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Research Paper

Analysis of volume ratio of castor/soybean oil mixture on minimum quantity lubrication grinding performance and microstructure evaluation by fractal dimension

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ABSTRACT

As a non-edible, degradable, and environment-friendly crop product, castor oil can be used as lubricating oil in material processing. However, its high viscosity results in poor flowability, thereby limiting its industrial applications. Although experiments have revealed the excellent lubrication performance of castor/soybean oil mixture, the volume ratio of castor oil and soybean oil can significantly influence their minimum quantity lubrication (MQL) grinding performance. In the current study, seven castor/soybean oil mixtures under different volume ratios ranging between 1:0.5 and 1:4 were prepared for MQL grinding of Ni-based alloy. The mixed oils were compared with pure castor oil (1:0) in terms of viscosity and tribological behaviors. The grinding experiment involved the evaluation of specific grinding force, surface roughness, surface microtopography, and grinding debris, conluding that the preferred castor/soybean volume ratios were found to be 1:0.5, 1:1, 1:1.5, and 1:2. The surface microtopographies of selected workpieces were analyzed further in terms of their fractal dimension and scale coefficient, finding that the maximum fractal dimension (D = 1.31) and minimum scale coefficient (G = 0.30) are achieved when the volume ratio is 1:2. Hence, the optimal volume ratio is determined.

1. Introduction

With the improvement of living quality, the traditional manufacturing industry can no longer meet people's demands for environment-friendly development, raising the urgency for the development of the traditional manufacturing industry toward high energy efficiency, clean production, water conservation, pollution control, and cyclic utilization. For this reason, the grinding field is improving its processing technology and aiming actively for green development. Selection of grinding condition and grinding liquid has become a key concern of engineers.

Grinding conditions include four cooling lubrication modes: flood grinding, dry grinding, minimum quantity lubrication (MQL), and nanofluid MQL (NMQL) grinding. Flood cooling lubrication achieves high cooling performance but has limited lubrication performance and causes considerable harm to the environment and human health. These limitations restrict its application in machining. Water-based grinding fluid for flood cooling lubrication is typically used because of its cooling and lubricating effects (Shen and Shih, 2009). Moreover, dry grinding not only imposes high requirements on the grinding wheel, workpiece materials, and machine tools, but also results in poor workpiece surface quality. MQL and NMQL integrate the advantages of dry grinding and traditional flood grinding (Hewson and Gerow, 1999). MQL and NMQL can reduce the consumption of grinding liquid to the minimum quantity, thereby reducing significantly the cost and harm to the environment and human health (Tawakoli et al., 2010; Zhang et al., 2015b). In addition, MQL utilizes cooling lubrication medium, which results in an improvement in lubrication conditions and a significant reduction in abrasion among the grinding wheel, workpiece, and grinding debris (Li et al., 2008; Mao et al., 2012).

Thus far, scholars have conducted numerous experimental studies using vegetable oils as MQL base oil. Vegetable oil possesses distinct advantages compared with other lubricating fluids. Vegetable oil is a nontoxic or slightly toxic renewable source that is relatively low-priced

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Nomenclature

MQL	Minimum quantity lubrication
VBCFs	Vegetable-based cutting fluids
v_s	Peripheral speed of grinding wheel (m/s)
v_w	Workpiece feed speed (mm/s)
a_p	Grinding depth (mm)
F_t’	Specific tangential grinding force (N/mm)
F_n’	Specific normal grinding force (N/mm)
t_p	Profile supporting length ratio
Rvk	the average depth from the core roughness profile to the inner profile valley
Rk	Depth of the residual core profile
Mr1	Separate the profile peak from the core roughness profile
Mr2	Separate the profile valley from the core roughness profile
Ra	Arithmetic average height (μm)
RSm	Mean spacing at mean line (mm)
T_{PT}	Weighted average value of profile supporting length
SEM	Scanning electron microscope
VI	Viscosity index
G	Scale coefficient
D	Fractal dimension
η	Dynamic viscosity (cP)
Rpk	the average height of the profile peak
Ti	Weight (%)
Tpi	the profile supporting length ratio of each c_i
c_i	Horizontal intercepts

(Cetin et al., 2011). Vegetable oil-based lubricants have excellent lubricity because of the high fatty acid content and high film-forming property of carboxyl in vegetable oils (Asadauskas et al., 1997; Zhang et al., 2015a; Wang et al., 2016) and can improve the quality of the workpiece (Lee et al., 2012; Silva et al., 2013; Kalita et al., 2010). However, the use of such lubricants is restricted because of their low level of thermo-oxidative stability and poor cold flow behavior (Erhan et al., 2006).

Castor oil can be used as lubricating oil because it is inedible, degradable, clean, and highly viscous. Because of its high viscosity, castor oil is more suitable for use as the base oil of lubricating grease compared with other vegetable oils (Prasenjit et al., 2008). Ye and Tao (2006) structurally modified castor oil and improved its rheological and tribological performances but not its oxidation stability. Vegetable oils can react with oleic acids at high temperatures to improve lubrication performance (Fox et al., 2004; Erciyes et al., 1991). Mixing castor oil with diesel and biodiesel can improve its viscosity, flash point, and other physical properties (Thomas et al., 2012; Mejía et al., 2013).

Previous studies revealed that castor oil can be used as lubrication oil of material machining due to its high viscosity. However, its high viscosity causes poor flowability, thereby restricting its industrial applications. The selection of the optimal castor/soybean mixture has been found through a verification experiment on mixtures of castor oil and different vegetable oils (Guo et al., 2016). Considering that volume ratio has been found to be crucial to the lubrication performance of the grinding process (Kabasakal et al., 1996), the current study aims to determine the optimal volume ratio of castor/soybean oil mixture for the MQL grinding of Ni-based alloy, infer its lubrication mechanism, and provide references for industrial production. Based on the above analysis, seven castor/soybean oil mixtures under different volume ratios were prepared in this study. Pure castor oil was used for comparison. Grinding performance was evaluated in terms of specific grinding force, surface roughness, workpiece surface microtopography, and grinding debris. The workpiece surface microtopography was analyzed further in terms of fractal dimension and scale coefficient to determine the optimal volume ratio of castor/soybean oil mixture.

2. Experiment

2.1. Experimental setup

The experiment was conducted using a numerical-control precision surface grinder (Model: K-P36; Make: Kőrber Schleifring, China). The main technological parameters are as follows: principal axis power of 4.5 kW, highest rotating speed of 2000 r/min, workbench driving motor power of 5 kW, and grinding scope of 600 mm × 300 mm. A white corundum-vitrified bond grinding wheel (Model: WA80MV12P; Make: Yikun Grinding Wheel Co., Ltd., China) was used in the experiment (Wheel Size: 300 mm × 20 mm × 76.2 mm; Grain Size: 160 mesh; Pore Size: large; Hardness: soft; Highest Peripheral Speed: 50 m/s). A vegetable oil transfer device called Bluebe minimum quantity oil supply system (Model: KINS KS-2106; Make: Shanghai Jinzhao Energy Saving Technology Co., Ltd., China) and a 3D dynamometer (Model: YDM-III99; Make: Dalian University of Technology, China) were also employed. Grinding temperature was measured using a clip-type thermocouple (Model: MX100; Make: Yokogawa Electric Corporation, Japan). The experimental device setup is shown in Fig. 1. For each experiment, a 3D grinding force dynamometer was used to measure and record the normal, tangential, and axial forces. The measured sample frequency of the grinding force was 1 kHz. The collected grinding force signal was filtered through system software to test dynamic grinding force. Finally, the grinding force image and grinding force data documents were obtained. A total of 100 data points were selected from the stable grinding force zone in each direction to evaluate the mean and obtain the corresponding average force. The calculated average value of the grinding force was used in data processing to calculate the specific grinding force for each grinding process. Grinding temperature was measured using a clip-type thermocouple, which measured the temperature during the whole grinding process as shown in Fig. 2, and a warm bath box, which determined the relationship between the viscosity and temperature of the liquid base. After the grinding experiment, the surface of the workpiece and the grinding debris were analyzed using a scanning electron microscopy (SEM) (Model: S-3400N; Make: HITACHI, Japan). The surface roughness of the workpiece was measured using a surface profiler (Model: TIME 3220; Make: Beijing Time High Technology Ltd., China). During data processing, large data need to be eliminated to reduce accidental and random errors. The grinding parameters in the experiment are shown in Table 1.

In each grinding experiment, no dressing test was performed for 60 passes to record the evolution of the grinding forces. To achieve controllable grinding process, the grinding wheel was dressed to maintain consistent conditions at the wheel’s surface before each experiment. The dressing parameters of the grinding wheel are listed in Table 2.

The grinding workpiece was a high-temperature Ni-based alloy named GH4169, which is a kind of Ni–Cr–Fe-based aging sclerotic alloy. Table 3 presents the chemical composition of the high-temperature Ni-based alloy, GH4169. The mechanical properties of GH4169 at high temperature are shown in Table 4. The size of the workpiece was 40 mm × 30 mm × 30 mm. According to Guo et al. (2016), castor/soybean mixture has the best lubrication performance. Therefore, castor oil (Ricinus communis L.) and soybean oil (Glycine max) were chosen as the base oil. Vegetable oil molecules contain a large number of C═C double bonds and thus can be oxidized easily, which is an occurrence that would invalidate the base oil. Thus, in the experiment, vitamin E as antioxidant was added to the vegetable base oils at a volume fraction of 0.2%. Table 5 presents the basic properties of the castor and soybean oils.