

Article

Correlation between Lubricating Oil Characteristic Parameters and Friction Characteristics

Yanshuang Wang ^{1,2,*}, Qingguo Qiu ^{1,2}, Pu Zhang ^{1,2} , Xudong Gao ^{1,2}, Zhen Zhang ^{1,2} and Pengcheng Huang ^{1,2}

¹ School of Mechanical Engineering, Qilu University of Technology (Shandong Academy of Sciences), Jinan 250353, China; qqg991217@163.com (Q.Q.); zhangpuqlu@163.com (P.Z.); gg824032455@163.com (X.G.); zhennzhang@126.com (Z.Z.); hpc0163@163.com (P.H.)

² Shandong Institute of Mechanical Design and Research, Jinan 250031, China

* Correspondence: hkd_wang_yan_shuang@126.com; Tel.: +86-182-2264-1850

Abstract: In order to help one to judge the friction properties of lubricating oils without tests, this paper intends to establish the correlation between the characteristic parameters of lubricating oils and the friction properties. The elastohydrodynamic and boundary friction properties of poly alpha olefin (PAO) synthetic oil, polyol ester oil and paraffin-based mineral oil were tested using a Mini-Traction Machine. Fourier transform infrared microscopy is used to identify material changes before and after friction tests. The kinematic and dynamic viscosities of the three lubricating oils were measured using a petroleum product viscosity tester and a rotating rheometer. The results show that the kinematic viscosity does not directly determine the COF (coefficient of friction) of the lubricating oil, but the higher the dynamic viscosity, the higher the COF of the lubricating oil. The higher the viscosity-pressure coefficient, the lower the viscosity index (the worse the viscosity-temperature performance), and the higher the COF of the lubricating oil, which is related to the adaptability of the molecular structure of lubricating oils to pressure and temperature. PAO synthetic oils and polyol ester oils have excellent friction properties resulting from their strong adaptability to temperature and pressure variations due to the presence of linear chains and flexible groups.

Keywords: friction properties; dynamic viscosity; characteristic parameters; molecular structure



Citation: Wang, Y.; Qiu, Q.; Zhang, P.; Gao, X.; Zhang, Z.; Huang, P.

Correlation between Lubricating Oil Characteristic Parameters and Friction Characteristics. *Coatings* **2023**, *13*, 881. <https://doi.org/10.3390/coatings13050881>

Academic Editors: Manuel António Peralta Evaristo and Giorgos Skordaris

Received: 8 April 2023

Revised: 20 April 2023

Accepted: 4 May 2023

Published: 8 May 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Rolling bearings are common mechanical components used in almost every engineering system in the industry. It has been reported that there are currently more than 50 billion bearings in operation in the world at any given time [1]. Bearing friction has an important effect on its life and running stability. Using a suitable low-friction lubricant is one of the most common ways to reduce friction losses in rolling bearings. Commonly used lubricants include oils and greases. In high-speed and high-temperature bearings, oil was commonly used for lubrication. The properties of the lubricant itself are strongly correlated with the friction properties and hence with the bearing lifetime. Therefore, it is of great significance to study the correlation between lubricating oil characteristic parameters and friction characteristics, and the mechanism of the correlation for development of high-performance lubricating oil and long-life bearings.

When the bearings are properly operated, there is an elastodynamic lubrication state between the rolling elements and the raceway [2]. Gunsell et al. [3] studied a variety of base oils with different refining processes and different kinematic viscosities, and found that the solvent-treated mineral base oils had higher friction than the hydro-treated oils. Rounds [4] measured the friction properties of several mineral and synthetic base oils using a thrust ball-bearing device and found that the naphthenic base oils had higher friction than the paraffinic base oils. Yang et al. [5] measured the temperature rise of the loaded thrust bearings and found that lubricants with a low elastohydrodynamic COF had a low temperature rise; then, they concluded that the elastohydrodynamic COF of lubricating oil

was one of the important characteristics that determine the efficiency of rolling bearings and the class III+, IV and V oils had a lower elastohydrodynamic COF. In the field of boundary friction, Wu [6] and Hu [7] evaluated lubricants containing nanoscale WS₂ and ionic liquids using a four-ball friction tester, and his work demonstrated the important role of micro/nanoscale WS₂ in improving the tribological properties of lubricants. The friction and wear performance of lubricants containing graphene materials have also been studied using the UMT friction and wear tester. The results show that graphene flakes can form boundary friction films between contacting pairs, thus reducing COF and wear [8–10].

A number of studies have shown that the friction properties of oil are related to the molecular structure of oil. Yang et al. [11,12] used infrared spectroscopy to monitor changes in the lubricant structure during friction to assess the stability of the lubricant and the substances affecting friction performance. Hentschel [13] and Muraki [14] compared the COF of oils with the ring and branched chain structure, and concluded that the molecular shape has a significant influence on the tribological properties, and found that for oils with branched chain structure, the COF increases with the increase in branching degree. Chang et al. [15] found that shear stress and friction force of the ester oil are closely related to their structure, and showed that long straight-chain esters have lower shear stress and friction force, while branched esters have relatively higher shear stress and friction force.

Michaelis et al. [16] investigated the effect of base oil types on gear and bearing energy losses, found that a lubricant with a high viscosity index could optimize the bearing system, and noted that synthetic base oils (including esters, polyethylene glycol, and poly alpha olefin (PAO)) had lower power losses compared to mineral base oils. Robinson et al. [17] prepared a series of high branch chain polyethylene (BPE), which is used as a viscosity and friction improver for Class I lubricating oils. Changes in polarity, topological structure and molecular weight have a significant effect on the viscosity index and friction properties of lubricating oils. Hu et al. [18] evaluated the density, kinematic viscosity, viscosity index, friction reduction and anti-wear properties of gallate ester oils at 20 °C and pointed out that the physical or chemical adsorption film formed by gallate ester molecules between friction pairs was the key factor for their friction reduction and anti-wear properties. Guan et al. [19] found that the modified nano-TMT base oil had excellent lubricating properties, good viscosity-temperature performance, thermal stability and anti-wear properties. Girma [20] analyzed the correlation between lubricant pressure-viscosity coefficients and molecular structure using the film thickness data of lubricants.

Although there are many kinds of research on the tribological properties of different lubricants, they mainly focus on the difference in the improvement of the tribological properties of lubricating oil by different additives, there are few studies on the correlation and interaction mechanism between characteristic parameters of base oils and their friction properties. In this paper, the kinematic and dynamic viscosities of three lubricating oils at different temperatures were measured by using the kinematic viscosity tester and rheometer of petroleum products, and the COF of three lubricating oils under elastohydrodynamic lubrication and boundary lubrication were measured on a Mini-traction Test Machine, and the lubricating oils before and after friction were characterized. Finally, the influence factors and friction mechanisms of lubricants are discussed from the molecular structure point of view. The results are important for the development of new lubricating oils with high performance and low friction, as well as for laying a theoretical foundation for the discussion of friction mechanisms in different lubrication regimes.

2. Materials and Experiments

2.1. Lubricating Oil Samples

All oil samples were provided by Sinopec Lubricating Oil Co., Ltd. (Tianjin, China). The lubricants used in this test were PAO synthetic oil, polyol ester oil, and paraffin-based mineral oil. The three lubricant samples were numbered, and their numbers and parameters are shown in Table 1, the parameters in the table were provided by Sinopec Lubricating Oil Co., Ltd. (Tianjin, China).

Table 1. The parameters for the lubricating oils tested.

Number	Test Sample	Viscosity at 40 °C (mm ² /s)	Viscosity at 100 °C (mm ² /s)	Viscosity Index (VI)	Viscosity-Pressure Coefficient at 25 °C (Pa ^{−1}) [21]
1#	poly alpha olefin (PAO) synthetic oil	68	10.06	132	1.7×10^{-8}
2#	Polyol ester oil	68	9.72	124	1.85×10^{-8}
3#	Paraffin-based mineral oil	68	9.53	120	2.21×10^{-8}

2.2. Experimental Equipment and Details

2.2.1. Kinematic Viscosity-Temperature Test

The SYP1003-6 petroleum products kinematic viscosity tester (SYP1003-6, BOLEA, Shanghai, China) was used to measure the kinematic viscosity of lubricating oils at different temperatures from 30 to 150 °C. For testing, glass capillary viscometers with inner diameters of 0.6 mm, 0.8 mm, 1.0 mm, 1.2 mm and 1.5 mm were selected. Table 2 shows the applicable temperatures for each viscometer with different inner diameters. The measurements were repeated three times at the same temperature and the mean values were taken. When the measurement time is less than 200 s or more than 500 s, the glass capillary viscometer was replaced and the measurement was repeated to ensure the accuracy of the measurement. Using the data measured in this test, a Vogel–Fulcher–Tammann (VFT) model was developed for each of the three lubricating oil samples used in the test, to calculate the kinematic viscosity of the three lubricating oils at other temperatures. The results obtained from the measurements are as follows:

Table 2. Selection of inner diameter of viscometer.

Temperature/°C	30	50	70	90	110	130	150
Inner diameter of viscometer/mm	1.5	1.2	1.0	0.8	0.8	0.6	0.6

2.2.2. Rheology Test

To study the dynamic viscosity of three lubricating oils, steady-state rheological tests were conducted at 30 °C, 70 °C and 130 °C using a rheometer (MCR302, Anton Paar, Graz, Austria), the maximum torque of the rheometer is 200 mN·m, and the torque resolution is 0.1 nN·m, steady-state experiments were performed at different shear strain rates, rotor selection tapered plate cp50-1. In the steady-state test, the shear strain rate ranges from 0.1 to 1000 s^{−1}, and the dynamic viscosity at different shear rates is obtained. All samples were tested at least three times to minimize test error.

2.2.3. Elastohydrodynamic Friction Experiment

Elastohydrodynamic friction tests are performed using rotation patterns on the Mini-Traction Machine (MTM, PCS Instruments, Ltd., London, UK). A friction pair consisting of a ball and a disc was used. The structure sketch of the MTM is shown in Figure 1. The ball is used to simulate the roller in the rolling bearing, and the disc simulates the raceway in the rolling bearing, and the test ball and disc are driven by two independent servo motors, respectively. The ball and disc specimens used are made of AISI 52100 steel with a hardness of 600 HV, the diameter of the ball is 19 mm, the diameter of the disc is 46 mm, the roughness values of the disc and ball are Ra 10 nm and Ra 15 nm, respectively, so the combined roughness value is 18 nm. According to the Hamrock–Dowson Formula (1) [22], the minimum film thickness of lubricating oils under elastohydrodynamic lubrication is more than 100 nm. Therefore, the film thickness ratio λ (the ratio of film thickness to the

comprehensive surface roughness R_a) is more than 3, and the contact area is in a state of fully flooded elastohydrodynamic lubrication.

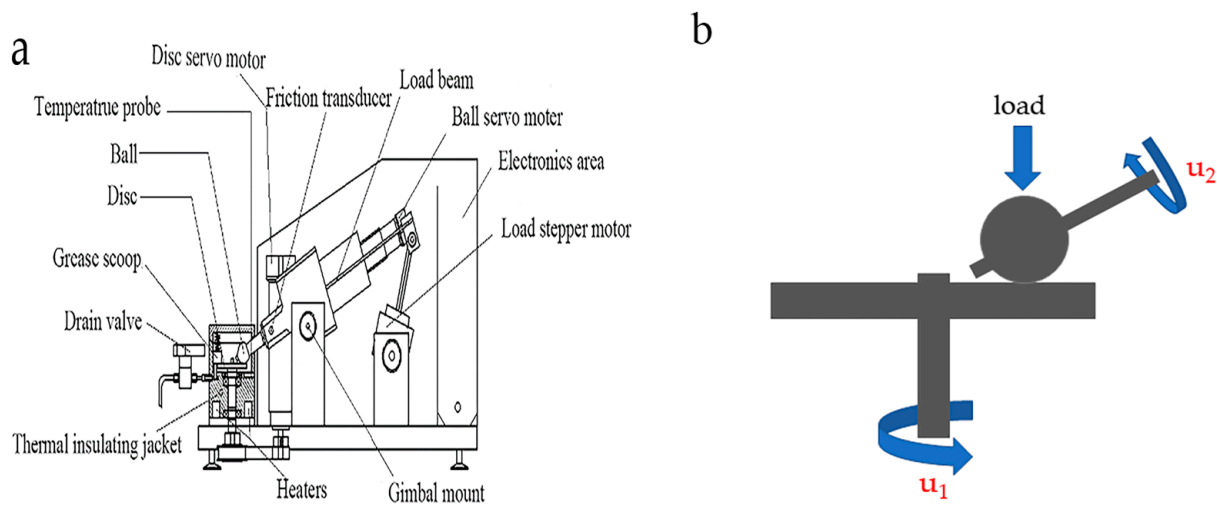


Figure 1. MTM structure sketch (a) and schematic representation of friction (b).

Hamrock–Dowson formula:

$$h_{min} = U^{0.68} G^{0.49} W^{-0.073} (1 - e^{-0.68k}) R \quad (1)$$

$$U = \eta U / (E^* R) \quad (2)$$

$$G = \alpha E^* \quad (3)$$

$$W = W / (E^* R^2) \quad (4)$$

In Formula (1): U is the dimensionless velocity parameter, G is the dimensionless material parameter, W is the dimensionless load parameter, k is the ellipticity, E^* is the equivalent elastic shear modulus, and R is the equivalent radius of curvature.

The rolling speed is defined as $u = (u_1 + u_2)/2$, the slide-to-roll ratio is defined as $s = \left(\frac{2(u_1 - u_2)}{u_1 + u_2} \right) \times 100\%$, where: u_1 is the linear velocity of the disc at the contact point and u_2 is the linear velocity of the ball at the contact point. The ball and disc were placed in a closed, temperature-controlled pot, to which the oil of the test was added in a quantity sufficient to immerse the disc specimen. The temperature-controlled pot is heated by two cylinder heaters underneath it to obtain oil at different temperatures, which can be measured by a thermocouple extending underneath the pot. The temperature measurement accuracy of thermocouple is 0.5 °C. The rolling speeds are 0.2 m/s, 2.4 m/s, and 3.2 m/s, and the set loads are 24 N, 38 N and 70 N. The corresponding Hertzian contact stresses are 0.8 GPa, 1.0 GPa and 1.2 GPa, respectively. Set the ambient temperature: 30 °C, 70 °C and 130 °C, and the slide-to-roll ratio of this test is set to 0%~50%.

2.2.4. Boundary Friction Experiment

Friction performance testing of three lubricating oils at 30 °C and 130 °C using the reciprocating mode of a Mini-Traction Machine (MTM, PCS Instruments, Ltd., London, UK). Pin and disc specimens were used for the test friction pair, which were made of AISI 52100 steel with a pin tip diameter of 1 mm, a disc diameter of 46 mm and a roughness value R_a of 275 nm. From the Hamrock–Dowson formula (1), the film thickness ratio in this lubricated state is calculated to range from 0.18 to 0.25 when $\lambda < 1$, the lubricated state

belongs to the boundary lubricated state. The test set was loaded with 38 N at a frequency of 10 Hz and a reciprocating amplitude of 5 mm for a test time of 30 min. Before the test, the friction pair was placed in petroleum ether for ultrasonic cleaning, and then they were mounted on the test machine and we used a pipette to apply 3–4 drops of lubricating oil to the contact surface. COF data is automatically recorded by the computer connected to MTM, and the test data is the average of three repeated tests.

3. Results and Analysis

3.1. Viscosity-Temperature Characteristics

According to Table A1 (Appendix A), the curves of kinematic viscosity versus temperature for the three lubricating oils are shown in Figure 2, where the data points are the measured data from the test and the solid lines are the fitted curves calculated from the Vogel–Fulcher–Tammann (VFT) model [23].

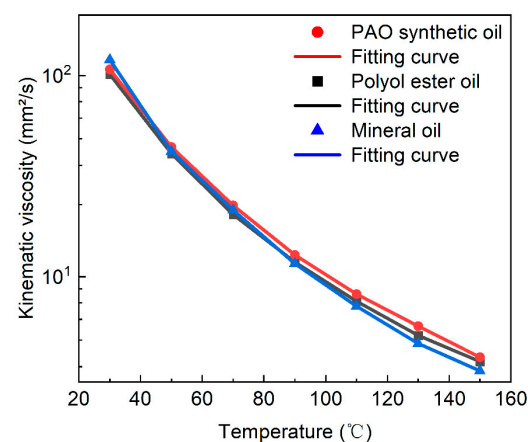


Figure 2. Viscosity-temperature data point plot and fitted curves for three lubricating oils.

The VFT model is: $v = a \times \exp\left(\frac{b}{T+273+c}\right)$.

Where a , b , c are coefficients to be determined; v is the kinematic viscosity in mm^2/s ; T is the temperature in $^{\circ}\text{C}$.

Based on the viscosity-temperature data of the three lubricating oils measured in the test, the VFT model was fitted to the measured data using a least squares method, and the VFT models for the three lubricating oils were derived as follows:

PAO synthetic oil: $v = 0.094 \times \exp\left(\frac{982.51}{T+273-163.49}\right)$.

Polyol ester oil: $v = 0.105 \times \exp\left(\frac{902.99}{T+273-171.65}\right)$.

Paraffin-based mineral oil: $v = 0.193 \times \exp\left(\frac{671.86}{T+273-198.57}\right)$.

The three fitted curves calculated with the VFT model in Figure 2 match the measured data with correlation coefficients of 0.99998, 0.99999, and 0.99996, respectively.

From Figure 2, it can be concluded that the kinematic viscosity of the three lubricating oils gradually decreases with increasing temperature, since the viscosity of a lubricant is determined by the gravity and momentum between molecules. An increase in temperature leads to an increase in the speed of molecular motion in the lubricant, thus increasing molecular momentum, and an increase in molecular speed also leads to an increase in intermolecular spacing, thus decreasing the intermolecular gravity. Under the combined effect of the above two factors, the kinematic viscosity of the lubricating oil is reduced. According to Figure 2, it can be seen that the kinematic viscosity of mineral oil varies the most with temperature, so its viscosity-temperature performance is poor, while the kinematic viscosity of PAO synthetic oil and polyol ester oil varies less with temperature, so their viscosity-temperature performances are better.

3.2. Rheological Properties

During the motion of the lubricating oil, there is a tangential friction between the lubricating oil and the contact surface, which causes the lubricating oil to undergo shear deformation, which is called dynamic viscosity or shear viscosity. Figure 3 shows the dynamic viscosity–shear rate curves of three lubricating oils at different temperatures and the maximum relative standard deviation (RSD) of each curve. As can be seen from the plots, the dynamic viscosity first decreases and then remains almost constant as the shear rate increases for different temperatures. At low shear rates, the decrease in dynamic viscosity of lubricating oil is due to the limitations of the instrument in the low torque limits [24] and the inertial and edge effects. The dynamic viscosity of the mineral oil is the largest, followed by polyol ester oil and PAO synthetic oil.

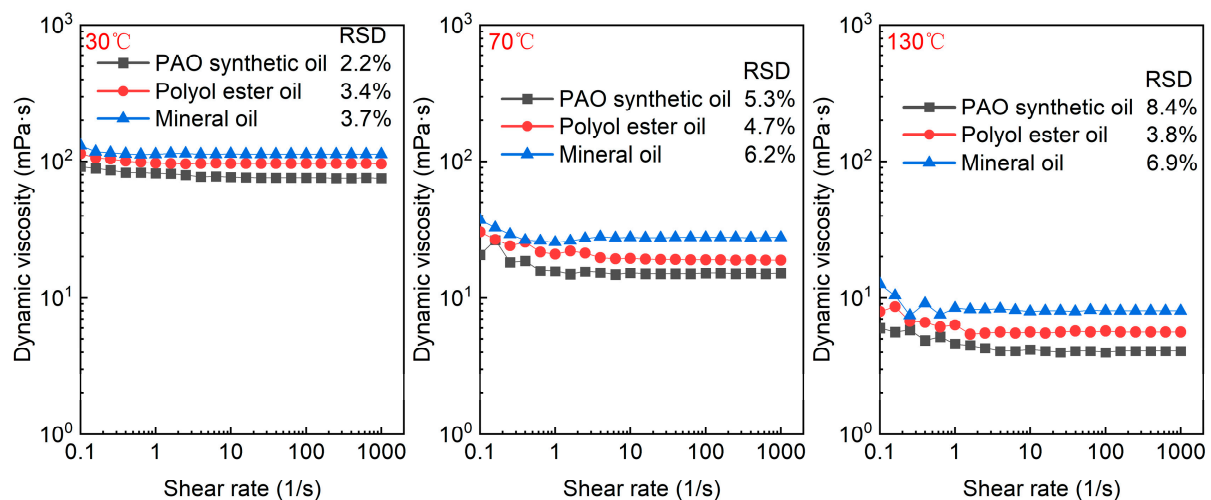


Figure 3. Dynamic viscosity–shear rate curves of three lubricating oils at different temperatures.

3.3. Elastohydrodynamic Friction Characteristics

3.3.1. Effect of Rolling Speed on Friction Characteristics of Three Lubricating Oils

Figure 4 shows the variation of COF with the slide-to-roll ratio for three lubricating oils (1#, 2#, 3#) at rolling speeds of 0.2 m/s, 2.4 m/s and 3.2 m/s, a contact load of 24 N and an ambient temperature of 30 °C. It can be seen from the figure that the COF of the three lubricating oils generally increase with the increase in the slide-to-roll ratio; when the slide-to-roll ratio is less than 10%, the COF of the three lubricating oils increases rapidly, and then the increase in the COF of the three lubricating oils slows down or slightly decreases. For rolling speeds higher than or equal to 2.4 m/s and slide-to-roll ratios increasing to higher values, the COF of the three lubricating oils remained stable or decreased slightly with an increasing slide-to-roll ratio. The COF of the three lubricating oils decreases with the increase in rolling speed, which is because the greater the rolling speed, the more oil can be entrained from the inlet area into the friction contact area during the same time, and it is easier to form an oil film, and the effect of friction reduction is better. At three rolling speeds, the COF of the three lubricating oils is in the order of greater to lesser: mineral oil, polyol ester oil and PAO synthetic oil. This is related to the viscosity-pressure coefficient of the lubricating oil at this temperature and load. At this temperature, mineral oils have the highest viscosity-pressure coefficient, followed by polyol ester oils, and PAO synthetic oils have the lowest viscosity-pressure coefficient. As the rolling speed increases, the COF of paraffin-based mineral oil changes the most, that of polyol ester oil changes the second most, and that of PAO synthetic oil changes the least. It can be seen that the rolling speed variation affects the friction properties of the three lubricating oils in the order of greater to lesser influence: mineral oil, polyol ester oil and PAO synthetic oil.

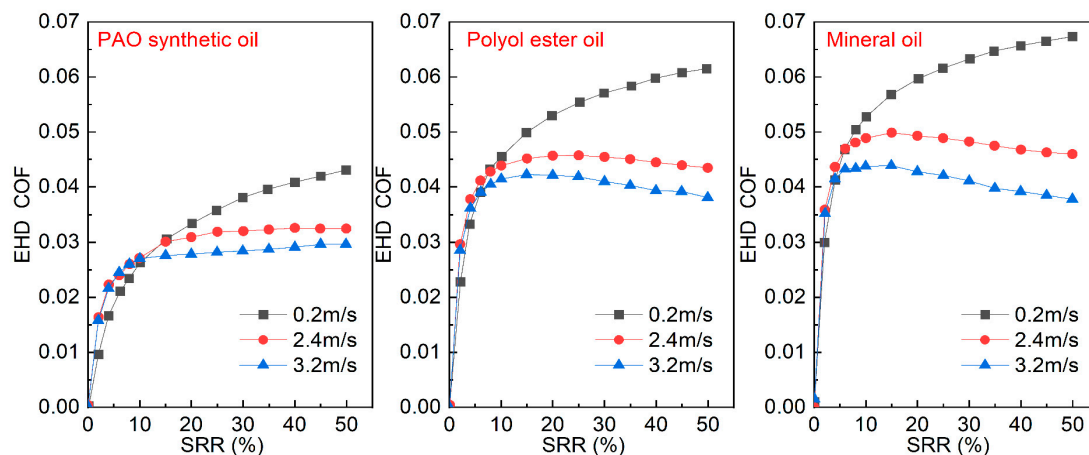


Figure 4. Friction characteristic curves for three lubricating oils (1#, 2#, 3#) at 30 °C and 24 N.

3.3.2. Effect of Contact Load on Friction Characteristics of Three Lubricating Oils

Figure 5 shows the variation of COF with the slide-to-roll ratio for three kinds of lubricant oils (1#, 2#, 3#) under the working conditions of contact load of 24 N, 38 N, and 70 N, a rolling speed of 3.2 m/s, and an ambient temperature of 30 °C. It can be seen from the graph that the greater the load, the greater the coefficient of friction, which is because the lubricating oil in the contact area was squeezed more and more seriously as the load increases, thus making the oil film formed by the lubricating oil in the contact area thinner to result in the increase in the coefficient of friction of the lubricating oils. In addition, as the load increases, the viscosity of the lubricating oil increases, which is one of the reasons for the increase in COF. It can be seen that the COF of the lubricating oil is positively correlated with the viscosity-pressure coefficient at any load. The magnitude of the change in the COF of the three lubricating oils during the load change is not very different; that is, the load change has a similar effect on the friction properties of the three lubricating oils. When the rolling speed is high (3.2 m/s in the figure), with the gradual increase in the slide-to-roll ratio, the COF of all three lubricating oils has a significant decreasing trend, which is caused by a combination of thermal effects and shear thinning, resulting in a reduction in the apparent viscosity of the lubricating oils [25]. The onset of thermal effects occurs at slide-to-roll ratios of 25%, 15% and 12% for PAO synthetic oil, polyol ester oil and paraffin-based mineral oil, respectively. It can be seen that thermal effects have the greatest influence on the friction properties of mineral oils, followed by polyol ester oils and PAO synthetic oils.

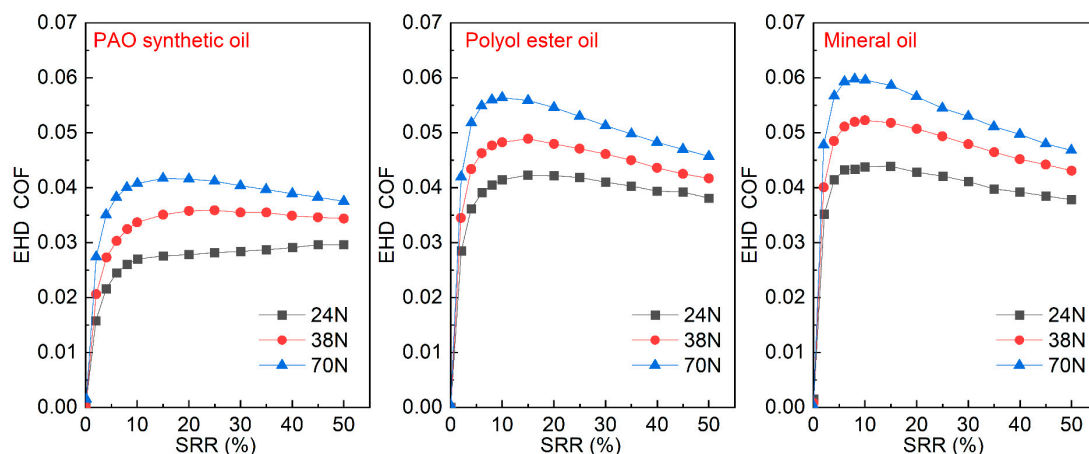


Figure 5. Friction characteristic curves for three lubricating oils (1#, 2#, 3#) at 30 °C, 3.2 m/s.

3.3.3. Effect of Ambient Temperature on Friction Characteristics of Three Lubricating Oils

Figure 6 shows the variation of COF with the slide-to-roll ratio for three lubricating oils at ambient temperatures of 30 °C, 70 °C and 130 °C, a rolling speed of 2.4 m/s, and the load of 24 N. As can be seen from the graph, the coefficient of friction of all three lubricating oils decreases significantly as the ambient temperature rises, which is mainly because the rise of temperature can result in the increase in the internal energy, microscopic motion and the molecular spacing of lubricating oil, resulting in the reduction of dynamic viscosity. In addition, mineral oils have the highest COF at any temperature, followed by polyol ester oils and PAO synthetic oils, which is proportional to the magnitude of the viscosity-pressure coefficient of the three lubricating oils.

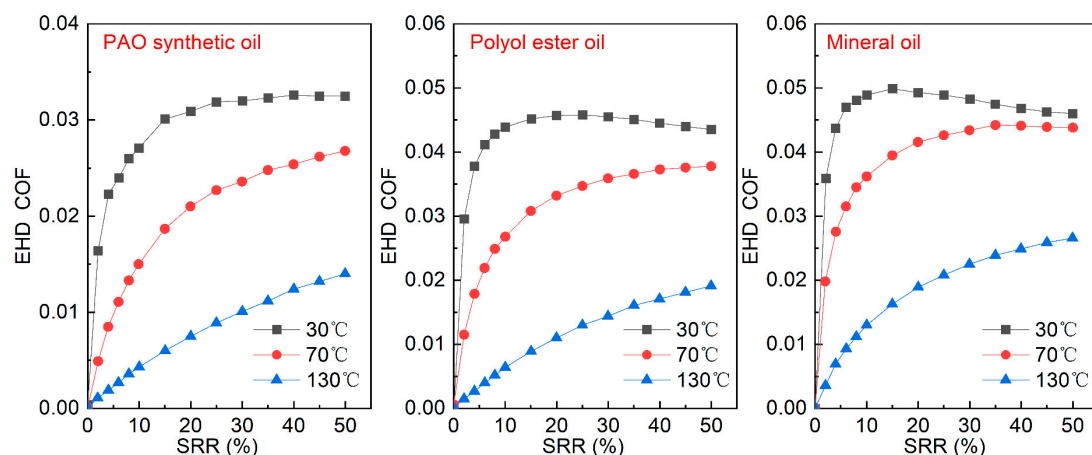


Figure 6. Friction characteristic curves for three lubricating oils (1#, 2#, 3#) at 2.4 m/s and 24 N.

3.4. Boundary Friction Characteristics

The results of the boundary friction experiments are presented in Figure 7. The Figure shows the COF of the three lubricating oils at high and low temperatures for boundary friction. The boundary COF lubricated by mineral oils is the largest, followed by polyol ester and PAO synthetic oils. This was positively correlated to the magnitude of their dynamic viscosity. According to the rheological test results in Section 3.2, the dynamic viscosity of mineral oils is the highest at 30 °C and 130 °C, followed by polyol ester and PAO synthetic oils. It can also be seen from the boundary friction test that the boundary COF of the lubricating oils is also positively correlated with their viscosity-pressure coefficients. In addition, it can be seen that the temperature has a certain influence on the friction characteristics, the coefficients of friction of the contact pairs lubricated by the three lubricating oils at 130 °C are lower than those at 30 °C. At 130 °C, the friction coefficient of the three lubricating oils changes dramatically in the run-in stage and then basically stabilizes at a constant value, implying that the friction pair enters the stable operation phase at this time, which indicates that the three lubricating oils form stable oil films to reduce friction after break-in. On the contrary, the COF of the three lubricating oils fluctuates to varying degrees throughout the test, indicating that the three oils do not form a stable oil film at 30 °C. Thus, it can be inferred that the high temperature helps the lubricant to form a stable oil film to reduce friction. This is because the Brownian motion of the lubricating oil molecules is strong and the molecular gap becomes large at high temperatures, giving the lubricating oil molecules enough space to arrange and combine to form a stable structure under continuous shear to cope with temperature changes. The time to form a stable oil film at 130 °C is shorter for PAO synthetic oil than for paraffin-based mineral oil, which is related to the structure of their molecular chains.

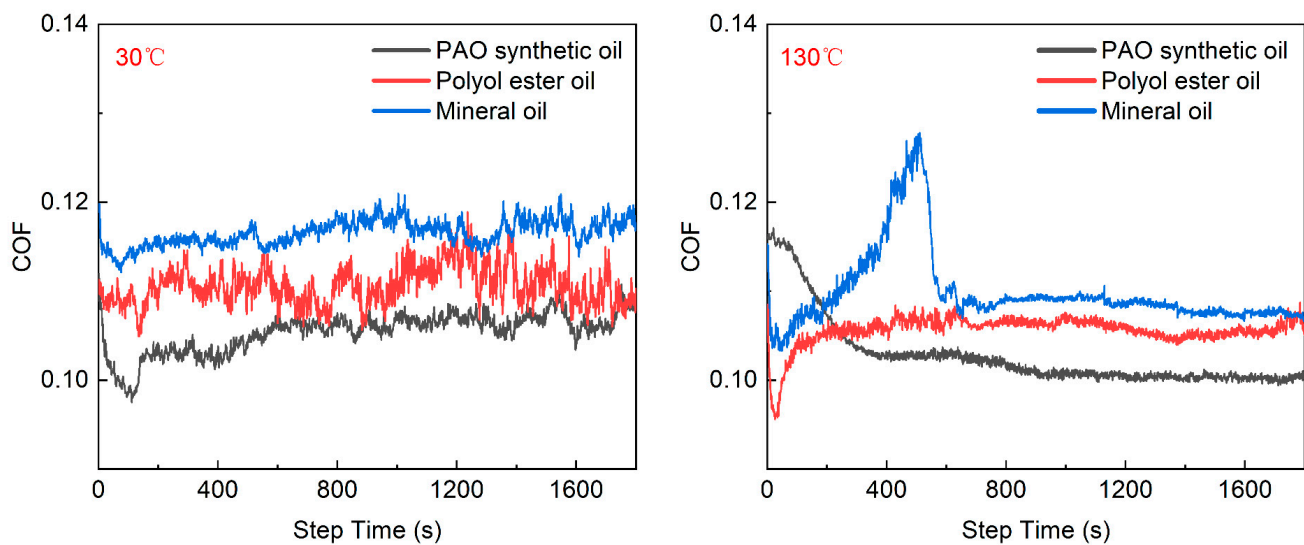


Figure 7. Boundary COF of three lubricating oils at low temperature (30 °C) and high temperature (130 °C).

To study the friction mechanism of the three lubricating oils, the lubricating oils on the disc surface before and after the friction test were characterized by Fourier transform infrared microscopy (LUMOS II, Bruker, Germany), comparing the differences in functional groups of lubricating oils before and after friction to determine if new functional groups are created during friction to affect the friction properties of the lubricating oil.

The microscopic infrared spectra of PAO synthetic oil before and after friction are given in Figure 8. Figure 8a shows the disc before the friction test and Figure 8b,c shows the disc after the friction test at 30 °C and 130 °C, respectively. Eight points on the disc were taken to measure the infrared spectrum before and after the friction test, and the measurements at point 7 were compared and analyzed. As seen in Figure 8d, the stretching vibration peaks correspond to $-\text{CH}_3$ and $-\text{CH}_2$ at 2925 cm^{-1} – 2840 cm^{-1} , the $-\text{CH}_3$ and $-\text{CH}_2$ in-plane bending vibration peaks are at 1464 cm^{-1} and 1371 cm^{-1} , and 722 cm^{-1} corresponds to the $-(\text{CH}_2)_n$ - out-of-plane wobble vibration peak.

The microscopic infrared spectra of the polyol ester oil before and after friction are given in Figure 9, with the test points taken in the same manner as for the PAO synthetic oil. Finally, the test results at point 6 of the three graphs a, b and c are selected to compare the IR spectra of polyol ester oils before and after friction. As can be seen from Figure 9d, polyol ester oil has an absorption peak at 1736 cm^{-1} ; this is the absorption peak of the stretching vibration of the $\text{C}=\text{O}$ bond in the ester group, 1464 cm^{-1} and 1361 cm^{-1} correspond to the $-\text{CH}_3$ and $-\text{CH}_2$ deformation vibration peaks, and the vibrational absorption peaks of the $\text{C}=\text{O}-\text{O}-$ bond in the ester group are at 1249 cm^{-1} , 1164 cm^{-1} and 1020 cm^{-1} .

In Figure 10, the test points are taken in the same manner as above, and finally, the test results for point 2 in the three Figure 10a–c are chosen for comparison with the mineral oil before and after friction. The IR spectra of paraffin-based mineral oils are similar to those of PAO synthetic oils, since PAO synthetic oils are refined from mineral oils and therefore the composition of both is the same.

The infrared spectra of the above three lubricating oils show that the transmission rate of the infrared spectrum of the three lubricating oils after friction at 30 °C is lower than that of the infrared spectrum after friction at 130 °C. It indicates that the amount of residual oil after friction at 30 °C is lower than that after friction at 130 °C, which indirectly demonstrates that the degree of wear at 30 °C is higher than that at 130 °C. The characteristic peaks in the IR spectra of the three lubricating oils before and after friction are the same, indicating that no new functional group is created during friction.

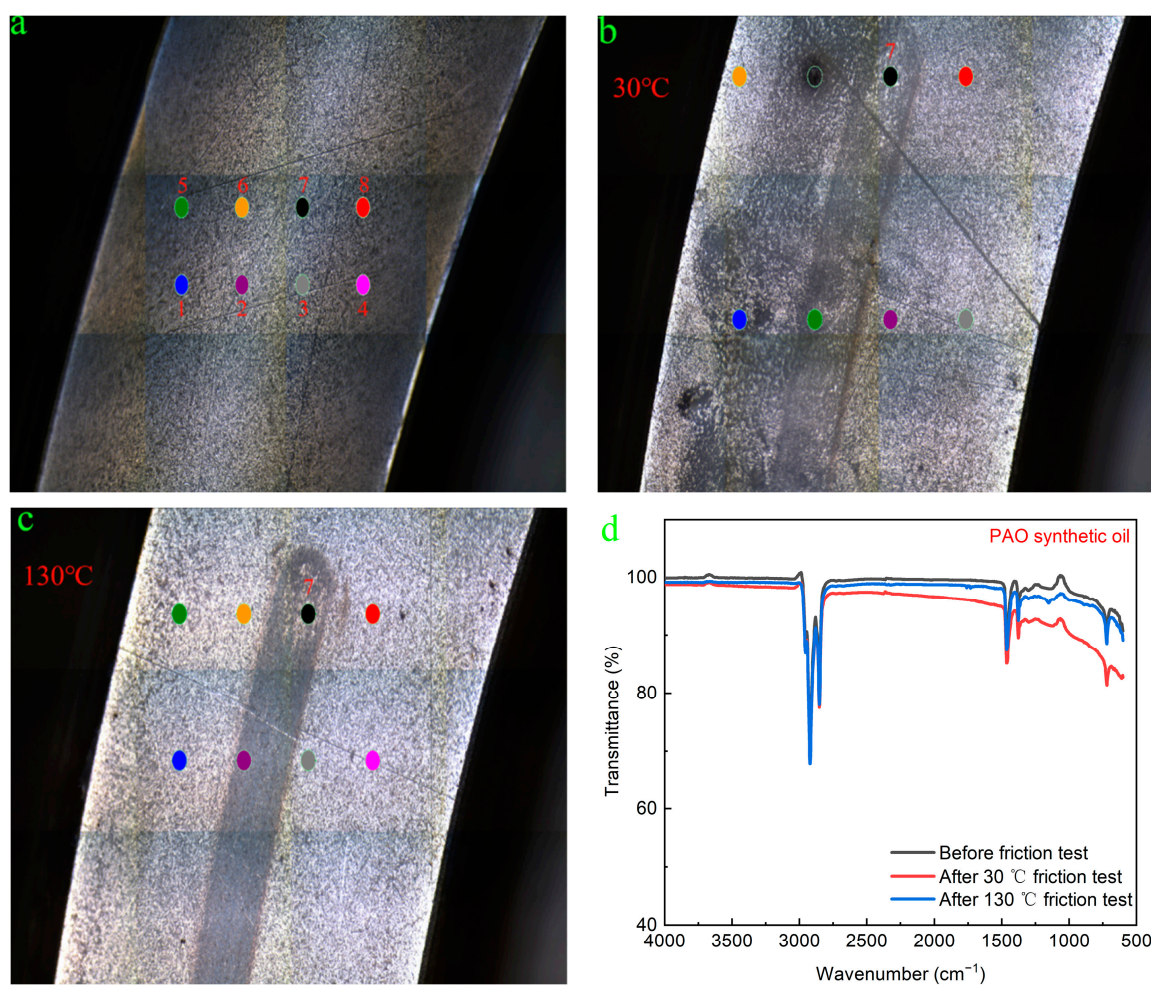


Figure 8. Micro-infrared spectra of PAO synthetic oil before and after friction: (a) disc surface before friction; (b,c) disc surface after friction test at 30 °C and 130 °C; (d) infrared spectra. (Note: The color spots are arbitrary points around the friction area. Figure d is the selection of test points within the friction area for analysis. The same goes for Figures 9 and 10).

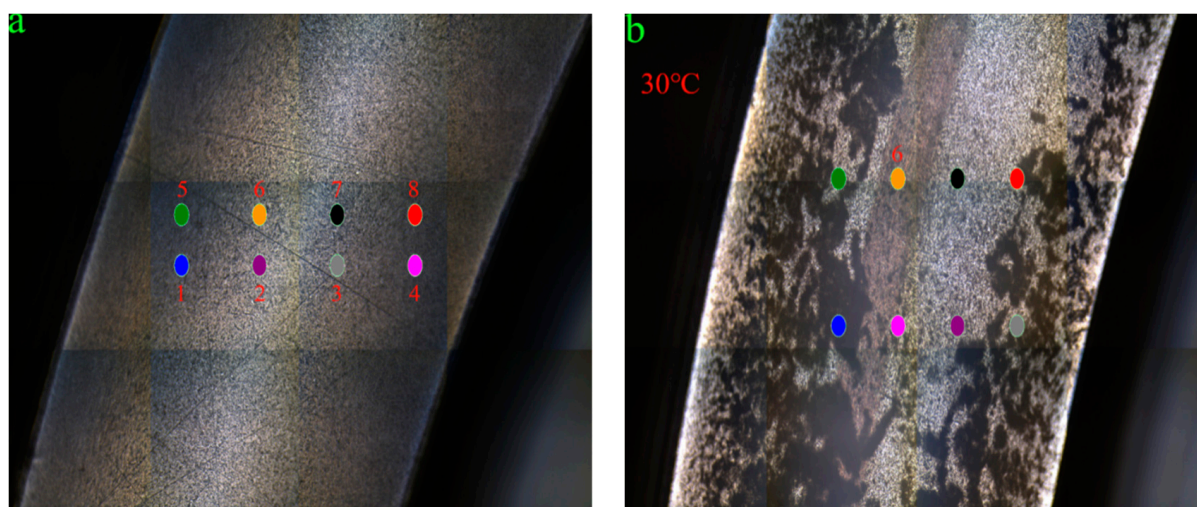


Figure 9. Cont.

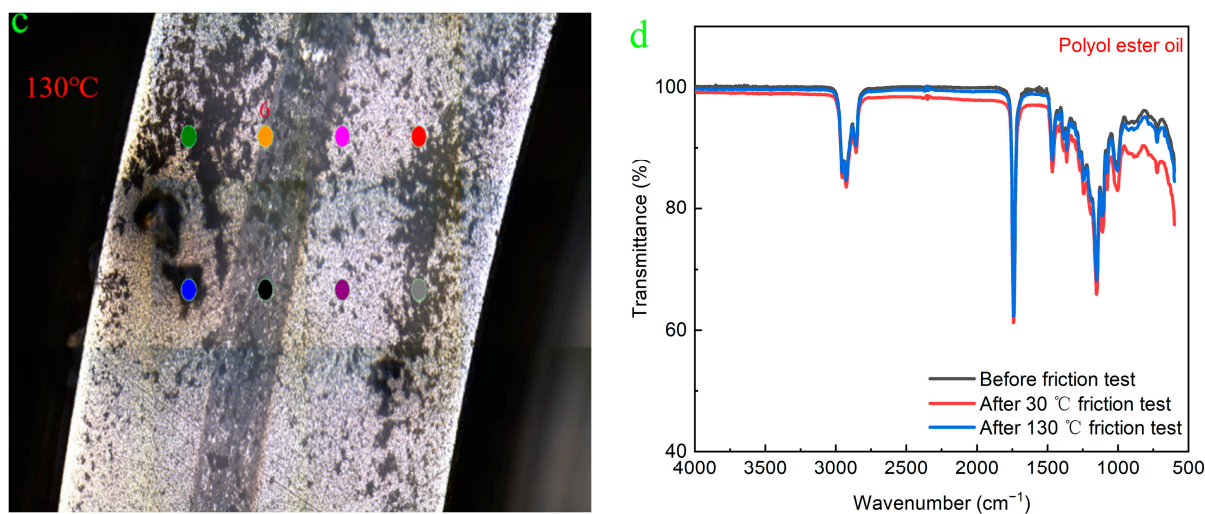


Figure 9. Micro-infrared spectra of the polyol ester oil before and after friction: (a) disc surface before friction; (b,c) disc surface after friction test at 30 °C and 130 °C; (d) infrared spectra.

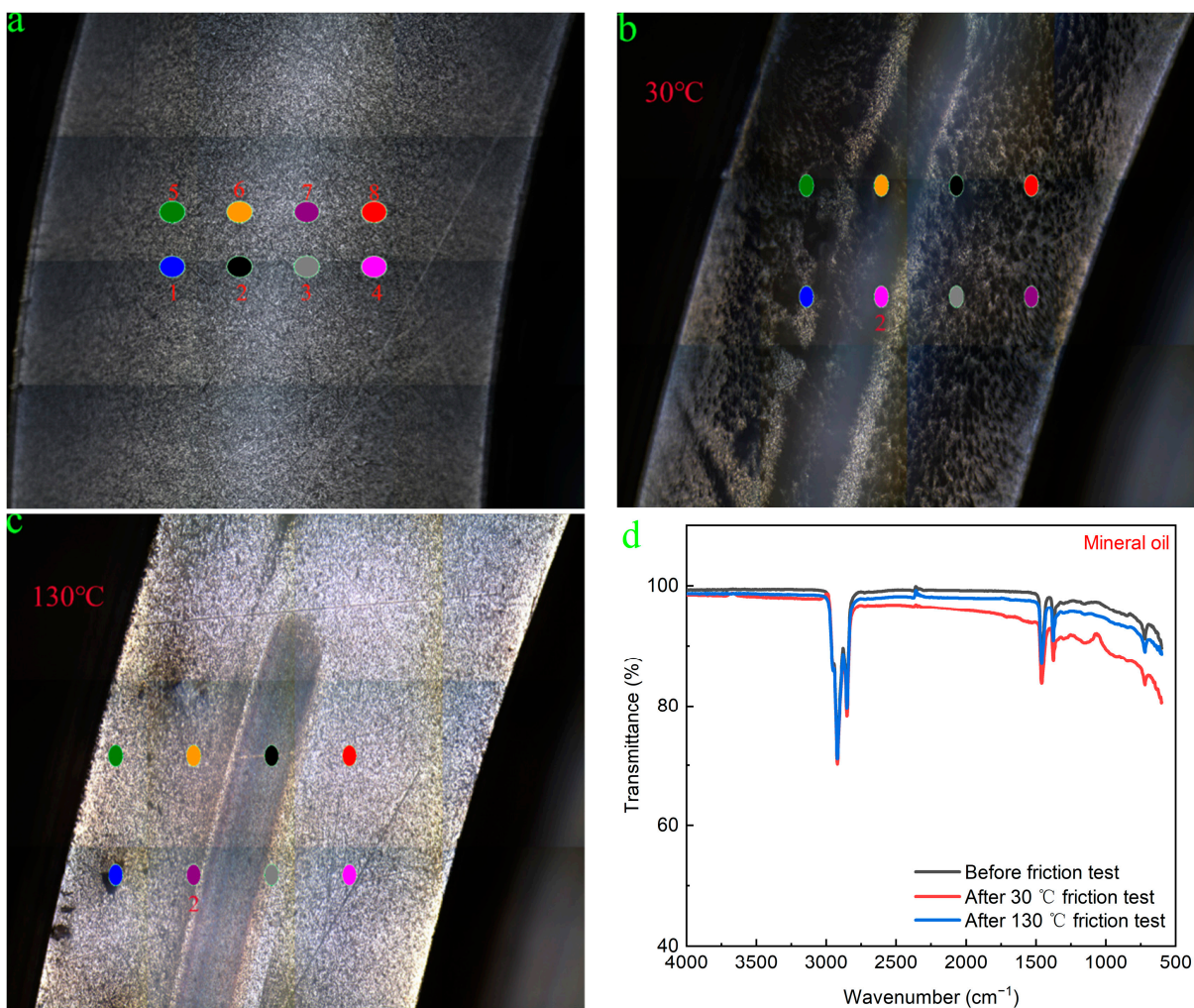


Figure 10. Micro-infrared spectra of the paraffin-based mineral oil before and after friction: (a) disc surface before friction; (b,c) disc surface after friction test at 30 °C and 130 °C; (d) infrared spectrogram.

4. Correlation between Lubricant Oil Characteristic Parameters and Friction Characteristics and Their Underlying Mechanisms

4.1. Correlation between Viscosity-Temperature Performance and Friction Characteristics

Figure 5 shows that the elastohydrodynamic COF of the mineral oil at any temperature is higher than that of the other two lubricating oils, and that the COF of ester oils is larger than that of PAO synthetic oils. Figure 11a shows the elastohydrodynamic COF of the three lubricating oils at 30 °C, 70 °C and 130 °C under the conditions of the rolling speed of 3.2 m/s, a contact load of 38 N and the slide-to-roll ratio of 15%. As can be seen in Figure 11a, the COF of the three lubricating oils all decreases significantly with the increase in temperature, indicating that the temperature rise has a great influence on the elastohydrodynamic friction properties of lubricating oils. Comparing the elastohydrodynamic COF at 30 °C to that at 130 °C, the decreasing rates of COF of PAO synthetic oils, polyol ester oils, and mineral oils are 74.64%, 72.19% and 58.11%, respectively, while the corresponding decreasing rates of kinematic viscosity are 94.69%, 94.96% and 96.16% (from Table A1), respectively. Obviously, the kinematic viscosity-temperature behavior does not explain the change of elastohydrodynamic friction behavior with temperature. Figure 11b gives the average COF derived from the boundary friction test for the three lubricating oils, and the decreasing rates of COF are 5.75%, 4.52% and 2.52%, respectively. In the same way, the kinematic viscosity-temperature behavior does not explain the variation of the boundary friction behavior with temperature.

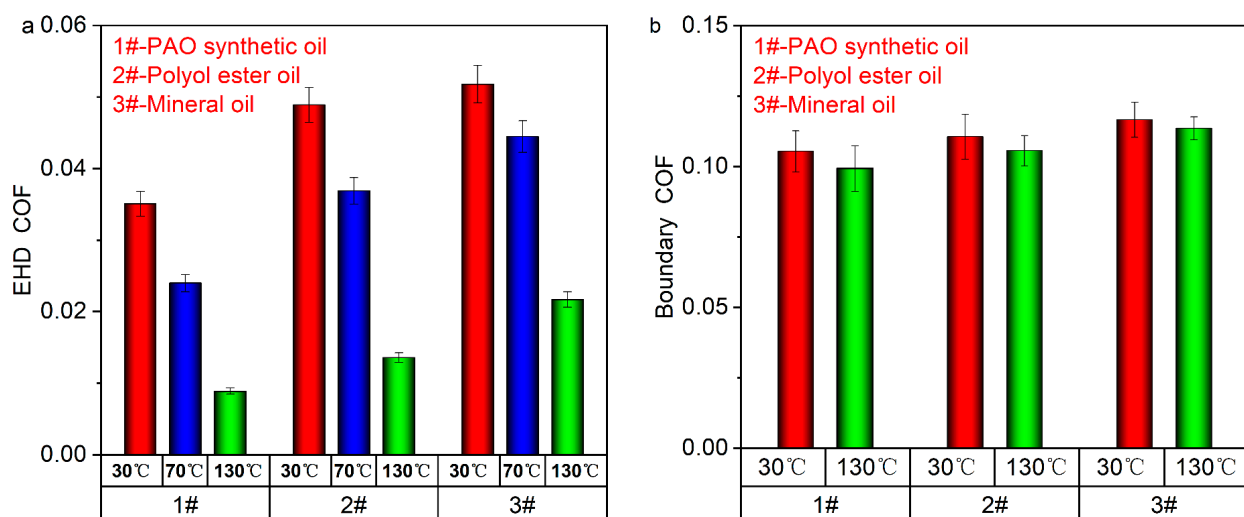


Figure 11. Elastohydrodynamic COF of three lubricating oils at different temperatures under the same rolling speed, contact load, and slide-to-roll ratio (a); mean boundary COF (b).

4.2. Correlation between Viscosity and Friction Characteristics

The kinematic and dynamic viscosities measured in this paper are important indicators to evaluate the performance of lubricating oils. Kinematic viscosity is an important indicator of the oiliness and fluidity of lubricating oils. Dynamic viscosity refers to the internal friction produced by the molecules when the oil is subjected to external forces due to relative motion [26].

It can be seen from Table 1 that the kinematic viscosities of the three lubricating oils are the same at 40 °C. When the temperature is lower than 40 °C, mineral oils have the highest viscosity, followed by PAO synthetic oils and polyol ester oils. When the temperature is higher than 40 °C and lower than 90 °C, the viscosity of PAO synthetic oils is the largest, followed by mineral oils, and the lowest is for polyol ester oils. The viscosity of PAO synthetic oil is the highest when the temperature is higher than 90 °C, followed by polyol ester oil and mineral oil. It can be seen that the kinematic viscosity of the lubricating oil is not directly related to the elastohydrodynamic COF of the lubricating oil. The kinematic

viscosity also does not determine the magnitude of the boundary COF, according to the results of the boundary friction test.

When the lubricating oil is sheared by an external force, the internal friction force between the lubricating oil molecules that hinders the motion is called dynamic viscosity. Figure 3 shows that mineral oils have the highest dynamic viscosity at any temperature, followed by polyol esters and PAO synthetic oils. The results of elastohydrodynamic and boundary friction tests show that the largest COF is for mineral oils, the second for polyol ester oils, and the last for PAO synthetic oils. As a result, the dynamic viscosity is found to be positively correlated with the boundary COF, as well as with the elastohydrodynamic COF.

4.3. Correlation between Viscosity-Pressure Coefficient and Friction Characteristics

As can be seen from Table 1, the viscosity-pressure coefficients from the largest to the smallest at room temperature for the three lubricating oils used in the test are mineral oils, polyol ester oils and PAO synthetic oils. The above experimental data indicate that the viscosity-pressure coefficient of lubricating oil is positively correlated with the elastohydrodynamic COF, which is consistent with the experimental results of Gunselt [27]. The results of the boundary friction test still show a positive correlation between the viscosity-pressure coefficient of the lubricating oil and the boundary COF.

4.4. Correlation between Viscosity Index and Friction Characteristics

The viscosity index indicates the degree to which the lubricant viscosity varies with temperature, and for oils with similar kinematic viscosity, the higher the viscosity index, the smaller the effect of temperature on the kinematic viscosity, and the better the viscosity-temperature performance, and vice versa. The three lubricating oils with the largest to smallest viscosity indices are PAO synthetic oil, polyol ester oil, and mineral oil, which coincide with the conclusion given by the viscosity-temperature curves in Figure 2. This indicates that the larger the viscosity index, the better the viscosity-temperature performance of the lubricating oil. PAO synthetic oils had the lowest COF in previous elastohydrodynamic and boundary friction tests, followed by polyols and mineral oils. Thus, it can be shown that the viscosity index is negatively correlated with the friction characteristics of the lubricating oil. A larger viscosity index indicates a smaller friction coefficient.

4.5. Mechanism of Correlation between Lubricating Oil Characteristic Parameters and Friction Characteristics

The structural formulae for the three typical lubricating oils are given in Figure 12 (Provided by Sinopec Oil Co., Ltd., Tianjin, China). PAO synthetic and mineral oils are both hydrocarbon oils. The mineral oils used in this paper belong to the class III base oils, which are isomeric alkanes with many carbon branches and complex compositions. PAO synthetic oils are Class IV base oils refined from mineral oils. They are n-alkanes with a comb-like structure and no vertical side chains. Elastohydrodynamic and boundary friction is largely dependent on the molecular structure and flexibility of lubricating oils, as they determine how easily the molecular layers move relative to each other during high-pressure shearing [28]. Zhang et al. [29] believe that oil owning linear chains, large free volume and flexible groups is conducive to reducing the elastohydrodynamic COF because linear chains give little interaction with neighboring and flexible groups (e.g., C-O-C), as well as the large free volume, which reduces the proximity of neighboring molecules and allows them room to adapt their conformation to applied stress.

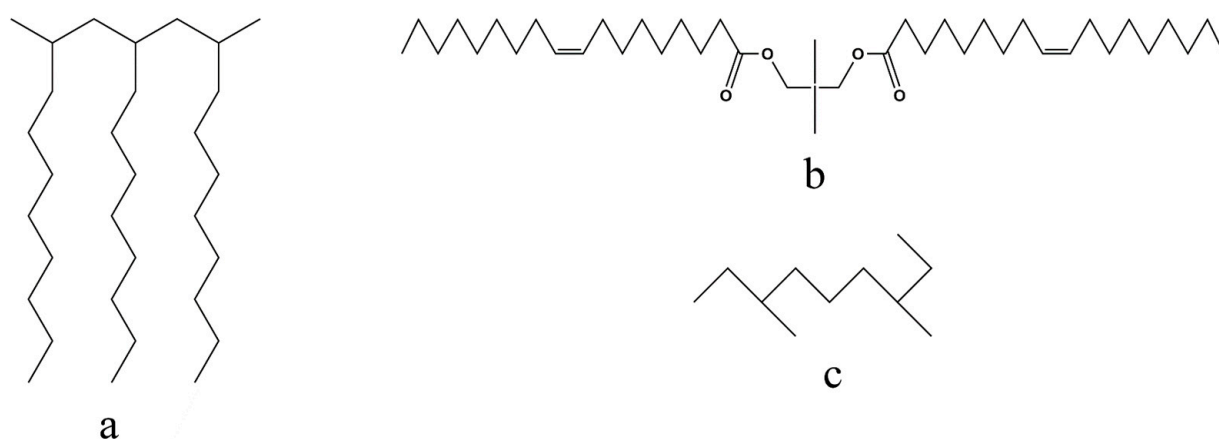


Figure 12. Structural formulae: (a) PAO synthetic oil, (b) polyol ester oil, (c) paraffin-based mineral oil.

In this paper, mineral oils contain many branching chains and do not have enough room to adapt their conformation to the applied stress, which hinders the movement of molecules to increase the friction under the action of external forces. When the temperature is increased, the intermolecular layers slip to accommodate the temperature change. The presence of branching chains reduces the free volume and there is not enough room for intermolecular adaptation. Therefore, the viscosity changes a lot, the viscosity-temperature performance is poor, and the friction performance is improved little for the mineral oil. The molecular structure of PAO synthetic oil is a long, straight alkyl chain, and the adjacent aligned chains interact less, resulting in a smaller COF of PAO than mineral oil. Polyol ester oils also exhibit relatively low COF based on flexible groups C-O-C and C=O-O—along with highly linear alkyl chains. Moreover, due to the presence of linear chains and flexible groups, PAO synthetic oils and polyol ester oils have high intermolecular polarities and are highly adaptable to temperature changes, and thus they have better viscosity-temperature performance.

There is also a general correlation between the viscosity-pressure coefficient, the viscosity-temperature performance, the viscosity index and the COF of lubricating oils [30]. By analyzing the viscosity index, viscosity-pressure coefficient (as shown in Table 1) and viscosity-temperature performance of the three lubricating oils measured in the test in this paper, it can be seen that lubricating oils with high viscosity-pressure coefficient also have low viscosity index and poor viscosity-temperature performance. The longer the chain of lubricating oil, the shorter the branch chain, and there is no aromatic ring or strong cohesive functional group, when the temperature changes, its deformation is less hindered by the surrounding molecules, the viscosity decreases with the temperature change (good viscosity temperature performance), and the viscosity index is higher. For hydrocarbon oils, the viscosity index of isomeric alkane mineral oils is lower than that of normal alkane PAO synthetic oils; that is, the viscosity-temperature behavior of PAO synthetic oils is better than that of mineral oils. For ester oils, the relative molecular weight is larger, the backbone is longer, and the viscosity index is larger. The study of Wang et al. [31] showed that as far as friction properties are concerned, the main influencing factor is the difference of viscosity index. Mineral oils with low viscosity index have branched chain structures and stiff molecules with large intramolecular resistance during friction, resulting in higher COF. There are many branching chains in mineral oils, and the degree of entanglement between the molecules is high. Molecular structures are less adaptable when pressure is increased, and the viscosity varies greatly with the pressure; that is, the viscosity-pressure coefficient increases. PAO synthetic oils and polyol ester oils with high viscosity indices have long chain structures and flexible molecular or ester groups, and their molecular structures are highly adaptable to stress and shear forces, thus reducing the COF and viscosity-pressure coefficients. This

means that lubricating oils with a high viscosity-pressure coefficient, a low viscosity index or a poor viscosity-temperature performance have high elastohydrodynamic and boundary COF.

5. Conclusions

The friction performance of three lubricating oils was tested under various operating conditions using MTM. Then, it was analyzed whether material changes occur in the lubricating oil before and after friction. The correlation between the characteristic parameters and friction performance of the three lubricating oils was summarized, and finally, the following conclusions were obtained:

1. Kinematic viscosity does not directly determine the COF of the lubricating oil. However, the larger the dynamic viscosity and viscosity-pressure coefficient of the lubricating oil, the larger the COF. Mineral oils have the largest COF, followed by polyalcohol esters and PAO synthetic oils. The kinematic viscosity-temperature behavior does not account for the shift of the elastic hydrodynamic and boundary friction properties with temperature;
2. Branching chains in mineral oils reduce the free volume, and there is not enough room for adaptation between molecules. Therefore, the viscosity changes greatly with the pressure and temperature to result in a lower viscosity index (poor viscosity-temperature performance), a higher viscosity-pressure coefficient and a higher COF;
3. Due to the presence of linear chains and flexible groups, PAO synthetic oils and polyol ester oils have high inter-molecular polarity and strong adaptability to temperature and pressure changes, so they have a higher viscosity index (better viscosity-temperature performance), a lower viscosity-pressure coefficient and a lower friction.
4. Lubricating oils with high viscosity-pressure coefficient or low viscosity index or poor viscosity-temperature properties have high elastohydrodynamic and boundary COF.

Author Contributions: Conceptualization, Y.W. and Q.Q.; methodology, Y.W. and Q.Q.; software, Q.Q. and P.Z.; validation, Y.W., Q.Q., and P.Z.; formal analysis, Y.W., Q.Q., and X.G.; investigation, Q.Q. and Z.Z.; resources, Y.W. and Q.Q.; data curation, Y.W., Q.Q., and Z.Z.; writing—original draft preparation, Q.Q., P.H., and P.Z.; writing—review and editing, Y.W. and Q.Q.; visualization, Q.Q.; supervision, Y.W.; project administration, Y.W.; funding acquisition, Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (Grant No. 52075274) and the Shandong Provincial Key Research and Development Program (Major Science and Technology Innovation Project) (Grant No. 2022CXGC010304).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

VFT Vogel–Fulcher–Tammann
COF coefficient of friction

Appendix A

Table A1. Kinematic viscosities of the three lubricating oils at different temperatures (unit: mm²/s).

Temperature/°C	30	50	70	90	110	130	150
PAO synthetic oil	107.27 ± 0.03	44.2 ± 0.04	22.61 ± 0.05	12.84 ± 0.03	8.2 ± 0.1	5.7 ± 0.09	3.99 ± 0.03
Polyol ester oil	101.58 ± 0.02	40.92 ± 0.03	20.41 ± 0.07	11.84 ± 0.06	7.55 ± 0.08	5.12 ± 0.06	3.79 ± 0.1
Paraffin-based mineral oil	119.96 ± 0.03	41.94 ± 0.05	21.4 ± 0.04	11.62 ± 0.08	7.14 ± 0.02	4.66 ± 0.04	3.41 ± 0.06

References

- Kanazawa, Y.; De Laurentis, N.; Kadiric, A. Studies of Friction in Grease-Lubricated Rolling Bearings Using Ball-on-Disc and Full Bearing Tests. *Tribol. Trans.* **2019**, *63*, 77–89. [\[CrossRef\]](#)
- De Laurentis, N.; Cann, P.; Lugt, P.M.; Kadiric, A. The Influence of Base Oil Properties on the Friction Behaviour of Lithium Greases in Rolling/Sliding Concentrated Contacts. *Tribol. Lett.* **2017**, *65*, 128. [\[CrossRef\]](#)
- Gunsell, S.; Korcek, S.; Smeeth, M.; Spikes, H.A. The Elastohydrodynamic Friction and Film Forming Properties of Lubricant Base Oils. *Tribol. Trans.* **1999**, *42*, 559–569. [\[CrossRef\]](#)
- Rounds, F.G. Effects of Lubricant Composition on Friction as Measured with Thrust Ball Bearings. *J. Chem. Eng. Data* **1960**, *5*, 499–507. [\[CrossRef\]](#)
- Yang, S.; Reddyhoff, T.; Spikes, H. Influence of Lubricant Properties on ARKL Temperature Rise and Transmission Efficiency. *Tribol. Trans.* **2013**, *56*, 1119–1136. [\[CrossRef\]](#)
- Wu, N.; Hu, N.; Zhou, G.; Wu, J. Tribological properties of lubricating oil with micro/nano-scale WS₂ particles. *J. Exp. Nanosci.* **2017**, *13*, 27–38. [\[CrossRef\]](#)
- Hu, N.; Zhang, X.; Wang, X.; Wu, N.; Wang, S. Study on Tribological Properties and Mechanisms of Different Morphology WS₂ as Lubricant Additives. *Materials* **2020**, *13*, 1522. [\[CrossRef\]](#)
- Tóth-Nagy, C.; Szabó, Á.I. Experimental investigation of the friction modifying effects of different nanoforms of graphene additives in engine lubricating oil. *FME Trans.* **2022**, *50*, 248–259. [\[CrossRef\]](#)
- Yu, B.; Wang, K.; Hu, Y.; Nan, F.; Pu, J.; Zhao, H.; Ju, P. Tribological properties of synthetic base oil containing polyhedral oligomeric silsesquioxane grafted graphene oxide. *RSC Adv.* **2018**, *8*, 23606–23614. [\[CrossRef\]](#)
- Zheng, D.; Wu, Y.-P.; Li, Z.-Y.; Cai, Z.-B. Tribological properties of WS₂/graphene nanocomposites as lubricating oil additives. *RSC Adv.* **2017**, *7*, 14060–14068. [\[CrossRef\]](#)
- Ding, J.; Fang, J.; Chen, B.; Zhang, N.; Fan, X.; Zheng, Z. Improved biodegradability and tribological performances of mineral lubricating oil by two synthetic nitrogenous heterocyclic additives. *Ind. Lubr. Tribol.* **2019**, *71*, 578–585. [\[CrossRef\]](#)
- Jin, Y.; Duan, H.; Wei, L.; Chen, S.; Qian, X.; Jia, D.; Li, J. Online infrared spectra detection of lubricating oil during friction process at high temperature. *Ind. Lubr. Tribol.* **2018**, *70*, 1294–1302. [\[CrossRef\]](#)
- Hentschel, K.-H. The influence of molecular structure on the frictional behaviour of lubricating fluids. *J. Synth. Lubr.* **1985**, *2*, 143–165. [\[CrossRef\]](#)
- Muraki, M. Molecular structure of synthetic hydrocarbon oils and their rheological properties governing traction characteristics. *Tribol. Int.* **1987**, *20*, 347–354. [\[CrossRef\]](#)
- Chang, H.-S.; Spikes, H.A.; Bunemann, T.F. The shear stress properties of ester lubricants in elastohydrodynamic contacts. *J. Synth. Lubr.* **1992**, *9*, 91–114. [\[CrossRef\]](#)
- Michaelis, K.; Höhn, B.; Hinterstoißer, M. Influence factors on gearbox power loss. *Ind. Lubr. Tribol.* **2011**, *63*, 46–55. [\[CrossRef\]](#)
- Robinson, J.W.; Zhou, Y.; Qu, J.; Bays, J.T.; Cosimbescu, L. Highly branched polyethylenes as lubricant viscosity and friction modifiers. *React. Funct. Polym.* **2016**, *109*, 52–55. [\[CrossRef\]](#)
- Hu, C.; Ai, J.; Ma, L.; Wen, P.; Fan, M.; Zhou, F.; Liu, W. Ester Oils Prepared from Fully Renewable Resources and Their Lubricant Base Oil Properties. *ACS Omega* **2021**, *6*, 16343–16355. [\[CrossRef\]](#)
- Guan, S.; Liu, X.; Zhang, Y.; Liu, Y.; Wang, L.; Liu, Y. Synthesis and Characterization of Polycaprolactone Modified Trimellitate Nano-Lubricant. *Materials* **2019**, *12*, 2273. [\[CrossRef\]](#)
- Biresaw, G.; Bantchev, G.B. Pressure Viscosity Coefficient of Vegetable Oils. *Tribol. Lett.* **2013**, *49*, 501–512. [\[CrossRef\]](#)
- Wen, S.; Huang, P. *Principles of Tribology*; John Wiley and Sons: Hoboken, NJ, USA, 2011. [\[CrossRef\]](#)
- Hamrock, B.J.; Dowson, D. Isothermal Elastohydrodynamic Lubrication of Point Contacts: Part III—Fully Flooded Results. *J. Lubr. Technol.* **1977**, *99*, 264–276. [\[CrossRef\]](#)
- Tammann, G.; Hesse, W. Die Abhängigkeit der Viskosität von der Temperatur bei unterkühlten Flüssigkeiten. *Z. Anorg. Allg. Chem.* **1926**, *156*, 245–257. [\[CrossRef\]](#)
- Ewoldt, R.H.; Johnston, M.T.; Caretta, L.M. Experimental challenges in shear rheology: How to avoid bad data. In *Complex Fluids in Biological Systems*; Springer: New York, NY, USA, 2015; pp. 207–241. [\[CrossRef\]](#)
- Habchi, W.; Bair, S.; Vergne, P. On friction regimes in quantitative elastohydrodynamics. *Tribol. Int.* **2013**, *58*, 107–117. [\[CrossRef\]](#)
- Fan, M.; Ai, J.; Zhang, S.; Yang, C.; Du, X.; Wen, P.; Ye, X.; Zhou, F.; Liu, W. Lubricating properties of ester oil prepared from bio-based 2,5-furandicarboxylic acid. *Friction* **2019**, *8*, 360–369. [\[CrossRef\]](#)

27. Gentle, C.R.; Cameron, A. An Investigation of Traction in Elastohydrodynamic Point Contacts Using Optical Interferometry. *A S L E Trans.* **1975**, *18*, 222–228. [[CrossRef](#)]
28. Spikes, H. Basics of EHL for practical application. *Lubr. Sci.* **2014**, *27*, 45–67. [[CrossRef](#)]
29. Zhang, J.; Tan, A.; Spikes, H. Effect of Base Oil Structure on Elastohydrodynamic Friction. *Tribol. Lett.* **2016**, *65*, 13. [[CrossRef](#)]
30. Spikes, H. A Thermodynamic Approach to Viscosity. *Tribol. Trans.* **1990**, *33*, 140–148. [[CrossRef](#)]
31. Wang, W.; Li, P.; Sheng, S.; Tian, H.; Zhang, H.; Zhang, X. Influence of Hydrocarbon Base Oil Molecular Structure on Lubricating Properties in Nano-scale Thin Film. *Tribol. Lett.* **2019**, *67*, 111. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.