The Effect of Temperature on the Tribological Behavior of RBD Palm Stearin

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The Effect of Temperature on the Tribological Behavior of RBD Palm Stearin

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The wide use of petroleum-based oils raises concerns with regard to pollution, and the rising of awareness of greenhouse gases has created a demand for the use of environmentally friendly and biodegradable lubricants for industrial applications. Vegetable oils are one of the bio-oils that have been promoted as a replacement for petroleum products, in part due to their environmentally friendly characteristics; they are non-toxic, biodegradable, and easy to dispose of. Many researchers have performed studies on sunflower oil, corn oil, and soy oil, but few have studied palm oil as a lubricant. Palm oil produced in a high-throughput manner could fulfill the demand for bio-based lubricants. In this study, the influence of temperature on friction and wear performance for refined, bleached, and deodorized (RBD) palm stearin and additive-free paraffinic mineral oil is presented. The experiments were conducted using a four-ball tribotester. Test temperatures of 55, 65, 75, and 85 °C were used. The sliding speeds were set to 1,200 rpm. Experiments were run for 1 h under a 392.4 N load. The results of RBD palm stearin were compared with those of paraffinic mineral oil. The experimental results showed that the RBD palm stearin had better performance compared to paraffinic mineral oil in terms of reducing frictional constraints.

KEY WORDS
RBD Palm Stearin; Paraffinic Mineral Oil; Four-Ball Tribotester; Friction Coefficient; Wear Scar Diameter

INTRODUCTION
The worldwide increase in concern over the health-related and environmental effects of petroleum oil, as well as its limited supply, has generated interest in the use of biodegradable products. Moreover, special attention has been paid to protecting the environment against pollution from petroleum-based lubricants. A survey by Delgado, et al. (1) found that nearly 12 million tons of lubricant waste is disposed of in the environment annually.

Biodegradable oils are becoming an important alternative to conventional lubricants as a result of the increased awareness of ecological pollution. Vegetable oil, including animal fat, was used as a lubricant thousands of years ago. As described by Nosonovsky (2), in ancient Egypt, vegetable oils were used in the construction of monuments. Thus, the use of vegetable oils as a lubricant in the industrial sector is not a new idea. For the last three decades, the lubrication industry has been trying to formulate environmentally friendly lubricants with technical characteristics equal to those of mineral oil. The advantages of choosing vegetable oil rather than oils from other sources are that they are biodegradable, less toxic compared to petroleum-based oils, easily produced, and renewable. Vegetable oils have lubricating abilities that are better than those of currently used mineral or synthetic oils because of the large amount of unsaturated and polar ester groups they contain, as reported by Alla and Richard (3). Kalin and Vizintin (4) explained that these components maintain the desired conditions during reciprocating sliding.

Randles and Wright (5) claimed that the long-chain fatty acids present in vegetable oils improve their intrinsic boundary lubrication properties. Vegetable oils have been shown to have good lubricating abilities, because they give rise to a low coefficient of friction. However, according to Bowden and Tabor (6), even though the coefficient of friction is low, the wear rate is high. This behavior is possibly due to a chemical attack on the surface by the fatty acids present in the vegetable oil. The metallic soap film rubs away during sliding and produces nonreactive detergents that increase wear.

In recent work, palm oil has been widely tested for engineering applications. The potential of palm oil as a fuel for diesel engines (Kinoshita, et al. (7); Bari, et al. (8)), hydraulic fluid (Wan Nik, et al. (9)), and lubricants (Obi and Oyinlola (10)) has been confirmed in previous studies. In the early 20th century, the Palm
Oil Research Institute of Malaysia (PORIM; presently referred to as the Malaysian Palm Oil Board, MPOB) successfully created palm oil methyl ester from crude palm oil using transesterification. The transesterification method shortened the molecular chain in the palm oil from about 57 to 20 molecules, thus improving the palm oil by reducing its viscosity and making it less polluting. In addition, Masjuki and Maleque (11) claimed that this process improved the thermal stability of the palm oil.

A study by Odi-owei, et al. (12) also showed that when scuffing takes place, thermal instability is responsible because a runaway increase in temperature takes place at some critical combination of load, speed, and material and lubricant properties. Under such conditions, a surface’s basic characteristics, such as hardness and texture, can change. Lubricant film failure criteria, which consider the critical temperature, relate failure load to temperature or sliding speed. As reported by Ravikiran and Jahanmir (13), traditionally, wear has been analyzed as a function of load rather than pressure due to the belief that wear is controlled by load alone.

Many researchers (Masjuki and Maleque (11); Yunus, et al. (14); Waleska, et al. (15)) have been using various vegetable-based oil lubricants and additives, but there are limited references to refined, bleached, and deodorized (RBD) palm stearin as a base lubricant or additive. The present research focused on investigating the lubricating properties of RBD palm stearin using a four-ball tribotester. The RBD palm stearin exists in a semi-solid state at room temperature. Additive-free paraffinic mineral oil (known simply as paraffinic mineral oil) was used as the comparative lubricant in this research. The experiments were run for 1 h at 1,200 rpm under a 392.4 N load. The results showed that RBD palm stearin demonstrated better lubricating properties compared to paraffinic mineral oil, especially in reducing the frictional constraint. However, RBD palm stearin produces higher wear at high temperatures compared to paraffinic mineral oil.

**EXPERIMENTAL METHOD**

**Apparatus**

The use of a four-ball wear machine, first described by Boerlage (16), is an established technique for investigating lubricant characteristics. This instrument uses four balls: three on the bottom and one on top. The upper ball is held in a collet at the lower end of the vertical spindle, which is driven by the motor. The bottom three balls are held firmly in a ball pot containing the lubricant being tested and are pressed against the upper rotating ball. The important components are the oil cup assembly, collet, locknut adaptor, and standard steel ball bearings. The components’ surfaces were cleaned with acetone before the tests. A schematic diagram of the four-ball tribotester is shown in Fig. 1.

**Materials**

The test balls used in this experiment were made of chrome alloy steel and met AISI E-52100 specifications. The test balls had a diameter of 12.7 mm, an extra polish (EP) grade of 25, and a hardness of 64–66 HRC. At the start of each new test, four new balls were cleaned with acetone and wiped with a lint-free industrial wipe.

![Schematic diagram of the four-ball tribotester assembly.](image)

**Lubricants**

The lubricants used for this experiment were RBD palm stearin and paraffinic mineral oil. The paraffinic mineral oil was used for comparison with the RBD palm stearin. The volume of lubricant used in this experiment was 10 mL for each test lubricant. The density and viscosity of RBD palm stearin and paraffinic mineral oil were measured and are shown in Table 1.

**Test Procedures**

In these experiments, the test temperatures, which were expected to influence the friction and wear characteristics of lubricant, were evaluated. The experiment was carried out for 1 h under a 392.4 N load and with a spindle speed (rotational speed) of 1,200 rpm. The three bottom balls in the wear test were evaluated, and the average diameter of the circular scar formed was measured. The lubricating ability of the RBD palm stearin was also evaluated based on the frictional torque produced in comparison with the paraffinic mineral oil. Prior to the experiments, all parts in the four-ball (upper and lower balls and oil cup) were cleaned thoroughly using acetone and wiped using a lint-free industrial wipe. No trace of solvent remained when the parts were assembled or when the lubricant was introduced. The steel ball bearings were placed into the oil cup assembly and the oil cup was tightened using a torque wrench to prevent the bottom steel balls from moving during the experiments. The upper spinning ball was locked inside the collet and tightened into the spindle. The test lubricant was introduced into the oil cup assembly. The

<table>
<thead>
<tr>
<th>Test Oil</th>
<th>RBD Palm Stearin</th>
<th>Paraffinic Mineral Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>862.0</td>
<td>848.0</td>
</tr>
<tr>
<td>Viscosity at 40°C (mPa·s)</td>
<td>47.0</td>
<td>96.5</td>
</tr>
<tr>
<td>Viscosity at 75°C (mPa·s)</td>
<td>17.5</td>
<td>21.5</td>
</tr>
</tbody>
</table>
researcher confirmed that the oil filled all of the voids in the test cup assembly. The oil cup assembly components were installed into the frictionless disc in the four-ball machine and, to avoid shock, the test load was applied slowly. The lubricant was then heated to the desired temperature. When the set temperature was reached, the drive motor, which was set to drive the top ball at the desired speed, was started. After the 1-h test period, the heater was turned off and the oil cup assembly was removed from the machine. The test oil was then drained from the oil cup and the scar area was wiped using a tissue. The bottom balls were placed on a microscope base that was designed to hold the balls during microscopic evaluation.

**Friction Evaluation**

A 20-kg beam-type load cell was used to measure the frictional torque. The load cell was fitted at a distance of 80 mm from the center of the spindle. The coefficients of friction in these experiments were calculated according to IP-239 standards as shown in Eq. [1], where \( \mu \) is the coefficient of friction, \( T \) is the frictional torque (kg·mm), \( W \) is the applied load (kg), and \( r \) is the distance from the center of the contact surface on the lower balls to the axis of rotation, which was determined to be 3.67 mm. A similar calculation was used by Husnawan, et al. (17) and Thorp (18).

\[
\mu = \frac{T \cdot r}{W \cdot d^2} \tag{1}
\]

The coefficient of friction plays a major role in determining the transmission efficiency via moving components where less resistance contributes to higher efficiency. Therefore, in terms of lubrication, less friction is desirable.

**Wear Tests**

The tests were carried out at a load of 40 kg (392.4 N) and at 1,200 rpm for 1 h from 55 to 85°C in 10°C increments. The wear scar diameter of the three balls was measured using a CCD microscope and scanning electron microscopy (SEM).

**Flash Temperature Parameter**

The flash temperature parameter (FTP) was calculated for all experimental conditions. The FTP is a single number that is used to express the critical flash temperature at which a lubricant will fail under given conditions. For the conditions used in the four-ball test, the following relationship was used:

\[
FTP = \frac{W}{d^2} \tag{2}
\]

where \( W \) is the load (kg) and \( d \) is the mean wear scar diameter (mm). These findings were explained in detail in previous research conducted by Bhattacharya, et al. (19) and Lane (20).

**RESULTS AND DISCUSSION**

**Coefficient of Friction**

The performance of RBD palm stearin as a lubricant was investigated using a four-ball tribotester under various bulk temperatures. Figure 2 shows the coefficient of friction of the ball bearings lubricated with RBD palm stearin (denoted PS) and paraffinic mineral oil (denoted P2). It can be seen that the coefficient of friction obtained increased when the bulk oil temperature was increased. This effect was due to the decreased lubricant viscosity caused by the increased temperature, as reported by Clark, et al. (21).

The coefficient of friction for the RBD palm stearin was lower compared to paraffinic mineral oil at 55, 65, and 75°C. However, at 85°C, the coefficient of friction for the RBD palm stearin was slightly higher compared to that for paraffinic mineral oil. According to Sharma, et al. (22), the fatty acid chains in vegetable oil permits monolayer film formation on the sliding surface, which prevents direct metal-to-metal contact. The frictional torque data were recorded by computer, and the frictional coefficient was calculated using Eq. [1]. The results are illustrated in Fig. 2. The coefficient of friction for the contact between the lubricated balls with the paraffinic mineral oil and the RBD palm stearin was increased with increasing normal loads. However, the coefficient of friction for paraffinic mineral oil was higher compared to that for the RBD palm stearin. This is because the stearic acid in the RBD palm stearin helps maintain the lubricant layer; therefore, the RBS palm stearin provides a lower coefficient of friction compared to the paraffinic mineral oil. A similar finding was reported by Syahrullail, et al. (23).

These results are similar to the results of other researchers, as shown in Table 2. As explained by Odi-owei, et al. (12), there is a good possibility that the scuffing phenomenon will occur in the first few minutes. Scuffing would cause an increment of load; however, this load would decrease when steady-state conditions were achieved. This observation was also described by Masjuki and Maleque (11). Other researchers have claimed that the fatty acid in vegetable oil (whether it comes from pure vegetable oil or a blend of vegetable oil and minerals) would reduce the coefficient of friction (Masjuki and Maleque (11); Waleska, et al. (15)) and provide better antiwear performance (Yunus, et al. (14); Adhvaryu, et al. (24)). However, the oxidation of vegetable oil when operating at high temperature should be one of the most important parameters to be alerted (Abdalla and Patel (25)).

**Mean Wear Scar Diameter**

After the experiments, the test balls (ball bearings) were separated from the oil cup and the wear scar on the surface of the
three ball bearings, which were locked at the bottom, were inspected with a CCD camera. From the images, the diameters of the wear scars were measured and average values were calculated. The distribution of the mean wear scar diameter (MWSD) was plotted as shown in Fig. 3.

At low bulk oil temperatures (55 and 65°C), the wear scar diameter on the ball bearings for both the RBD palm stearin and the paraffinic mineral oil increased with increasing temperature. The MWSD for RBD palm stearin was smaller compared to that for the paraffinic mineral oil. RBD palm stearin showed better lubricity in preventing metal-to-metal contact, as shown by the lower wear scar diameter value. However, at the higher bulk oil temperatures (75 and 85°C), the performance of the RBD palm stearin decreased, as shown by the higher wear scar diameter value compared to the paraffinic mineral oil. According to Isaac (26), the decrease in viscosity caused by the increase in temperature is attributed to the decrease in the likelihood of oil molecules forming thermally stable “molecular clusters.” This is because the viscosity of oil molecules is proportional to the effective hydrodynamic volume of the oil molecule. More ordered molecular clusters will occupy a larger volume, resulting in higher viscosities. The study by Maleque, et al. (27) also showed that, at higher temperatures, the films formed by the fatty acid chains seem to be less stable and cause comparatively higher wear compared to paraffinic mineral oil. Wu, et al. (28) and Masjuki and Maleque (29) claimed that this phenomenon could be related to the thinning of the fatty acid thin film, which acts as an effective barrier against metal-to-metal contact, resulting in the breakdown of the thin film at temperatures greater than 75°C.

**Flash Temperature Parameter**

Figure 4 shows the effect of test temperature on the flash temperature for RBD palm stearin and paraffinic mineral oil. As seen in the figure, in general, the flash temperature for paraffinic mineral oil increased with increasing test temperature. However, for

<table>
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<th>Wear Analysis</th>
<th>Coefficient of Friction</th>
<th>Lubricant</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wear scar diameter</td>
<td>0.06–0.11: before scuffing</td>
<td>SAE 10 mineral oil</td>
<td>Odi-owei, et al. (12)</td>
</tr>
<tr>
<td>SEM, wear particle micrograph</td>
<td>0.34–0.36: during scuffing</td>
<td>Palm kernel oil</td>
<td>Yunus, et al. (14)</td>
</tr>
<tr>
<td>Average wear scar diameter</td>
<td>Bar graph of the coefficient of friction: palm kernel methyl ester showed comparable wear and friction properties to commercial hydraulic oil</td>
<td>Refined and modified soybean oil</td>
<td>Waleska, et al. (15)</td>
</tr>
<tr>
<td>Wear characteristic</td>
<td>Average coefficient of friction: soybean oil shows a low coefficient of friction</td>
<td>Palm oil methyl ester</td>
<td>Masjuki and Maleque (11)</td>
</tr>
<tr>
<td>Wear scar diameter</td>
<td>Coefficient of friction: 5% palm oil methyl ester decreased the coefficient of friction</td>
<td>Modified soybean oil</td>
<td>Adhvaryu, et al. (24)</td>
</tr>
<tr>
<td>Micrograph of the worn surface</td>
<td>Coefficient of friction: fatty acids enhanced the antiwear properties of vegetable oil</td>
<td>Coconut oil, sunflower oil, rapeseed, palm olein</td>
<td>Abdalla and Patel (25)</td>
</tr>
<tr>
<td>Wear track analysis</td>
<td>No graph of the coefficient of friction</td>
<td></td>
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</tr>
<tr>
<td>SEM analysis: wear morphology</td>
<td>Vegetable oils show almost similar wear scar diameter compared to mineral oil</td>
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</table>

![Fig. 3—Wear scar diameter.](image)

![Fig. 4—Flash temperature parameter for RBD palm stearin and paraffinic mineral oil under various test temperatures.](image)
Fig. 5—Wear scars of ball specimens: (a) RBD palm stearin, 55°C; (b) RBD palm stearin, 65°C; (c) RBD palm stearin, 75°C; (d) RBD palm stearin, 85°C; (e) paraffinic mineral oil, 55°C; (f) paraffinic mineral oil, 65°C; (g) paraffinic mineral oil, 75°C; and (h) paraffinic mineral oil, 85°C. (color figure available online.)
RBD palm stearin, the opposite results were seen. The maximum flash temperature for paraffinic mineral oil was obtained at a test temperature of 85°C, but for RBD palm stearin the maximum flash temperature was obtained at 55°C.

According to Bhattacharya, et al. (19), the possibility of lubricant film breakdown is greater at low flash temperatures, which indicates poor lubricity. Therefore, it was concluded that the fatty acid thin film became less stable at higher temperatures in sliding contact. Therefore, at the higher temperatures (75°C and above), paraffinic mineral oil showed better lubricating performance compared to RBD palm stearin.

Pressure is the force (normal load) per unit area. In this study, the area was the contact area of the ball bearings, which was almost circular in shape. Because the value of the normal load was constant (40 kg), the pressure on the contact area depended on the wear scar diameter. The larger the wear scar diameter, the less pressure that was applied to the contact surface. As shown in Fig. 3, at 85°C the MWSD of the ball bearings lubricated with RBD palm stearin was larger compared to those lubricated with paraffinic mineral oil, which means that the lubrication condition had collapsed and metal-to-metal contact occurred. Yu, et al. (30) stated that there is a high possibility of plastic deformation during the sliding contact that occurs at high contact pressures, which generates heat on the sliding surface. Referring to Fig. 4, the flash temperature was highest at a test temperature of 85°C. Based on this result and other studies, the possibility of plastic deformation at higher temperatures was greater for RBD palm stearin than for paraffinic mineral oil.
Worn Surface Characteristics

Figure 5 shows the representative wear scar from the bottom ball bearings for both RBD palm stearin and paraffinic mineral oil at different lubricant temperatures. For RBD palm stearin, it is clear that the wear scar diameter increased when the temperature increased. For paraffinic mineral oil, the largest wear scar was at a lubricant temperature of 65°C; however, the difference in the wear scar diameter was in the range of 0.1 mm (Fig. 3).

For the RBD palm stearin at lubricant temperatures of 55 and 65°C, the wear scar was circular. At lubricant temperatures of 75 and 85°C, the edge of the wear scar was slightly ragged and obscured by metal. With RBD palm stearin at high temperatures, the lubricant chain started to break down and metal-to-metal contact occurred. In addition, the wear particles that existed between the mating surfaces of the ball bearing caused adhesive wear. For paraffinic mineral oil at all lubricant temperatures the wear scar was circular. There was a slightly rough edge found in the wear scar at a temperature of 75°C. This observation is parallel with the results plotted in Fig. 4 for the flash temperature. RBD palm stearin had a low flash temperature at high temperatures, which means that the possibility of lubricant breakdown is high. Micrographs of the worn surfaces, produced after 1-h tests and lubricated with the RBD palm stearin and the paraffinic mineral oil under different test temperatures, are shown in Fig. 6.

The RBD palm stearin and the paraffinic mineral oil were compared in regard to the effects of temperature on the wear surfaces. At a low working temperature, a thin lubricant film with parallel grooves formed to prevent metallic contact and create smooth surface regions. Some of the grooves were deep and the others were shallow grooves in between. In this region, abrasion was seen as the dominant wear mechanism. At a high working temperature, the thin lubricant films were broken and adhesive wear appeared to be predominant. For both lubricants, material transfer occurred from one ball to another, and grooves were found on the worn surface. For RBD palm stearin, the long-chain fatty acid molecules that formed on the metal surface effectively reduced the wear and friction. A similar finding was previously reported by Farooq, et al. (31).

For experimental lubrication with paraffinic mineral oil, the ball bearings were heated above the austenizing temperature (at the local contact point) and then rapidly cooled, due to the lubricant reservoir (collet). The breakdown of the hydrocarbon lubricant in the contact zone led to increased carbon content due to the diffusion of the carbon and gases into heated deformed material. Thus, an increased coefficient of friction resulted from an increase in the operating temperature. A similar finding was previously described by Jones and Scoot (32). Haseeb, et al. (33) found that the fatty acids in RBD palm stearin undergo an oxidation process to form inorganic oxides, such as Fe$_3$O$_4$, which play an important role in the formation of a lubricant film on rubbing surfaces. This can be observed as the dark-colored zone in Fig. 6. In extreme working temperatures, the color of the lubricant may become darker due to the contamination of the inorganic oxides; analyses using Fourier transform infrared (FTIR) may be one of the best methods to find any impurities in a lubricant, as described by Waleska, et al. (15). In addition, the stearic acid in RBD palm stearin shows a greater affinity to be absorbed into the steel surfaces, as reported by Farooq, et al. (31). This interaction of the acid molecules with the steel surface resulted in the formation of chemically polymerized molecules, which play an important role in reducing friction and wear during sliding. It is the result of a tribochemical reaction on the metal surface, which reduced the wear and friction at the low working temperatures used in this experiment. Figure 7 compares the topographies of the worn surfaces for each experimental condition. The topography was measured perpendicular to the direction of rotation (perpendicular to the scar line), shown as line A-B in Fig. 6e. In this surface topography graph, the surface asperities, consisting of valleys and hills, were compared. At working temperatures of 55 and 65°C, the asperities on the worn surface for both the RBD
palm stearin and the paraffinic mineral oil were almost the same. At higher working temperatures (75 and 85°C), the worn surfaces of the ball bearings lubricated with paraffinic mineral oil no significant changes in the surface topography pattern were observed compared to paraffinic mineral oil at a low temperature. However, for the RBD palm stearin, there were a few areas where the hills collapsed, creating a slightly larger wear scar compared to lubrication with paraffinic mineral oil. When the upper and lower ball bearing make contact, in the microscopic view, the asperities junctions (hills) on the ball bearing surfaces would contact each
other. Due to the normal load applied to the operational system, the contacted asperities would deform plastically. Then, the material would be removed or plucked from the asperities on the wear surface. As explained by Williams (34), this adhesive wear phenomenon can usually be observed on a surface with a “blocky” shape or dimension (Figs. 7c and 7d). Worn material and debris (including abrasive and wear particles) was swept out of the contact and contaminated the lubricant. Due to the rotation of the upper ball bearing, the lubricant swept the contaminant to the next ball bearing contact point (ball bearing gap). Particles that were larger than the lubricant film thickness damaged the surface. In general, at this stage, the wear was classified as abrasive wear due to the long wear groove found on the worn surface. Further confirmation of the wear behavior of the ball bearing surfaces lubricated by RBD palm stearin and paraffinic mineral oil were obtained by analyzing the wear scar using SEM at appropriate magnifications, as shown in Fig. 8. Overall observation of the worn surface of the ball bearings lubricated with the RBD palm stearin at a working temperature of 55°C showed that there were uneven grooves, with varying scar depths, indicating abrasive wear. At this working temperature (55°C), fatty acid molecules in the RBD palm stearin help maintain the lubricant layer and establish the boundary lubrication condition, which effectively prevents metal-to-metal contact. The coefficient of friction was lowest value compared to other experimental conditions. A few grooves were spotted with metallic flakes dislodged from the contact surface, as shown in Fig. 8a. The flakes were continuously deforming along the groove. According to Ge, et al. (35), the flakes were formed due to plastic deformation in the sliding contact area. At a working temperature of 65°C (Fig. 8b), parallel grooves with various depths could clearly be seen; Singh and Gulati (36) reported similar parallel grooves resulting from stiff particulate debris that caused abrasion wear. Lubricant breakdown occurred at higher working temperatures of 75 and 85°C. Figures 8c and 8d clearly show the rough surface from the discontinuous plastic deformation on the worn surface caused by adhesive wear, indicating breakdown of the lubricant film (Masjuki and Maleque (11)). In the most severe conditions, the metal surface would fuse or weld. As a result, the coefficient of friction for RBD palm stearin increased with an increase in temperature. Yufu, et al. (37) reported that vegetable oil could oxidize at high temperatures, leading to corrosive wear. For paraffinic mineral oil at working temperatures of 55 and 65°C (Figs. 8e and 8f), light ploughs with a few spots of material transfer could be seen, indicating that abrasive wear was the dominant wear mechanism. At a working temperature of 75°C (Fig. 8g), parallel grooves could be seen, with no material transfer observed. As reported by Ren, et al. (38), this could be associated with abrasion caused by the debris from the detached ball bearing surface. Kim, et al. (39) suggested that a polishing process could occur in this situation, resulting in a reduced coefficient of friction (Fig. 2). At a working temperature of 85°C (Fig. 8h), the worn surface showed both shallow and deep parallel grooves with rough ploughing, indicating breakdown of the lubricant film. However, the condition was not as severe as that found for lubrication with RBD palm stearin; the coefficient of friction for the latter was slightly higher than for the paraffinic mineral oil.

CONCLUSION

The tribological behavior of RBD palm stearin at four different elevated temperatures was evaluated using a four-ball tribotester machine. All results were compared with additive-free paraffinic mineral oil. The findings can be summarized as follows:

1. RBD palm stearin showed better lubricity compared to the paraffinic mineral oil at lower test temperatures, as shown by a low coefficient of friction and less possibility of lubricant film breakdown (evaluated using the FTP value). However, at higher test temperatures, the paraffinic mineral oil showed better performance.

2. In wear scar diameter analysis under several test temperatures, the RBD palm stearin showed smaller wear scar diameters at the lower test temperatures. At higher test temperatures, the RBD palm stearin showed larger wear scar diameters compared to the paraffinic mineral oil. This is due to the fact that at high temperature, the lubricant film formed by fatty acids tended to be less stable or was more likely to break down.

3. Abrasive wear was the dominant wear mechanism for both RBD palm stearin and paraffinic mineral oil at all working temperatures; a few spots of adhesive wear were observed at a working temperature of 85°C.

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