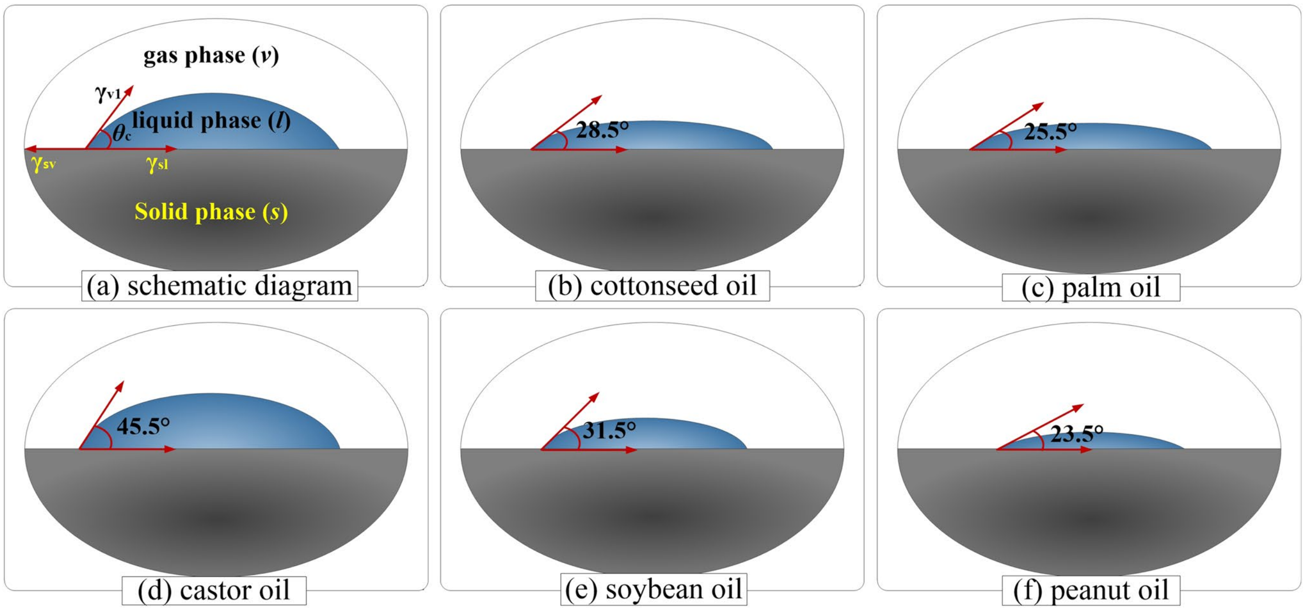

Fig. 15 Different base oil contact angle

highest surface tension and contact angle (34.28 mN/m and 45.5°). Obviously, palm oil and peanut oil can obtain large infiltration areas and provide sufficient lubrication on the tool–workpiece interface. The large wetting area can cover more lubrication areas, which is conducive to obtain sufficient lubricating effect [60, 61]. Accordingly, the milling force and surface roughness of the workpiece are decreased, whereas the surface quality of the workpiece is improved [62].

According to the physicochemical properties of different vegetable oils, peanut can form the largest lubricating oil film for the smallest contact angle, but the lubricating oil film is thin and weak for the low viscosity. Consequently, the lubricating effect of peanut oil is not satisfying. On the contrary, the lubricating oil film formed by palm oil is large and strong because of the small contact angle and high viscosity. Additionally, palm oil contains a high content of saturated fatty acids in favor of lubricating effect. Therefore, the MQL milling based on palm oil achieves the smallest friction coefficient and the lowest *Ra*.

5 Conclusion

The milling parameters (milling force, friction coefficient, surface roughness, surface morphology of chips and workpiece) are analyzed on the basis of the experimental studies. The lubricating effects of six base oils in the MQL milling of AISI 1045 are investigated. Furthermore, the physicochemical properties (composition, molecular structure, viscosity, surface tension, and contact angle) of vegetable oils are explained. Some conclusions can be drawn.

1. MQL milling based on the synthetic cutting fluids achieves the highest milling force and friction coefficient. The milling force and friction coefficient in MQL milling based on palm oil are the lowest. In addition, the surface quality of the workpiece in MQL milling based on synthetic cutting fluids is the poorest. The surface qualities of the workpiece in MQL milling based on vegetable oils are improved to different extents. In particular, MQL milling based on palm oil achieves the best surface quality of workpiece. MQL based on palm oil achieves the best friction resistance, and it meets the requirements of environment-friendly manufacturing.
2. Chip morphologies under different lubricating conditions are observed. Many scratches are found on the chip surfaces in the control group. On the contrary, chip surfaces in MQL milling based on palm oil are smooth with the least scratches and uniform metal deformation. Moreover, the workpiece surface of the control group is the poorest, which are manifested by serious burn damages and peel-offs and many scratches. The surface qualities of workpiece in MQL milling based on vegetable oils are improved to some extent. The workpiece surfaces in MQL milling based on cottonseed and palm oils are relatively satisfying and even.
3. The strength of lubricating oil film is related to the type and content of fatty acids in vegetable oil. Vegetable oil with high content of saturated fatty acid is beneficial to reduce cutting force and friction coefficient. Only

one fatty acid with C = C (monounsaturated fatty acid) forms a stronger lubricating film than those with multiple C = C bonds (polyunsaturated fatty acid). Palm oil with the highest saturated fatty acid content can form the most stable lubricating oil film, and the lubricating effect is better than other vegetable oil.

4. The lubrication effect of cutting fluid increases with the increase of viscosity, but decreases when the viscosity reaches a certain value. The viscosity of castor oil is very high, but the lubrication effect is not ideal. The oil film formed by higher viscosity of palm oil is more favorable for lubrication. At the same time, the surface tension of palm oil is large, the contact angle is small, the oil film spreading area is larger, and the lubrication effect is the best.

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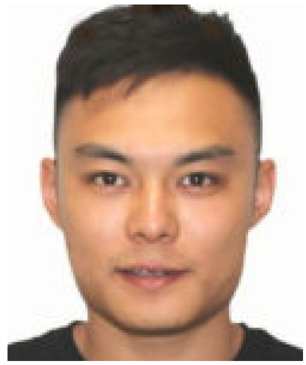

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